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# Thermal conductivity of soils and rocks from the Melbourne (Australia) region

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The thermal conductivity of soils and rocks is an important property for the design of thermally active ground structures such as geothermal energy foundations and borehole heat exchange systems. This paper presents the results of a laboratory study of the thermal conductivity of soils and rocks from around Melbourne, Australia. The thermal conductivity of six soils and three rock types was experimentally measured using both a thermal needle probe and a divided bar apparatus. Soil samples were tested at a wide range of moisture contents and densities. The results demonstrated that the thermal conductivity varied with soil moisture content, density, mineralogical composition and particle size. Coarse grained soils were observed to have a larger thermal conductivity than fine grained soils. In addition, the thermal conductivity of soils increased with an increase in dry density and moisture content. Siltstone, sandstone and basalt rock samples were tested dry and water saturated. They demonstrated an increase in thermal conductivity with an increase in density when dry. However, when water saturated, siltstone and sandstone showed no significant correlation between density and thermal conductivity; whereas a linear increase in thermal conductivity with density was observed for the saturated basalt samples. These differences were attributed to both variations in mineralogy and anisotropy of each sample. The thermal conductivity data obtained from this study provides an initial database for soils and rocks from the Melbourne (Australia) region which can serve for the design of thermo-active structures installed locally and in locations with similar ground conditions.



## 1. Introduction

Thermally active ground structures, such as geothermal energy foundations and borehole heat exchange systems are gaining interest in Australia due to the great potential use as an aid in tackling climate challenges and meeting legislation requirements for greenhouse gas emissions (DeMoel et al., 2010; Bouazza et al., 2011; Johnston et al., 2011; Wang et al., 2012). Their efficiency and performance are dependent on the heat transfer and storage capacity of soils and rocks in which they are embedded in. In this respect, knowledge of the thermal conductivity of local soils and rocks is essential for their design. However, information on thermal conductivity of Australian soils is scarce and feasibility design values often rely on data sourced from overseas.

Measurement of soil and rock thermal conductivity can be undertaken by either laboratory or field methods (Mickley, 1951; Van Rooyen and Winterkorn, 1957; Nakshabandi and Kohnke, 1965; Penner et al., 1975; Farouki, 1986; Ewen and Thomas, 1987; Brandon and Mitchell, 1989; Abu-Hamdeh and Reeder, 2000; Ochsner et al., 2001; Dali Naidu and Singh, 2004; Chen, 2007; Abuel-Naga et al., 2008, 2009; Singh and Bouazza, 2013). Field tests tend to give a gross value of thermal conductivity, while the laboratory tests provide a point value. Laboratory methods are typically used as they are relatively inexpensive, quick and allow for greater control over the boundary conditions compared to field methods. Furthermore, laboratory tests are useful for the calculation of the length of the heat exchangers thus allowing the cost evaluation of a thermo active ground structure project to be made especially during planning stages. In some other cases such as in the case of smaller residential projects where in-situ tests are seldom carried out due to financial constraints, only laboratory tests can be used to calculate the length of heat exchangers.

Laboratory approaches to measuring soil and rock thermal conductivity can be divided into two main groups: steady state and transient state. Both methods have been used extensively to study the thermal conductivity of soils. Mitchell and Kao (1978) evaluated several methods of testing soil thermal conductivity and found that transient state methods, in particular the thermal needle probe, were most suitable because of their relative simplicity and short measurement time. Jackson and Taylor (1986) found that the main advantages of transient state methods were: (1) moisture migration in response to temperature

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gradients was minimised and (2) a long wait for thermal gradients to equilibrate was not required. However, transient methods such as thermal needle probes can be difficult to apply to rocks. Samples large enough to eliminate boundary effects of the needle probe are required, and contact resistance errors are created when a hole is drilled into the rock sample. Therefore, in this study a transient state thermal needle probe was used to measure the thermal properties of soil samples and a steady state apparatus was used to measure the thermal conductivity of rock samples.

This paper presents the results of an experimental study on the effects that moisture content, density and mineralogy have on the thermal conductivity of six soils and three rock types from the Melbourne region. Thus, providing the necessary information needed for the design of thermo-active structures installed locally and in locations with similar ground conditions.

## 2. Thermal conductivity measurement methods

### 2.1. Thermal needle probe

The thermal needle probe used in this study was a commercially manufactured probe referred to as a KD2 Pro thermal properties analyser manufactured by Decagon Devices. It is based on the infinite line heat source theory and calculates the thermal conductivity by monitoring the dissipation of heat from the needle probe. Its use in the present investigation followed the procedure described in the KD2 Pro user manual (Decagon Devices, 2006). The needle probe was heated for a time, $t_b$ (approximately 30 s) where the temperature was monitored in the needle during heating, and for an additional time of $t_b$ after heating. The final two thirds of the heating and cooling data are used in a simultaneous least squares computation which determines the thermal conductivity while removing the effects of temperature drift during computation.

In this study the KS-1 probe (60 mm in length and 1.27 mm in diameter) was used to measure the thermal conductivity of the soils. The probe was calibrated prior to testing using glycerol which was supplied by the manufacturer. The manufacturer claims that the needle can measure the thermal conductivity to an accuracy of $\pm$5% between 0.2 and 2 W/mK. The KD2 Pro calculates the accuracy of each measurement by comparing the experimental temperature data to the modelled temperature predicted by the analytical solution of infinite line source theory by Carslaw and Jaeger (1959). The difference between experimental and modelled temperature is displayed as the coefficient of correlation. Measurements with correlations of less than 0.9995 were discarded and retested.

A small number of measurements on samples of moist, dense sands were outside the manufacturer's recommended measurement range. Thermal conductivities of up to 3 W/mK were measured in these samples. We consider the thermal needle probe used in this study capable of measurements up to 3 W/mK without any significant errors in these types of soils. This was backed up by the coefficient of correlation readings of above 0.9998 from the KD2 Pro in all samples tested above 2 W/mK.

The accuracy of the probe was found to be influenced by contact resistance errors which were created during insertion of the needle into the soil specimen. Contact resistance errors were found to be most common in low and high density soils. In soils with low densities, insertion of the needle caused disturbance of soil which resulted in regions of poor contact between the soil and the probe. For higher densities it was not possible to push the thermal needle into the samples; in these cases a 1.3 mm diameter hole was pre-drilled in the soil to facilitate needle insertion. However, the drilling caused extra disturbance within the soil and thus regions of poor soil probe contact developed. To reduce the poor contact the needle was coated with high thermal conductivity grease (thermal grease) prior to insertion. In all cases the use of thermal grease improved the accuracy of the thermal needle probe. However, in some instances in loose soils this did not improve the accuracy to an acceptable level (coefficient of correlation of 0.9995). In these cases the thermal needle probe was removed from the sample, reinserted in a different location and the measurement was repeated.

### 2.2. Divided bar apparatus

A steady state method in the form of a divided bar apparatus was adopted for testing the rock samples. This was used instead of the thermal needle probe as it was impractical to insert a needle into the rock samples. The divided bar apparatus used in this study is illustrated in Fig. 1 and was designed based on devices described by Sass et al. (1984), Beardsmore and Cull (2001) and Jones (2003). The divided bar consists of two temperature controlled plates at the top and bottom of the cell. The bottom plate contains an electric heater which generates a heat source of constant temperature, while cool water is circulated through the top plate from a temperate controlled water bath. Heat flux sensors 50 mm in diameter positioned either side of the rock sample measured the heat flux flowing through the rock and the temperature gradient across the specimen. When the sample reached equilibrium the thermal conductivity was determined using Fourier's law of heat conduction as follows:

$$\lambda = \frac{Q}{\Delta T/L} \quad (1)$$

where $\lambda$ (W/mK) is the thermal conductivity, $Q$ (W/m$^2$) is the heat flux, $\Delta T$ (K) is the imposed temperature gradient, and $L$ (m) is the height of the rock specimen. The heat flux sensors used were manufactured by placing a 1 mm polycarbonate disc between two 3 mm aluminium discs. Holes were drilled in the aluminium discs and thermocouples inserted to measure the temperature of the disc (Figure 1). The heat flux was calculated by rearranging Eq. (1) where the thermal conductivity of the polycarbonate disc was 0.20 W/mK.

In practice it is not possible to simulate pure heat flow through the sample due to radial heat losses. In the present case, the samples were insulated with polyethylene foam to minimise any radial heat losses. In addition, contact resistance errors between the sample and heat flux sensors were minimised by coating the sample surface with thermal grease and by applying an axial load on the sample to ensure that good contact was established. Heat losses were monitored by taking heat flux measurements at the top and bottom of the sample. Any difference in heat flux measurements effectively represents heat loss from the sample. The heat flux measurements recorded showed minimal heat loss occurring across the sample.

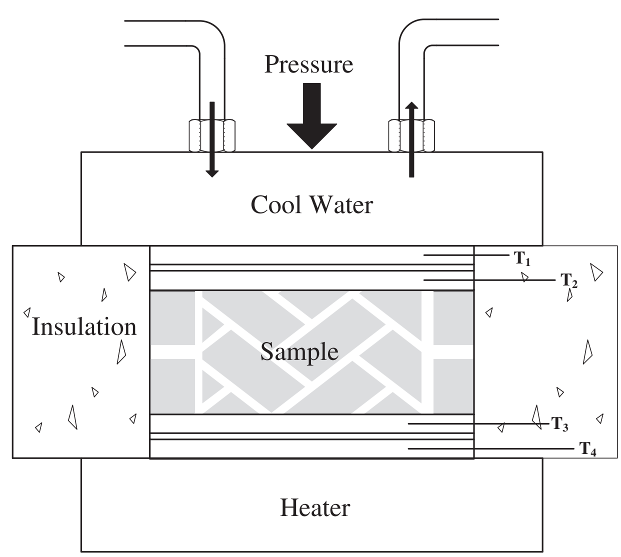


**Fig. 1.** Cross-section of divided bar apparatus for measuring thermal conductivity. $T_1$–$T_4$ represent temperature measurements from the heat flux sensors.