THERMAL PROPERTIES OF SOME MELBOURNE SOILS AND ROCKS

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ABSTRACT

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 on the thermal conductivity and volumetric heat capacity of soils and rocks from around Melbourne, Australia. The thermal conductivity and volumetric heat capacity of six soils were experimentally measured using a thermal needle probe and the thermal conductivity of three rock types were measured using 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 and that volumetric heat capacity was strongly dependent on the moisture content of the soils. Rock samples were tested dry and water saturated. Rock samples demonstrated an improvement in thermal conductivity with an increase in density when dry. However, when water saturated, siltstone and sandstone rocks showed no significant correlation between density and thermal conductivity. This was attributed to both variations in mineralogy and anisotropy. The thermal conductivity and volumetric heat capacity data obtained from this study provides an initial dataset of soils and rocks thermal conductivities for the design of thermally active ground structures installed throughout Melbourne, Australia.

1   INTRODUCTION

Thermally active ground structures, such as geothermal energy foundations and borehole heat exchange systems are generating interest in Australia due to the great potential they hold as an aid in tackling climate challenges and meeting legislation requirements for greenhouse gas emissions (De Moel *et al.,* 2010, Bouazza *et al*., 2011, Johnson *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 this respect, knowledge of the thermal properties of local soils and rocks is essential for their design. However, information on thermal properties of Australian soils is scarce and feasibility design values often rely on data from overseas sources.

This paper presents the results of an experimental study on the effect of moisture content, density and mineralogy on the thermal properties of six soil and three rock types from Melbourne, Australia. This study enables the estimation of thermal properties for Melbourne soil and rock over a wide range of conditions. Thus, providing necessary information for the design of thermally active ground structures installed locally.

2   THERMAL CONDUCTIVITY MEASUREMENT METHODS

Soil and rock thermal properties can be measured by either laboratory or field methods. Laboratory methods are typically preferred over field methods as they are relatively quick, inexpensive and allow for greater control over the boundary conditions. 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. 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, this study used a transient state thermal needle probe to measure the thermal properties of soil samples and a steady state apparatus was used to measure the thermal conductivity of rock samples.

2.1   THERMAL NEEDLE PROBE

In this study a commercial thermal needle probe referred to as a KD2 Pro thermal properties analyser manufactured by Decagon Devices was used to measure the thermal conductivity, volumetric heat capacity and diffusivity of the soils. The thermal needle probe 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 single needle probe was used to measure the thermal conductivity of the soils and the dual needle probe used to measure their volumetric heat capacity and diffusivity. The probes were calibrated prior to testing using glycerol and a delrin block supplied by the manufacturer.

A small number of thermal conductivity tests were measured outside the manufacturer's recommended measurement range (0.2 – 2 W/mK) on samples of moist, dense sands. 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 finding was supported by correlation readings between the experimental data and model of above 0.9998 from the KD2 Pro in samples tested above 2 W/mK.

Two sources of user controlled error were identified in the study. The first error was introduced through poor soil-probe contact. The accuracy of the probes was found to be influenced by contact resistance errors created during the insertion of the needles into the soil specimens. Contact resistance errors were found to be most common in low and high density soils. In soils with low densities needle insertion caused disturbance of soils, which resulted in regions of poor contact between the soil and the probe. At very high densities the needle probe was unable to penetrate the sample. In these instances 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 led to the development of regions of poor soil-probe contact. To reduce the poor contact condition 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. In these cases the thermal needle probe was removed from the sample and reinserted in a different location and the thermal conductivity was remeasured.

The second source of user error was applicable to the dual needle probe and the measurement of the volumetric heat capacity and diffusivity. This error can develop due to incorrect needle spacing during the insertion of the needle probe into the soil. Needle spacing errors occur when the two needles are inserted slightly skewed and the tips of the needles move closer together or further apart during insertion. This can result in significant errors, as for every 1% change in needle spacing the error in the calculated volumetric heat capacity is 2% (Decagon Devices, 2006). This error was not monitored in the early testing stage of this study, and hence the volumetric heat capacity data collected for one of the soils (i.e. Coode Island silt, CIS) soil was influenced by needle spacing errors and has not been reported in this paper.

2.2   DIVIDED BAR APPARATUS

A steady state method in the form of a divided bar apparatus was adopted for testing the thermal conductivity of rock samples. This method was preferred to the thermal needle probe as inserting a needle into the rock samples was impractical. The divided bar apparatus used in this study is illustrated in Figure 1 and was designed similar to 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:

$$\lambda = \frac{Q}{\Delta T / L} \tag{1}$$

where λ (W/mK) is the thermal conductivity, Q (W/m^2) is the heat flux, ΔT (T_3-T_2) (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 disk between two 3 mm aluminium disks. Holes were drilled in the aluminium disks and thermocouples inserted to measure the temperature of the disk (Figure 1). The heat flux was calculated by rearranging Equation 1 where the thermal conductivity of the polycarbonate disk was 0.20 W/mK.

In practice it is not possible to simulate pure heat flow through the sample due to radial heat loss. To minimise the errors introduced due to radial heat loss the samples were insulated by radially surrounding them with polyethylene foam and running tests at close to room temperature. 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 good contact was established between the sensors and the rock samples. Heat loss was 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 in this study showed minimal heat losses occurring across the rock samples.
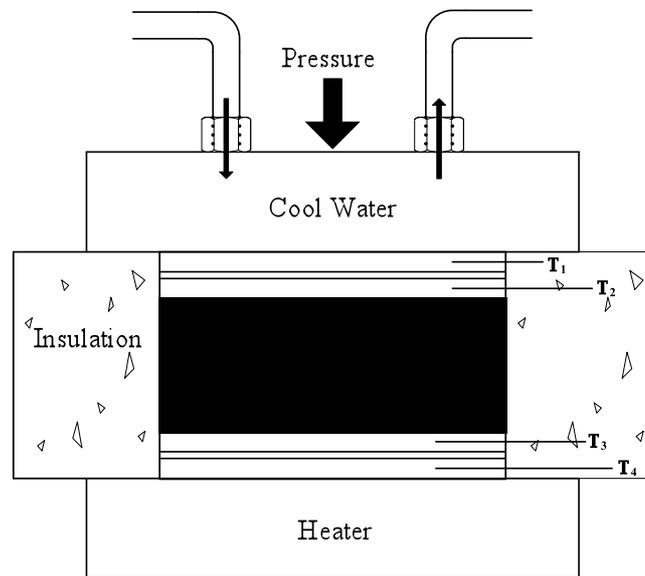

Figure 1: Divided bar device used in this study.

The rocks samples were first tested fully saturated, then oven dried and re-tested dry. The tests were run with an average sample temperature of close to 28°C, with a thermal gradient ΔT across the sample of between 6 and 15°C. In order to minimise moisture migration run times were kept as short as possible with each test taking between 20 and 45 minutes to reach equilibrium.

3   SOIL PROPERTIES AND SAMPLE PREPARATION

The thermal properties of six soils were tested at a range of moisture contents and densities. The six soils comprised: Coode Island Silt (CIS) (silty clay), Fishermans Bend Silt (FBS) (sandy clay), Residual Siltstone (RS) (silty clay), Basaltic Clay (BC) (silty clay), and Brighton Group sediments (sand and clayey sand). Two soils the BGS and BGCS are predominantly coarse grained soils while four soils the CIS, FBS, RS, and BC are fine grained soils. The soils were sampled from drill spoil during bored or continuous flight auger (CFA) pile construction or from test pit excavations. A summary of the soil properties is presented in Table 1.

Samples at different dry densities and moisture contents were prepared by static compaction for thermal conductivity testing. The soils were first oven dried at 105°C. The fine grain soils were then ground to a powder using a mechanical grinder and coarse grain were broken up by a hammer where necessary. The soils were moisture conditioned by spraying and mixing water through them to achieve the desired moisture content. Soil samples were then sealed in air-tight bags and left to cure for up to one week in order to achieve a homogenous moisture distribution throughout the sample.

A cylinder 200 mm in length and 100 mm in diameter and a loading ram 200 mm in length and 98 mm in diameter were used to compact the sample. The soil samples were statically compacted in 5 even layers under a loading frame. Each soil sample was compacted at different forces of 1 kN, 5 kN, 10 kN, and 20 kN per layer to achieve a range of densities. The height of each layer was measured after compaction. The thermal needle probes were then inserted into the compacted soil sample and the thermal properties were measured.

Table 1: Soil properties (Barry-Macaulay, 2013)

Sample	Basaltic clay (BC)	Coode Island silt (CIS)	Fishermans Bend silt (FBS)	Residual siltstone (RS)	Brighton Group clayey sand (BGCS)	Brighton Group sand (BGS)
Linear shrinkage (%)	19.7	13	9	10.2	-	-
Liquid limit (%)	70	82	42	47	-	-
Plastic limit (%)	20	30	18	22	-	-
Plasticity index (%)	50	52	24	25	-	-
Specific gravity	2.67	2.64	2.70	2.68	2.59	2.61
Clay (%)	60	25	31	37	23	0
Silt (%)	36	61	48	55	16	3
Sand (%)	4	14	21	8	61	97
USCS	CH	CH	CL	CL	SC	SP
Quartz content (%)	57	66	51	50	63	93

4   THERMAL CONDUCTIVITY OF SOILS

The thermal conductivity of soil is defined as the rate at which heat energy is transferred across a unit area of soil subjected to a unit temperature gradient by conduction. The use of the term thermal conductivity implies heat transfer is taking place through thermal conduction only. However, as pointed out by Farouki (1986), other mechanisms may and usually do contribute to the heat transfer in some way. Therefore, the definition should be understood to represent an 'effective thermal conductivity'.

Figure 2 and Figure 3 present the results of the thermal conductivity tests undertaken on the six soil samples. The results demonstrate that the thermal conductivity increases with increasing density and increasing gravimetric moisture content.
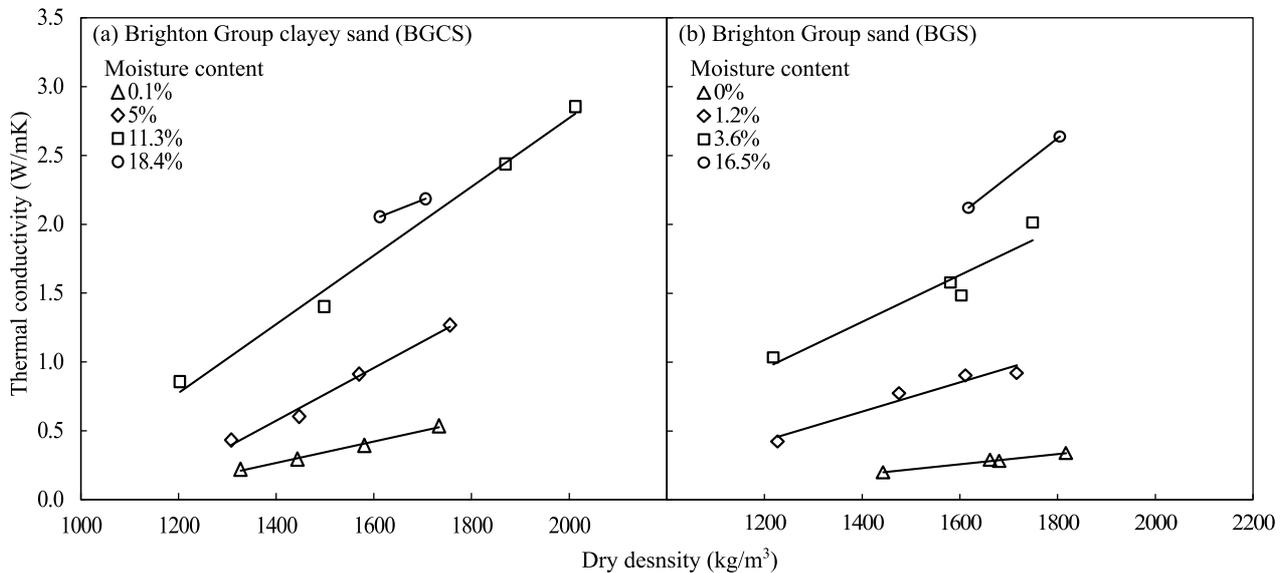

Figure 2: Experimental thermal conductivity results of coarse grain soils.
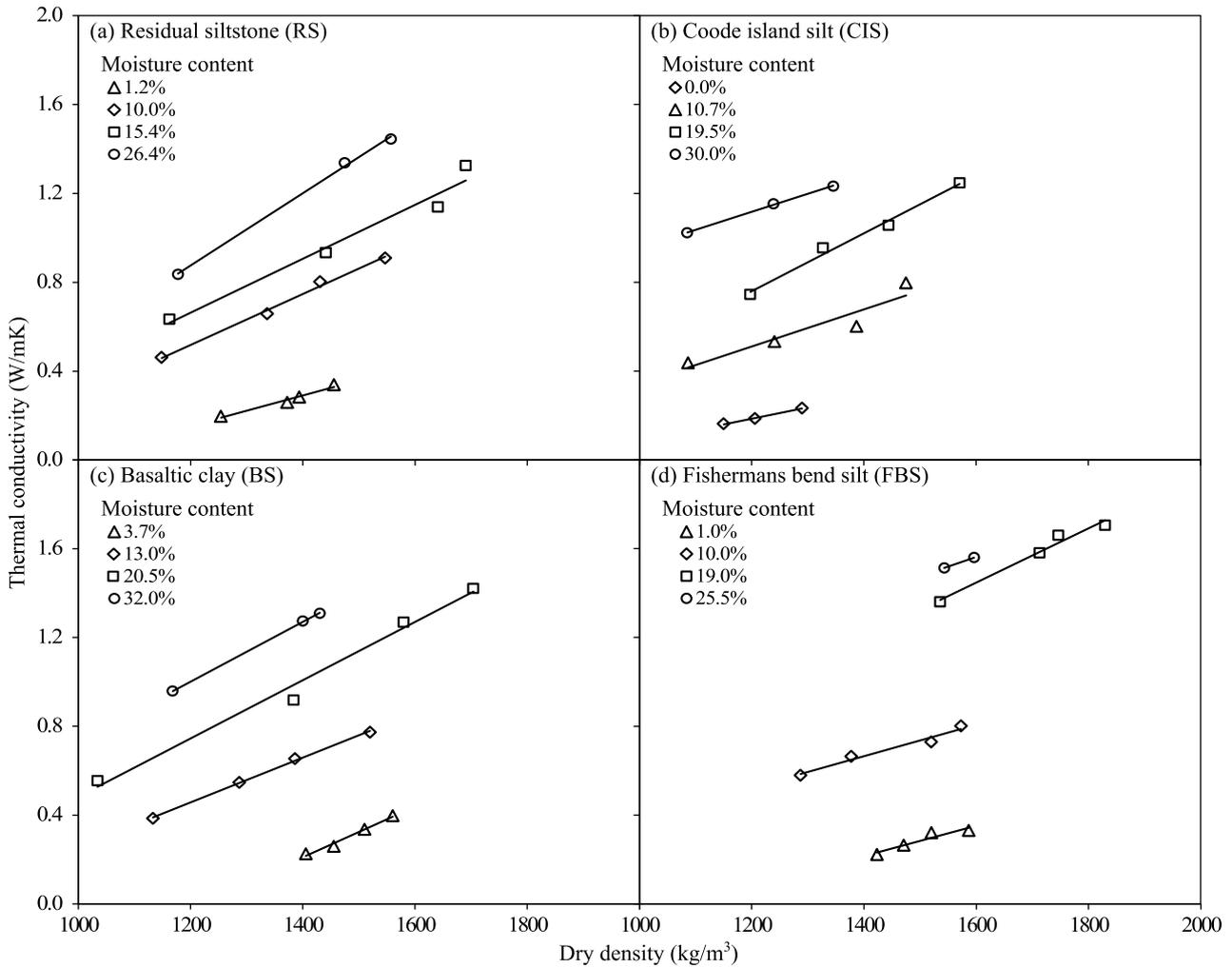
Figure 3: Experimental thermal conductivity results of fine grain soils.

The thermal conductivity of a soil is largely affected by the volume of air in the soil. Ochsner *et al.* (2001) attributed the strong correlation between air volume and thermal conductivity to the low thermal conductivity of air compared to the thermal conductivity of water and soil minerals. Air has a thermal conductivity about 25 times lower than water and 100 times lower than most soil minerals.

Given the low thermal conductivity of air, the increase in thermal conductivity with increasing density can be expected as samples with higher densities will have more soil solid particles and less air molecules per unit volume. In addition, improved packing of the soil particles will improve the inter-particle contact points and lead to better heat flow between solid particles.

Moisture content influences the thermal conductivity of a soil in two ways which are highlighted in Figure 4. The figure shows the soil thermal conductivity variation against degree of saturation at a density of 1500 kg/cm^3. Since not all experimental tests were conducted at a density of 1500 kg/m^3 data points were extrapolated from Figure 2 and Figure 3 where necessary.

Figure 4 shows that the thermal conductivity of granular soils increases rapidly at low saturations and only slightly thereafter. On the other hand, the thermal conductivity of fine grain soils shows a relatively uniform increase in conductivity with increasing saturation. The difference in the response of the soils to the increasing saturation is due to their particle size. Granular soils contain less particle contact points and hence only a small addition of water is needed to saturate the inter-particle contact points. This significantly increases the thermal conductivity because the thermal conductivity of the soil solid particles is larger than both air and water and the preferred method of thermal transfer is through the solid particles. Further addition of moisture only replaces the air between the particles and slightly increases the thermal conductivity of the granular soils. The steady increase in thermal conductivity with saturation in the fine grain soils is because there are significantly more particle contact points and thus soil moisture contents must be higher to saturate all the inter-particle contact points.
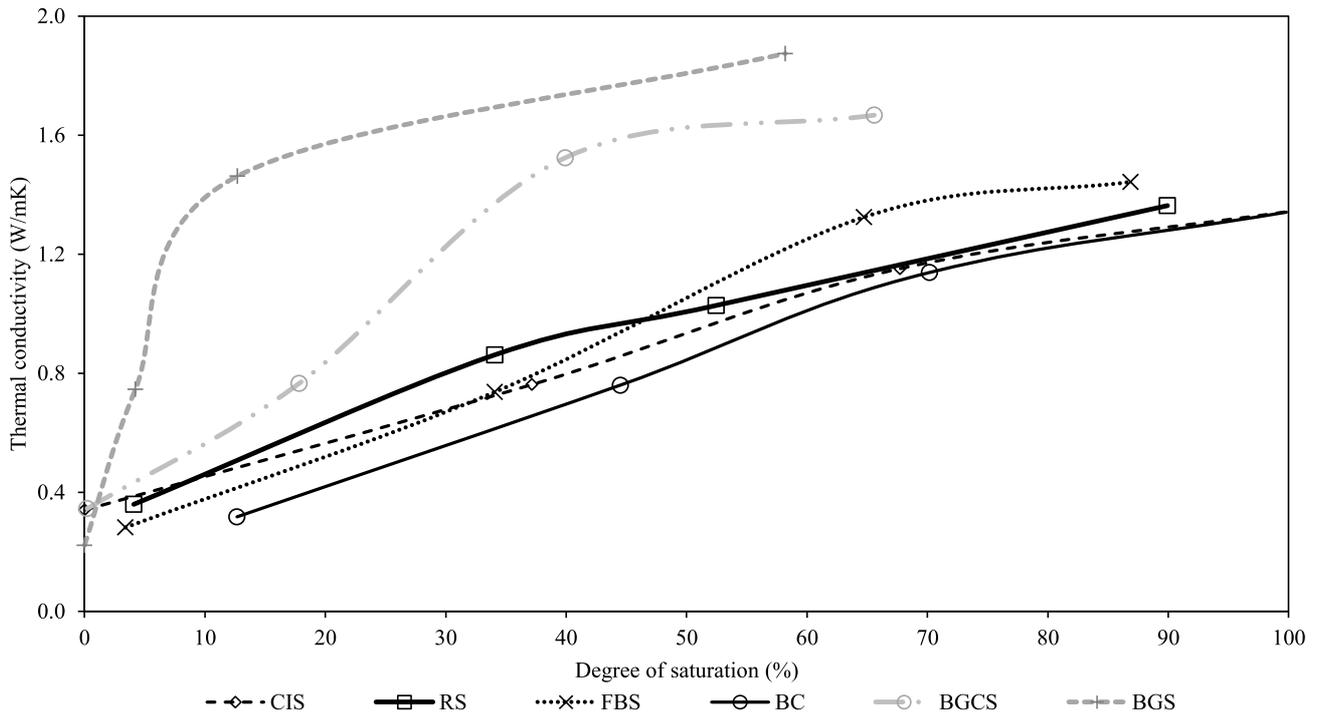
Figure 4: Influence of saturation on thermal conductivity of soils at soils at a dry density of 1500 kg/m³ across different soil types.

Mineralogy affects the thermal conductivity of a soil because different soil minerals have different thermal conductivities. The amount of quartz in a soil will significantly affect its thermal properties as the thermal conductivity of the quartz mineral is 7.7 W/mK (Horai, 1971) compared with most other soil minerals which are typically between 1.8 – 3.0 W/mK (Horai, 1971).

In this study the soils contained between 50% and 92% silicates. However, the majority of the silicates in the fine grain soils were silt or clay sized particles. The percentage of silicates in the fine grain soils did not show a correlation to the thermal conductivity of the soils. This is because only crystalline quartz has a high thermal conductivity and that although clays and silts also contain silicates, it is generally not in crystalline form (Peters-Lidard *et al*., 1998).

5   VOLUMETRIC HEAT CAPACITY

Heat capacity is a measurement of the energy required to change the temperature of a material. It can either be expressed on a mass basis (specific heat capacity) or volume basis (volumetric heat capacity). The volumetric heat capacity is most commonly used by engineers.

Figure 5 shows the influence of the volume fraction of air (v_a), water (v_w) and soil solid particles (v_s) on the volumetric heat capacity of the soils investigated in this study. The volumetric heat capacity data shown in Figure 5 were obtained at a range of different moisture contents and densities. The data shows that the volumetric heat capacity is most strongly dependent on v_a and v_w. This is due to the high heat capacity of water particles compared to soil solid and air particles. Water has a heat capacity of 4.18 MJ/m³K, which is almost double that of soil solid particles (2 - 2.5 MJ/m³K) and several orders of magnitude greater than air (0.0012 MJ/m³K). In most *in situ* scenarios an increase in water content of soils will result in a decrease in air, while the soil solid particles will remain relatively constant and likewise a decrease in moisture content will result in an increase in the amount of air particles within the soil.
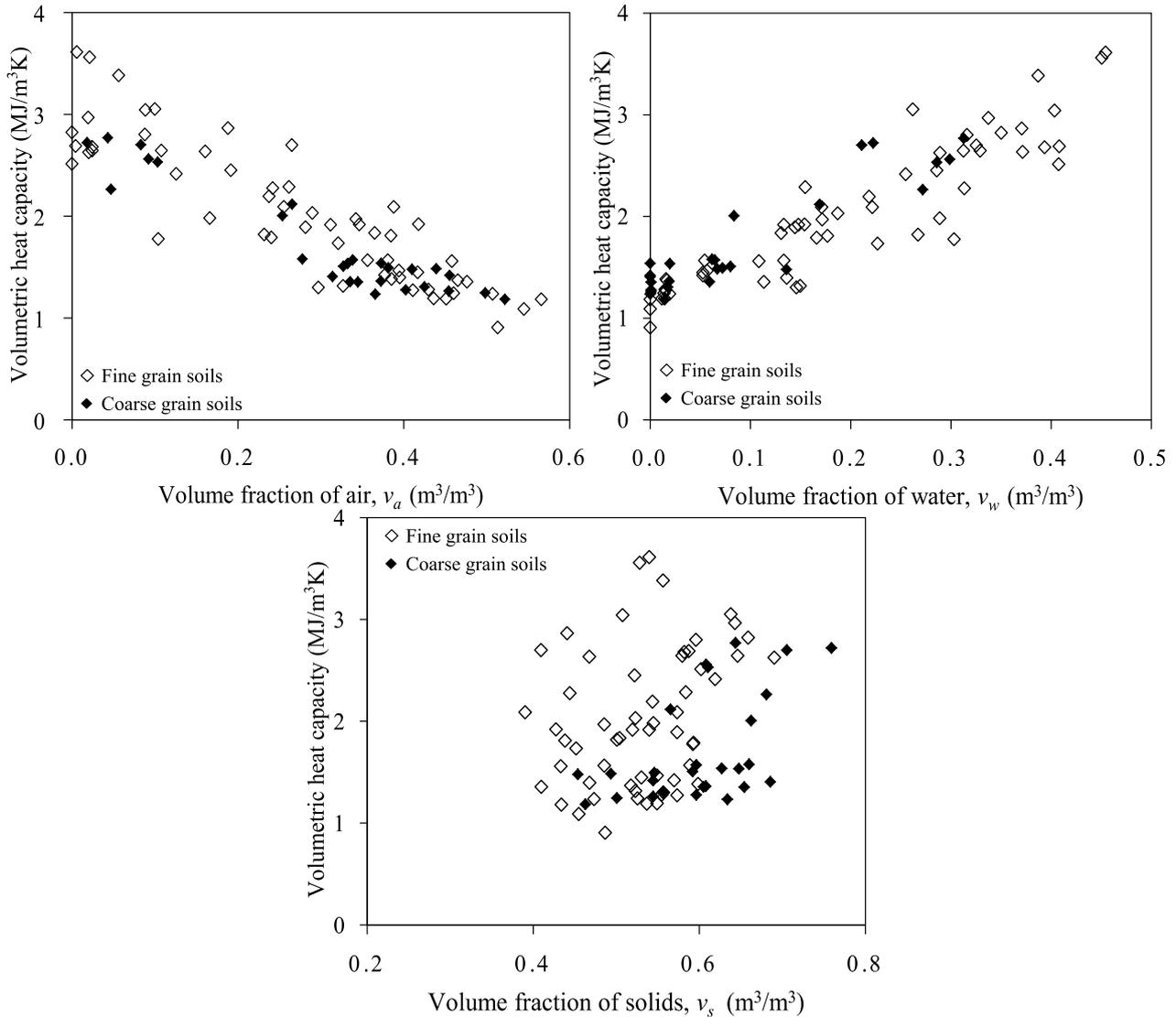
Figure 5: Effect of volume fraction of air, water and soil solid particles on the volumetric heat capacity of soils tested.

5.1   VOLUMETRIC HEAT CAPACITY MODEL

The volumetric heat capacity of a soil can be defined as the energy required to raise the temperature of 1 cm^3 of soil by 1ºC and is the product of the specific heat capacity (J/g.K) and density (g/m^3). Therefore, the volumetric heat capacity can be calculated by adding the sum of the heat capacities of the different soil constituents. The volume fractions of air (v_a) water (v_w) and solid particles (v_s) can be multiplied by the heat capacities C_a, C_w, and C_s of air, water, and solids to give:

$$C = v_a C_a + v_w C_w + v_s C_s \tag{2}$$

The contribution of air can be neglected given it has a very low heat capacity (0.0012 MJ/m^3.K) and the volume fraction of water and soil solid particles can be multiplied by the heat capacity of water (4.18 MJ/m^3) and soil solid particles (2.0 – 2.5 MJ/m^3) to give the volumetric heat capacity of the soil. To provide an accurate estimation of the soil volumetric heat capacity the soil solid particle heat capacities must be known. The heat capacity of typical soil solid particles found from various literature sources are presented in Table 2.

The soil solid volumetric heat capacities were calculated for each soil in this study by comparing the experimental data to the modelled data (Equation 2). Modelled data was initially obtained by using the soil solid particle heat capacity (C_s) recommended by Campbell (1985). C_s was then adjusted until the modelled data provided the best statistical correlation to the experimental data. Statistical correlation was undertaken using the coefficient of correlation (R^2). The R^2 value measures how well the modelled data fits the experimental data along a linear regression line. R^2 varies between 0 and 1; $R^2 = 1$ indicates that the regression line fits perfectly to the data (i.e. the modelled and measured data are the same).

In this analysis, $R^2 = 0.93$ for all soils and varied between 0.90 and 0.96 for individual soils (Table 2). This suggests that the experimental results are accurate. Ochsner et al. (2001) found a similar agreement of, $R^2 = 0.94$ between modelled and measured heat capacities for four medium textured soils.

Table 2: Estimated volumetric heat capacity of soil solid particles.

Soil (literature)	Volumetric heat capacity (10^6 J/m^{3}K)	Reference	Soil (this study)	Volumetric heat capacity (10^6 J/m^{3}K)	R^2
Sandy loam	2.07	Ochsner et al. (2001)	Basaltic clay	2.40	0.96
Clay loam	2.20	Ochsner et al. (2001)	Residual siltstone	2.47	0.90
Silt loam	2.35	Ochsner et al. (2001)	Fishermans Bend silt	2.16	0.95
Silty clay loam	2.44	Ochsner et al. (2001)	BGCS	2.23	0.96
Quartz	2.13	Campbell (1985)	BGS	2.14	0.90
Clay minerals	2.39	Campbell (1985)			

Figure 6 demonstrates the comparison between the measured and modelled heat capacity for the Residual Siltstone soil. The figure highlights the inaccuracy of some experimental data points, particularly at high densities where the measured and modelled results vary the greatest. Many of the variations are within the ± 7% accuracy of the dual needle probe set by the manufacturer, however, some values are outside this range. Results showing large deviations from the expected linear increase in heat capacity with density are attributed to needle spacing errors which were discussed in section 2.1. Controlling the needle spacing was found to be most difficult in dense soils. This is observed in the comparison of the measured and modelled data for the Residual siltstone where the majority of the variation between the modelled and measured data was observed at high densities (Figure 6).
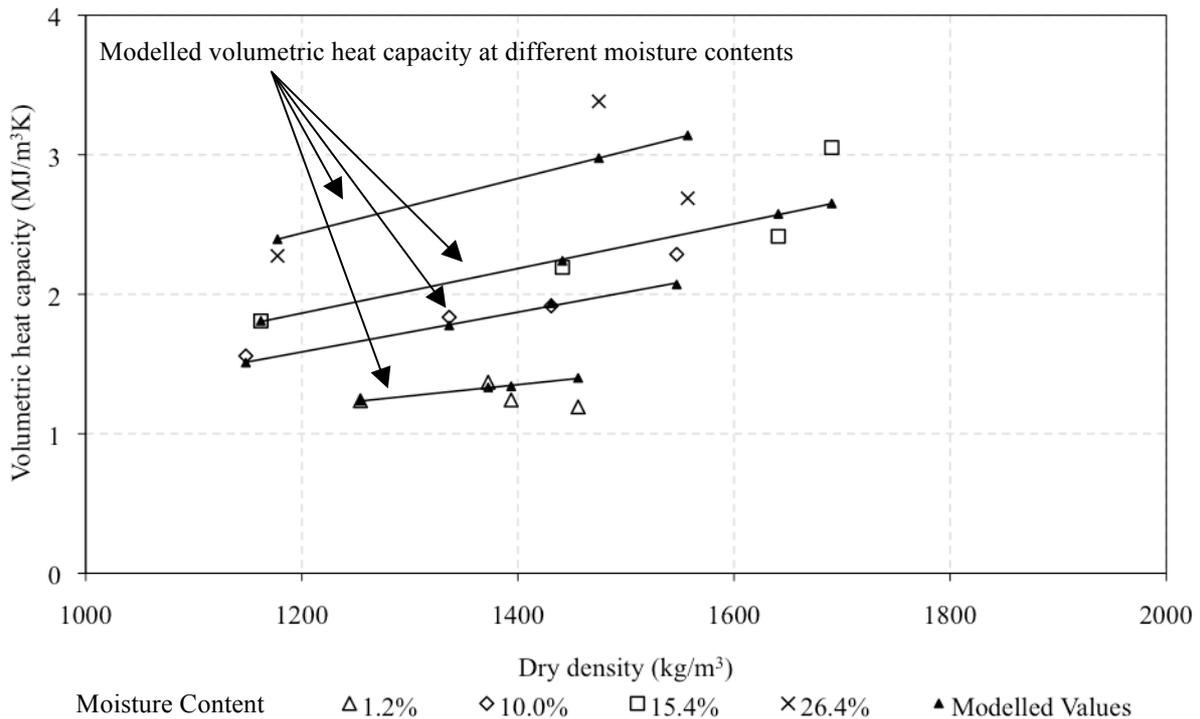

Figure 6: Measured volumetric heat capacity compared to modelled capacity for residual siltstone soil.

The measurement of the heat capacity with the dual needle probe was quick, easy and provided accurate results if used correctly. However, when testing high density soils controlling the needle spacing became difficult and lead to erroneous results from the dual needle probe. If soil densities and moisture contents are known then the use of equation 2 is recommended over the dual needle probe for calculating the volumetric heat capacity if C_s is known.

6   THERMAL DIFFUSIVITY

The thermal diffusivity (*D*) of a soil is the ratio of the thermal conductivity and volumetric heat capacity and is given by:

$$D = k \,/\, C \tag{3}$$

where *D* is the thermal diffusivity, *k* is the thermal conductivity and *C* is the volumetric heat capacity. The diffusivity is a measurement of how easily soils undergo temperature changes. Soils with large thermal diffusivities have the capability to undergo rapid and considerable changes in temperature (Farouki, 1986).

In this study the thermal diffusivity was calculated for all soils using Equation (3). The experimental thermal conductivities and modelled volumetric heat capacities were used. The modelled heat capacities were chosen over the experimental values to eliminate the errors that were encountered with the needle spacing of the dual needle probe.

Experimental thermal diffusivity results and modelled thermal diffusivity curves are plotted against degree of saturation in Figure 7. The modelled curves were calculated using the thermal conductivity model developed by Côté and Konrad (2005) to calculate thermal conductivity and Equation (2) to calculate heat capacity. These values were then substituted into Equation (3) to calculate the diffusivity.
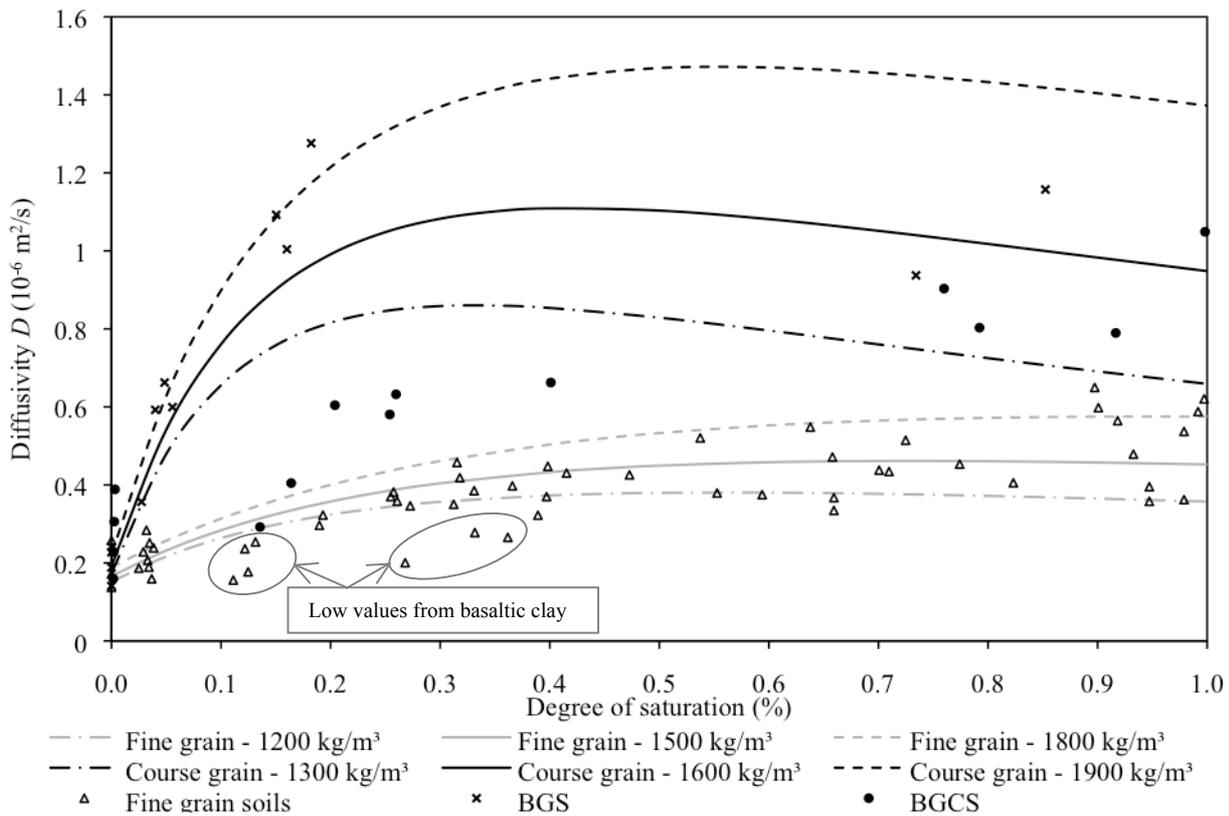

Figure 7: Influence of saturation and dry density on thermal diffusivity for fine and coarse grained soils.

The Côté and Konrad (2005) thermal conductivity model was selected to estimate the thermal conductivity as an extensive data set was used to develop the model. The thermal conductivity model was validated against the soils used in the study and showed a good correlation between experimental and modelled data (Barry-Macaulay 2013).

The modelled curves show that the diffusivity increases with saturation, reaches a peak, and then slowly decreases as the water content continues to increase to full saturation. The experimental results in general agreed with the modelled results. A number of data points for the fine grain soils at low saturations were situated below the modelled curves. The majority of these were from low saturation or low density samples of basaltic clay and were mostly due to discrepancies between the modelled and measured thermal conductivity.

The diffusivity increased at a rapid rate in coarse grain soils whereas the fine grain soils only showed a gradual increase. This is attributed to the large increase in thermal conductivity at low saturations in coarse grain soils. The diffusivity of the coarse grain soils was also much larger than fine grain soils. This is due to a combination of higher

thermal conductivity and lower volumetric heat capacity in coarse grain soil. Once the soil reaches a certain moisture content the diffusivity begins to decrease; at this point the moisture content is affecting the volumetric heat capacity more than the thermal conductivity. The decrease is more pronounced in granular soils because the increase in thermal conductivity at moderate to high saturations is minimal. The calculated diffusivity using the experimental thermal conductivity and modelled heat capacity show a good fit to the modelled data. The BGSC soil was observed to behave somewhere between the coarse and fine grain soils.

The effect of density on the diffusivity is illustrated in Figure 7 by the different modelled lines. The lines were modelled assuming that the coarse grain soils contained 100% quartz and the fine grain soils 0% quartz. This demonstrates that the influence of density is very small for clayey soils. However, the density has a greater influence on the diffusivity of coarse soils, especially above a degree of saturation of 0.1.

Overall the thermal diffusivity was observed to be much larger in coarse grain soils. This is mainly due to the large thermal conductivity of coarse grain soils, particularly at low moisture contents. Soils with high crystalline quartz contents would be expected to yield large thermal diffusivities as the quartz mineral has a very high thermal conductivity and slightly lower heat capacity than most other soil minerals.

7   THERMAL CONDUCTIVITY OF ROCKS

The thermal conductivity of 54 samples of siltstone, sandstone, and basalt were tested under both water saturated and air saturated conditions using the divided bar apparatus described in Section 2.2. The rocks were collected from various sites around Melbourne between depths of 5 m and 40 m below the ground surface. Samples were visually classified as either sandstone or siltstone. The siltstone samples ranged from highly weathered to slightly weathered, the sandstone from highly weathered to moderately weathered and the basalt from extremely weathered to slightly weathered. The core samples were trimmed to approximately 20 mm in length and 50 mm in diameter. Prior to thermal conductivity testing each sample was saturated in a desiccator. The samples were weighed every few days and assumed to be fully saturated when the weight stabilised. Once the samples were fully saturated the saturated thermal conductivity was tested in the divided bar apparatus. The samples were then oven dried at 105ºC and re-tested to measure the dry thermal conductivity. A summary of the experimental thermal conductivity results are presented in Figure 8 for both air and water saturated samples.
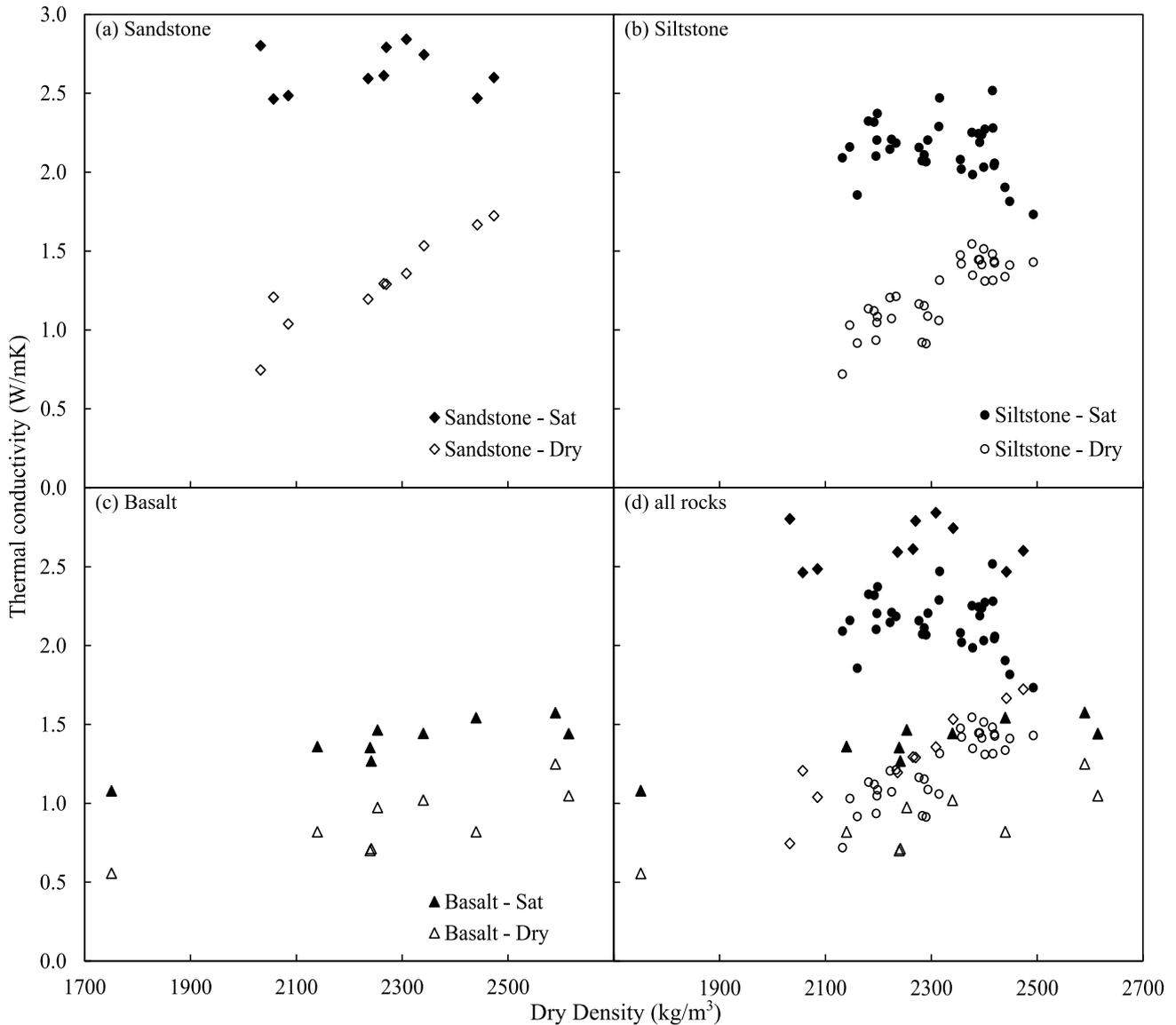
Figure 8: Variation in thermal conductivity of Melbourne rocks with density, tested dry and water saturated.

7.1   INFLUENCE OF DENSITY

The density of the rock samples collected varied significantly, particularly in basalt samples. The variation in density of basalt samples was due to the amount and size of vesicles and also the state of weathering. In general, the density of all rock types increased with depth in samples taken from the same borehole. However, the density was observed to be more closely related to the weathering grade of the rock rather than that sample depth.

Air saturated samples showed a general linear increase in thermal conductivity as the density of the samples increased. This is attributed to the rock particles having a much higher thermal conductivity than air. Rock particles typically have thermal conductivities between 2 and 7.7 W/mK compared to air which is 0.024 W/mK.

When air was replaced with water the thermal conductivity of the rock significantly increased due to the higher thermal conductivity of the water (0.6 W/mK) allowing greater heat flow. Therefore, the influence of density on the thermal conductivity of water-saturated samples is significantly lower. The results from this study demonstrate no significant relationship between the thermal conductivity of water-saturated samples and dry density for the siltstone and sandstone rocks. However, a linear increase in thermal conductivity with density was observed in the saturated basalt samples.

The thermal conductivity of the siltstone, and to a lesser extent the sandstone was observed to vary considerably between samples of the same or similar densities. This suggests that factors other than density influence the thermal conductivity of the rocks. The samples in this study were collected from a number of different sites, boreholes and depths. As such each sample is unique and may contain slightly different mineralogy and structure. Both Jones (2003) and Popov et al. (2003) noticed large variations in experimental thermal conductivities between samples of the same

rock type. Jones found that mineralogical composition was the main factor influencing the thermal conductivity of the different rocks he tested. Jones also found other factors such as anisotropy, porosity and temperature can be important. Popov et al. (2003) tested the thermal conductivity of a number of sedimentary rocks. They found that the anisotropy of the rocks significantly affected the thermal conductivity.

7.2   INFLUENCE OF ANISOTROPY

The anisotropy of rocks has been found by many researchers to influence the thermal conductivity of sedimentary rocks (Midttømme and Roaldset, 1999, Beardsmore and Cull, 2001, Popov et al., 2003,). Midttømme and Roaldset (1999) reported thermal conductivities parallel to the grain were in some cases up to twice that measured perpendicular to it in sedimentary rocks. While Beardsmore and Cull (2001) noticed in several documented cases that the thermal conductivity of shale does not increase with density in the same way that other rocks do. This is because shale is comprised of highly anisotropic silicate sheets. The thermal conductivity parallel to the mineral sheet can be many times greater than perpendicular to it and as the density of the shale increases the particles arrange themselves into a preferred horizontal alignment.

In this study the bedding orientation was used to investigate the influence of anisotropy of siltstone samples. The bedding orientation was measured for 30 of the 35 siltstone samples and plotted against the thermal conductivity (Figure 9). A bedding orientation could not be definitively recognized in five of the siltstone samples and these samples were subsequently excluded from Figure 9. The results showed a slight increase in thermal conductivity as the bedding orientation approached the direction of the heat flow, which is attributed to the anisotropic behaviour of the siltstone.
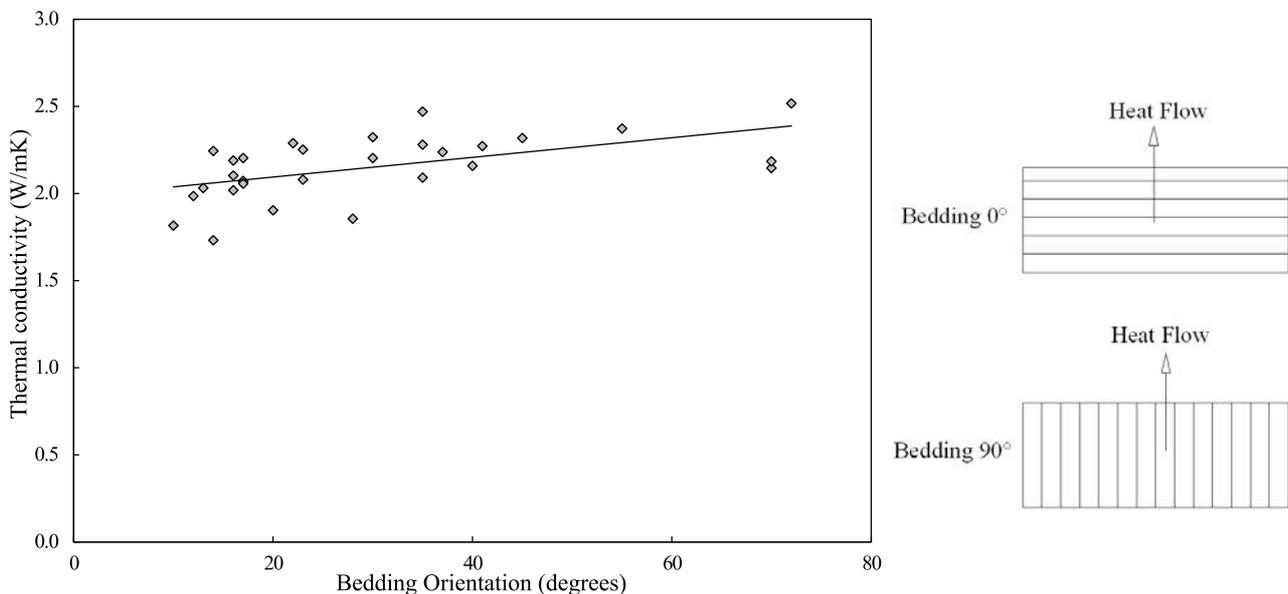

Figure 9: Influence of bedding orientation on thermal conductivity in samples of siltstone.

7.3   INFLUENCE OF MINERALOGY

Rock samples were collected from different sites, boreholes and depths. So it is likely that each sample contains a slightly different mineralogical makeup. As discussed in Section 4, quartz is the main mineral that influences the thermal conductivity of soils and rocks. This study used the percentage of quartz to assess the variation in the thermal conductivity of the rocks.

The quartz content of ten samples of siltstone were analysed in this study. Samples were selected to incorporate a range of densities, thermal conductivities and bedding orientations. Thirty micron thin sections were produced for each sample and petrographic analysis was performed on each of the thin sections and the quartz content was quantitatively calculated.

The results of the petrographic analysis yielded quartz contents of the siltstone between 10% and 26%. Figure 10 presents the quartz content plotted against the thermal conductivity. Of the ten samples, five samples had bedding orientations of between 12 ° and 17° and densities of between 2330 kg/m³ and 2350 kg/m³ and two samples had bedding orientations of 35° and densities of approximately 2350 kg/m³. The remaining samples contained a range of bedding orientations and densities. The thermal conductivity was observed to generally increase with increasing quartz content for all samples. The variation observed between samples is attributed to the different bedding orientation and density.
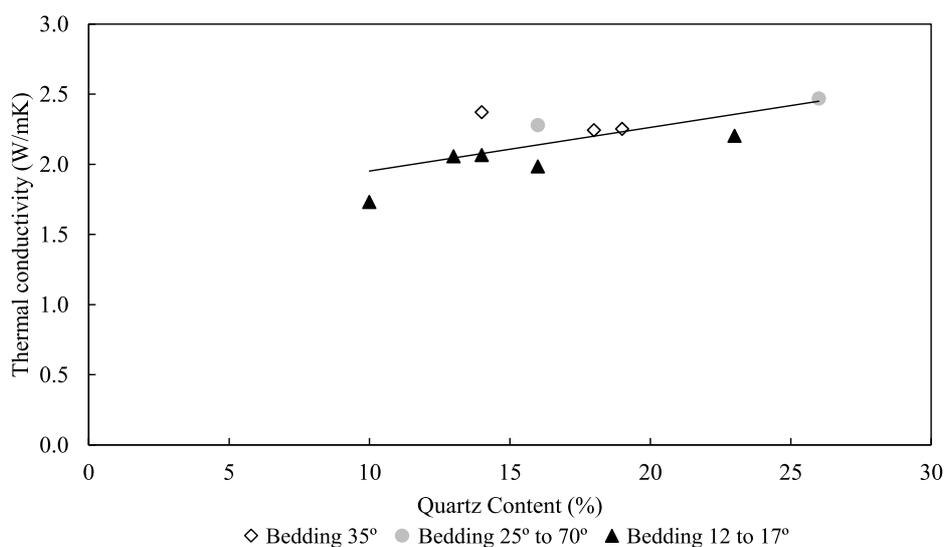
Figure 10: Influence of quartz content on thermal conductivity.

8   CONCLUSIONS

Soil and rock thermal properties are a key parameter in the design of many thermally active ground structures. This study has presented a comprehensive laboratory analysis of the thermal properties of Melbourne soils and rocks over a wide range of moisture contents and densities. The laboratory tests demonstrated that soil thermal properties vary with soil moisture content, dry density, mineralogical composition and particle size.

The thermal conductivity of the rocks was observed to improve with increasing density when tested dry. However, when tested water saturated only the basalt rocks showed a correlation between density and thermal conductivity. The siltstone and sandstone rocks showed no distinct correlation between density and thermal conductivity. The difference between the thermal conductivity of samples of saturated siltstone and sandstone rocks were attributed to a combination of different mineralogical composition, anisotropy and density. When estimating the thermal conductivity of saturated sandstone and siltstone, the mineralogy, density and bedding orientation should all be taken into consideration.

The soil and rock data collated in this study provides new knowledge of the thermal properties of Melbourne soils and rocks. This knowledge provides an invaluable resource for the estimation of thermal properties for the design of thermally active ground structures constructed in Melbourne.

9   ACKNOWLEDGEMENTS

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