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THERMAL PROPERTIES OF MALAYSIAN COHESIVE SOILS

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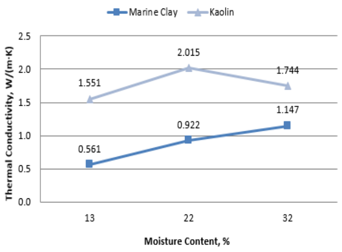
Graphical abstract



Abstract

The thermal properties of soils surrounding energy piles are required for the efficient and optimal design of shallow geothermal energy pile systems. In this study, the thermal conductivity, thermal resistivity and volumetric specific heat of two types of Malaysian cohesive soil were obtained through a series of laboratory experiments using a thermal needle probe. This study was conducted to determine the effect of moisture content on the thermal conductivity, thermal resistivity and volumetric specific heat values of the cohesive soil at a given value of soil density. For soils with low to medium moisture content, a linear increase in the thermal conductivity and volumetric heat capacity was observed as the moisture content gradually increased, while the thermal resistivity values of the soil had decreased. Meanwhile, for soils with high moisture content, the thermal conductivity was observed to have decreased, and a marked increase was seen in the thermal resistivity. This is due to the disruption of the thermal flow continuity in the soil matrix with the presence of moisture in the soil which adversely affects the thermal conductivity.

Keywords: Shallow geothermal energy pile; thermal properties; cohesive soil

Abstrak

Sifat-sifat terma tanah di sekeliling cerucuk tenaga adalah diperlukan untuk reka bentuk sistem cerucuk tenaga geoterma cetek yang efisien dan optimum. Bagi kajian ini, kebolehaliran haba, keberintangan haba dan haba tentu isipadu bagi dua jenis tanah jeleket Malaysia telah diperolehi melalui satu siri eksperimen makmal dengan menggunakan kuar jarum haba. Tambahan pula, kajian ini dijalankan untuk menentukan kesan kandungan lembapan kepada nilai kebolehaliran haba, keberintangan haba dan haba tentu isipadu tanah jeleket bagi suatu nilai ketumpatan tanah. Bagi tanah yang mempunyai kandungan kelembapan di dalam julat rendah ke sederhana, didapati bahawa peningkatan linear dalam kebolehaliran haba dan muatan haba isipadu telah berlaku apabila kandungan kelembapan meningkat secara beransur-ansur, manakala nilai keberintangan haba tanah telah menyusut. Sementara itu, bagi tanah dengan kandungan lembapan yang tinggi, nilai kekonduksian terma didapati telah menyusut, dan peningkatan yang ketara dilihat dalam keberintangan haba tanah tersebut. Ini disebabkan oleh gangguan aliran haba di dalam matriks tanah dengan wujudnya kelembapan di dalam tanah yang menimbulkan kesan negatif kepada kebolehaliran haba.

Kata kunci: Cerucuk tenaga geoterma cetek; sifat terma; tanah jeleket

1.0 INTRODUCTION

Shallow geothermal energy pile systems are designed to achieve energy efficient space heating and cooling for residential and commercial buildings of various sizes; while satisfying load bearing requirements of the underlying foundation [1]. This sustainable geostructure system uses the ground as a high capacity heat sink, which supplies constant-temperature fluids for direct cooling or for heat pump applications. Shallow geothermal cooling systems are sized to maximize heat exchange, based on the heat transfer through soil to and away from buried heat exchange elements. [2]

Recently, geothermal energy piles has generated some interest amongst researchers in the field of energy geotechnics, given its successful implementation in various countries all over the world, namely in Switzerland [3], United Kingdom [4], Australia [5] and the United States [6]. Even so, this sustainable geostructure technology has not been widely implemented in other countries, including Malaysia.

As such, this study represents a small part of an on-going study conducted to assess the viability of shallow geothermal energy pile systems installed in the Malaysian environment. Cohesive soils native to Malaysia were tested to obtain the thermal conductivity, thermal resistivity and volumetric heat capacity values, where a total of fifteen tests were conducted. The aim of this paper is to determine the soil thermal properties, and to determine the correlation between the aforementioned properties to the soil moisture content, at a given soil density. It is hoped that this study will be able to address the need for further understanding of the energy pile performance in tropical weather conditions.

2.0 MATERIAL AND TESTING PROGRAMME

2.1 Material

To determine the thermal properties of Malaysian cohesive soils, the experimental works were carried out on marine clay obtained from the Southern Coast of Johor [7,8] and kaolin soil obtained from the state of Selangor [9,10]. The thermal properties test results for both soils are presented in this study. Relevant standard laboratory tests were conducted to obtain the basic properties of the compacted kaolin soil. Both the marine clay and kaolin soil were characterised according to the British Standard [11] and ASTM [12]. More specifically, the soil characterisation tests included the Particle Size Distribution test, Atterberg Limit tests and Specific Gravity test. The results are presented in Table 1.

Based on the Unified Soil Classification System (USCS), the kaolin soil sample had been classified as ML (low plasticity SILT) while the marine clay sample was classified as MH (high plasticity SILT). Meanwhile, for the liquid limit and plasticity index results of the kaolin, the obtained values falls within the range of typical kaolinite material. Marto [13,14] stated that the liquid limit (LL) range for typical kaolinite material is 40-60 % and the plasticity index (PI) range is 10-25 %. On the other hand, the LL, plastic limit (PL) and PI values of the marine clay are 58 %, 22 % and 36 %, respectively, which is in agreement with the findings of other researchers [7,8].

Table 1 Physical indices of marine clay and kaolin

Physical Properties	**Values**	
	Marine Clay [7]	**Kaolin**
Particle Density (Mg/m^3)	2.62	2.66
Atterberg Limits		
Liquid Limit (%)	58	38
Plastic Limit (%)	36	27
Plasticity Index (%)	22	11
Standard Proctor Compaction Parameters		
Maximum Dry Density (Mg/m^3)	1.60	1.63
Optimum Moisture Content, OMC (%)	21	17
Soil Classification (USCS)	MH	ML

2.2 KD2 Pro Thermal Needle Probe

In order to measure the thermal conductivity of soils, the thermal needle probe (classified as transient line heat source method) was a preferred and selected testing method, since the testing method involved a fast and simple operation [15]. A typical setup for this type of thermal testing method consists of a thermal needle probe, which contains a needle with a heater and a temperature sensor inside.

For this study, the thermal needle probe used was the KD2 Pro Thermal Properties Analyser, manufactured by Decagon Devices. The KD2 Pro equipment was designed based on the transient state method of obtaining the thermal properties of a wide range of materials. The thermal properties determined in the scope of this study included the thermal conductivity, thermal resistivity and volumetric heat capacity of soils.

The Decagon Devices KD2 Pro thermal needle probes comes in two varieties, which are the KS-1 single needle probe, and the SH-1 dual needle probe. Contrary to the study conducted by Barry-Macaulay *et al.* [17], the use of KS-1 single needle probe in soils are discouraged, since it was not recommended by the manufacturers of the KD2 Pro Thermal Probe [16]. As such, only the results obtained with the SH-1 dual needle probe was considered for the data analysis in this study.

Figure 1 KD2 Pro thermal properties analyser controller [16]

The SH-1 dual thermal needle probe consists of two probes with 1.3 mm diameter and 30 mm length for each probe, spaced 6 mm apart as shown in Figure 2. In addition, the SH-1 is compatible for use with most solid and granular materials, but its use in liquids should be avoided as it produces a large heat pulse, resulting in free convection within the liquid samples. Prior to testing, both thermal needle probes were calibrated by verifying that the sensors were operating according to the manufacturer's specifications. Specifically, the SH-1 dual thermal needle probe sensors were verified using a two-hole Delrin block. Care was taken to minimise the error during the measurement of temperature i.e. from external thermal sources such as body heat.

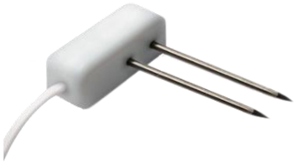


Figure 2 SH-1 dual thermal needle probe [16]

For a dual needle probe, the heater and temperature sensors were placed in separate probes, which allows the measurement of thermal conductivity and volumetric heat capacity to be obtained.

2.3 Sample Preparation and Testing

Soil samples for marine clay and kaolin soil were prepared at a similar dry density, but with varying moisture contents. Both soil types were oven dried overnight at 105°C to prevent any biological activity within the sample [18]. Then, the oven-dried soil was mixed with distilled water to achieve the desired moisture content. Three (3) different values of moisture content at 13, 22 and 32 % were chosen as recommended by [17]. To ensure a uniform moisture distribution throughout the sample, the soil sample was sealed and cured for one week before it was subjected to the thermal characteristics tests.

After curing, the sample was compacted according to the Standard Proctor Compaction method as stipulated in the British Standard [11]. In order to carry out the test, a cylinder with internal dimensions of 105 mm in diameter and 115.5 mm height was used. Soil samples made from the marine clay and kaolin were compacted in three layers, using a metal rammer weighing 2.5 kg, with a 50 mm diameter face.

Consequently, to ensure the homogeneity and uniformity of the soil samples, the height of each layer was measured after it was compacted, allowing a tolerance of 5 mm for each compacted layer. More specifically, the soil was compacted to a height of 38 to 43 mm for the first layer, 76 to 81 mm for the second layer, and 114 to 119 mm for the third and final layer.

After the compaction, the SH-1 dual thermal needle probe was inserted into each soil sample in order to obtain the thermal characteristics of the soil. For the SH-1 sensor, the read time was set for two minutes, and an additional 30 seconds for temperature equilibrium phase to take place prior to the testing phase [16]. To obtain good quality data, the soil sample had been made to be as close to equilibrium as possible. This was achieved by placing the KD2 Pro sensor and sample in an isothermal chamber prior to the actual test, and to allow around 15 minutes between readings for accurate results.

3.0 RESULTS AND DISCUSSION

Heat capacity and thermal conductivity vary greatly between soils because different soils are made up of different proportions of sand, silt, clay and organic matter, and are of different structure [19]. In this section, the results of the conducted tests to determine the thermal characteristics of the Malaysian cohesive soils are presented and analysed. Table 2 presents the summary of results obtained from the series of tests conducted in this study.

Meanwhile, Figure 3 shows the results of the Thermal Conductivity (TC) test against moisture content for marine clay and kaolin soil. It can be observed that the marine clay exhibits an almost linear increased in thermal conductivity as the moisture content increased. Meanwhile, for kaolin soil the TC value reached its peak at 22 % moisture content, which was 2.015 W/m.K but showed a downward trend as the moisture content increased beyond the 22 % moisture content threshold. Water greatly increased thermal conductivity when present in sufficient quantities to exist as films on soil surfaces. As such, thermal contact between particles is improved by water 'bridges' [19].

Table 2 Summary of thermal properties for marine clay and kaolin

Soil Thermal Properties	Moisture Content (%)	Marine Clay	Kaolin
Thermal Conductivity Unit: W/(m·K)	13	0.561	1.551
	22	0.922	2.015
	32	1.147	1.744
Thermal Resistivity Unit: °C·cm/W	13	181.383	64.633
	22	108.733	49.717
	32	87.260	57.350
Volumetric Heat Capacity Unit: MJ/(m³·K)	13	2.072	2.269
	22	2.699	2.899
	32	3.098	2.923

With further increased in moisture content, the thermal contact between soil particles continued to improve, until up to a certain moisture content where the thermal conductivity reached a maximum value. Moisture in excess of this critical point does not provide any further improvement to the thermal contact [19].

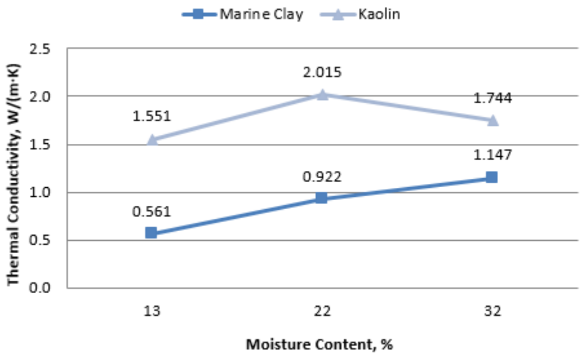


Figure 3 Thermal conductivity values for marine clay and kaolin

The diminishing value of thermal conductivity at higher levels of moisture content is due to the disruption of the thermal flow continuity in the soil matrix with the presence of moisture in the soil, adversely affecting the thermal conductivity. In addition, since the marine clay has a higher liquid limit (58 %) compared to the kaolin soil (38 %), it can be said that at 32 % moisture content, the kaolin soil possesses a high moisture content while the marine clay has a medium level of moisture content. As such, at a similar level of moisture content, soils with higher liquid limits are less susceptible to loss of thermal conductivity when subjected to an increase of moisture content. Similar findings were made by [19-21] regarding the effect of moisture content to the thermal conductivity of cohesive soils.

Meanwhile, Figure 4 illustrates the data obtained for the Thermal Resistivity (TR) test, plotted against a range of moisture content values. Soil thermal resistivity is a measure of the resistance to heat flow through soil and is a function of soil composition, soil density, and soil water content [22].

A sharp decrease was observed when the marine clay moisture content increased from 13 % to 22 % at the same dry density, and this downward trend continued as the moisture content increased to 32 %. However, for kaolin soil, a slight decreased of the thermal resistivity value (from 64.6 to 49.7 °C.cm/W) was observed as the moisture content increased from 13 % to 22 %.

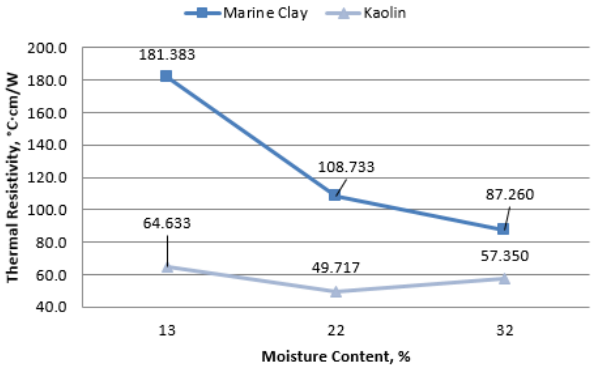


Figure 4 Thermal resistivity values for marine clay and kaolin

Subsequently, as the moisture content value increased from 22 % to 32 %, an increase of the TR value was observed. This trend is consistent with the trend observed in Figure 3 for kaolin soil, since thermal conductivity is inversely correlated with the thermal resistivity value.

Moreover, for a shallow geothermal cooling system designed using inaccurate soil thermal resistivity values, greater heat exchanger length would be installed, increasing the use of construction materials and increasing the overall cost of the project. As such, it is imperative to obtain accurate values of soil thermal resistivity values, which is required to optimise the geothermal cooling system design.

On the other hand, the results of the Volumetric Heat Capacity (VHC) plotted at different moisture contents are shown in Figure 5.

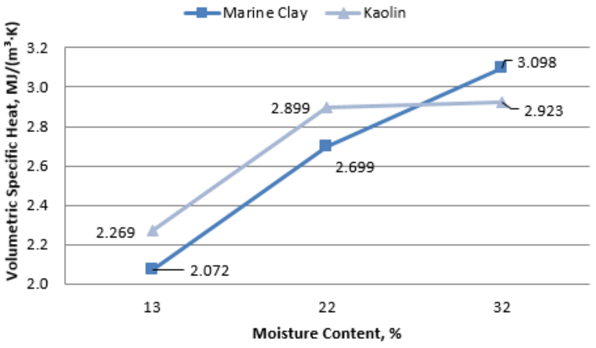


Figure 5 Volumetric specific heat values for marine clay and kaolin

For marine clay, an almost linear increase in the VHC value was observed as the moisture content increased. Meanwhile for kaolin, the VHC was observed to have a sharp increasing trend as the moisture content increased from 13 % to 22 %, but this was followed with a small increment in the VHC value as the moisture content value approached 32%. The volumetric heat capacity increased linearly with volumetric moisture content [17]. The increase was linear because the only component that increased was water, while the bulk density was almost constant [19].

4.0 CONCLUSION

In this study, the SH-1 dual thermal needle probe was used to obtain the preliminary soil thermal parameters (namely thermal conductivity, thermal resistivity and volumetric heat capacity) of Malaysian cohesive soils. The results could provide valuable information on the predicted behaviour of energy piles in Malaysia.

Correlations were made between the soil thermal parameters against varying moisture content values. In general, there are two types of trends observed in this study. For soils with low to medium moisture content, these soils exhibited a linear increase in the thermal conductivity and volumetric heat capacity as the moisture content gradually increased, while the thermal resistivity values of the soil had decreased. This trend was seen in the marine clay, as the chosen moisture content values were lower than its liquid limit, valued at 58 %.

Meanwhile, for soils with high moisture content (moisture content approaching the liquid limit), an opposite trend was observed. This phenomena was observed for kaolin soil, in which as the thermal conductivity decreased, a marked increase was seen in the thermal resistivity as the moisture content increased from 22 % to 32 %. Since the liquid limit of kaolin is valued at 38 %, it can be concluded that the 32 % moisture content is classified as high moisture content for kaolin.

The research works carried out in this study was part of an on-going research programme at the Universiti Teknologi Malaysia, solely focused on assessing the viability of shallow geothermal energy pile systems installed in the Malaysian environment. In this paper, the preliminary results of the soil thermo-physical properties are presented. Future research works will encompass the studies carried out to determine soil thermal properties of a wider range of Malaysian cohesive and cohesionless soils, and eventually to create a database of the aforementioned data. In addition, the effect of cyclical and cumulative thermal loading on the mechanical properties of cohesive and cohesionless soils will also be investigated in the research program.

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References

[1] Gao J., Zhang X., Liu J., Li K. and Yang J. 2008. Numerical and Experimental Assessment of Thermal Performance of Vertical Energy Piles: An Application. *Applied Energy.* 85(10): 901-10.

[2] Brandl, H. 2009. "Energy Piles Concepts", *Deep Foundations on Bored and Auger Piles* - Van Impe and Van Impe, Taylor & Francis Group, London, ISBN 978-0-415-47556-3, 77 – 95.

[3] Laloui, L., Nuth, M. and Vulliet, L. 2006. Experimental and numerical investigations of the behaviour of a heat exchanger pile. *International Journal for Numerical and Analytical Methods in Geomechanics* 30 (8): 763–81.

[4] Bourne-Webb, P. J., Amatya, B., Soga, K., Amis, T., Davidson, C. and Payne, P. 2009. Energy Pile Test at Lambeth College, London: Geotechnical and Thermodynamic Aspects of Pile Response to Heat Cycles. *Géotechnique*. 59(3): 237–48.

[5] Wang, B., Bouazza, A., Singh, R. M., Barry-Macaulay, D., Haberfield, C., Chapman, G., and Baycan, S. 2013. *Field investigation of a geothermal energy pile: initial observations. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering. Paris, France*. 3415-3418.

[6] Murphy, K. D., McCartney, J. S., and Henry, K. H. 2014. Thermo-mechanical characterization of full-scale energy foundations. *Proceedings of the GeoCongress ASCE.* 617-628.

[7] Pakir, F., Marto, A., Yunus, N.Z.M., Tajudin, S.A.A. and Tan, C.S., 2015. Effect of Sodium Silicate as Liquid Based Stabilizer on Shear Strength of Marine Clay. *Jurnal Teknologi*. 76(2): 45-50.

[8] Yunus, N.Z.M., Marto, A., Pakir, F., Kasran, K., Azri, M.A., Jamal, S.N.J. and Abdullah, N. 2015. Performance of Lime-Treated Marine Clay on Strength and Compressibility Characteristics. *International Journal of GEOMATE.* 8(2): 1232-1238.

[9] Marto, A., Makhtar, A.M. and Amaludin, A. 2015. Comparisons on the Response of Shallow Geothermal Energy Pile Embedded in Soft and Firm Soils. *Jurnal Teknologi*. 77(11): 137-143.

[10] Amaludin, A. 2015. *Performance of Geothermal Energy Piles under Thermo-Axial Loads.* M.Eng. Thesis, Universiti Teknologi Malaysia. (Unpublished)

[11] British Standard 1377-1. 1990. Methods of Test for Soils for Civil Engineering Purposes. General Requirements and Sample Preparation. BSI Group

[12] ASTM D2487-11.2011 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System), ASTM International.

[13] Marto, A. 1996. Critical State of Keuper Marl Silt. *Jurnal Kejuruteraan Awam.* 9(2): 34-58.

[14] Marto, A. 1999. Pore Pressure Response of Undrained Two-Way Cyclic Loading of Silt. *Jurnal Kejuruteraan Awam.* 11(1): 35-62.

[15] Mitchell, J. K. and Kao, T C. 1978. Measurement of Soil Thermal Resistivity. *Journal of Geotechnical and Geoenvironmental Engineering. 104*: 1307 - 1320.

[16] Decagon Devices, 2006. KD2 Pro Thermal Properties Analyzer Operator's Manual. Decagon Devices, Inc.

[17] Barry-Macaulay, D., Bouazza, A., and Singh, R. 2011. Study of Thermal Properties of a Basaltic Clay. *Geo-Frontiers 2011. Dallas, TX.*480-487.

[18] Effendi, R. 2007. *Modelling of the settlement Interaction of Neighbouring Buildings on Soft Ground*. PhD Thesis, University of Sheffield, UK.

[19] Mohammed, H.G. 1985. The Thermal Characteristics of Some Highly Weathered Soils of Peninsular Malaysia. *MARDI Research Bulletin*. *13*(3): 219-224.

[20] Gao, Y., Zhao, J., Ma, J. and Song, X. 2012. Experiment of Soil Thermal Properties Based on Thermal Probe Method. In *Advances in Intelligent Systems*. 251-261. Springer Berlin Heidelberg.

[21] Barry-Macaulay, D., Bouazza, A., Singh, R.M., Wang, B. and Ranjith, P.G. 2013. Thermal Conductivity of Soils and Rocks from the Melbourne (Australia) region. *Engineering Geology*. *164*: 131-138.

[22] Woodward, N.R. and Tinjum, J.M. 2012. Impact of Moisture Migration on Thermal Resistivity Testing in Unsaturated Soil. *GeoCongress 2012*. *Oakland, CA*. 4426-4435.