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Thermal Conductivities of Some Agricultural Soils in Trinidad as Affected by Density, Water and Peat Content

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Abstract: *The thermal conductivities of twenty-six (26) agricultural soils in Trinidad were measured in the field and the laboratory with a KD2 sensor and probe. The effect of compacting four of the soils (two clayey and two sandy) to five bulk densities (1.2 to 1.6 Mg m^{-3}) with zero and 4% peat content at four water contents (5, 12, 19 and 26%) on thermal conductivity was further investigated in the laboratory. The thermal conductivity measured in the field ranged from 0.73 to 1.69 W m^{-1} ^{o}C^{-1} and were within 0.11 W m^{-1} ^{o}C^{-1} of the corresponding laboratory-measured values for the individual soils. Thermal conductivity of the laboratory-compacted soils ranged from 0.25 to 2.00 W m^{-1} ^{o}C^{-1}, increased with increasing bulk density and water contents but decreased with the addition of peat. The clay soils exhibited lower values of thermal conductivity than the sandy soils, at given values of bulk density, water content and peat content. Good agreement was found between the laboratory and field measurements of thermal conductivity and the corresponding predicted values using the Campbell model of thermal conductivity. The results obtained are discussed in relation to pipe laying and agricultural operations in Trinidad and Tobago. Apart from soils with appreciable sand contents, most soils would require standard backfills during cable laying.*

Keywords: *Thermal, conductivity, peat, cable, soil, water, density*

1. Introduction

This paper reports the findings of the study and discusses the importance of the property of soil thermal conductivity which determines the ability of a soil to conduct heat (Bristow, 2002). It is required in many areas of engineering, agronomy and soil science. The engineering aspects include the design of underground telecommunication and power transmission cables (Campbell and Bristow, 2002) and underground thermal energy storage, as well as ground source heat pump systems (Spitler et al., 2000). In agronomic practice, seed germination, seedling emergence and establishment are affected by their surrounding climate, which is influenced by soil thermal properties (Ghuman and Lal, 1985; Abu-Hamdeh, 2000).

The thermal properties of soils have been studied in recent literature with a growing interest in laying cables in the ground as an alternative to running them overhead on poles or transmission towers. Sizing of cables for transmission towers is based upon the required current-carrying capacity. Electricity flowing in a conductor including cables generates heat and the resistance to heat flow between the cable and the surrounding environment that makes the cable temperature to rise. The thermal conductivity of the surrounding soils on which the cables are laid determines how much heat the cable is able to dissipate and whether or not or by how much the temperature rises (Campbell and Bristow, 2002; Ekwue et al., 2011). The ideal soil is one that has high thermal conductivity. A simplified solution to the problem is to assume the relevant soil properties and to oversize the cables so that temperature increases are avoided or reduced (Campbell and Bristow, 2002).

Another way of solving the problem is to lay cables in a relatively large trench surrounded with a backfill of stabilised soil or sand with high thermal conductivity. Both techniques are expensive, particularly in situations where cable lengths of many kilometers are planned. An alternative solution is the direct ploughing into a minimum width trench and backfilling with removed local soil. This latter approach could be economically preferable, provided that the thermal dissipation capabilities of the local soil can be guaranteed never to fall below certain minimum values when exposed to different bulk densities and water content. This, therefore, makes the determination of the thermal capacity of local soils to be very essential.

Information on the thermal properties of major soils in Trinidad is rare. Ekwue et al. (2011) started the process of providing information of thermal properties in Trinidad by providing the values for 12 soils. Knowledge of these properties is especially important in relation to underground pipe and cable laying as well as the agricultural needs of the country. This study continues to one started by Ekwue et al. (2011) and extends to 26 soils. This extended work is particularly necessary because of the increased underground pipe laying connected to the growing liquefied natural gas (LNG) industry in the Island. As far as agriculture is concerned, soil thermal properties dictate the rate and amount of heat flow throughout the soil.

The incorporation of organic materials into soils to improve soil physical and hydraulic properties is a common practice. Organic matter is known to reduce soil bulk density which affects soil thermal properties. Recent studies by Abu-Hamdeh and Reeder (2000) and Ekwue et al. (2005, 2006) found that peat decreased the thermal conductivity of soils. It is, however, unclear whether the reduction was as a result of the low conductivity of the peat material or because of its effect in reducing soil bulk density. Several models exist for estimating the thermal conductivity of soils. Some of these include the ones by Kersten (1949) and Campbell (1985). Ekwue et al. (2005, 2006, 2011) found that the Campbell model could be used to predict the thermal conductivity of the twelve Trinidadian soils they studied. It is not clear whether this will be also applicable for the rest of twenty six soils studied in this research.

The objectives of this study as a follow-up of the work by Ekwue et al. (2011) were:

- To measure the thermal conductivity of twenty six major agricultural Trinidadian soils both in the field and the laboratory.
- To examine the effects of bulk density and water content on thermal conductivity for four of these soils representing the range of textural properties.
- To define the effect of peat on soils compacted to the same water contents and bulk densities.
- To assess the adequacy of the well-known Campbell model for estimating thermal conductivity of a wide range of Trinidadian soils.
- To determine the suitability of the soils for use as backfill material in underground pipe laying.

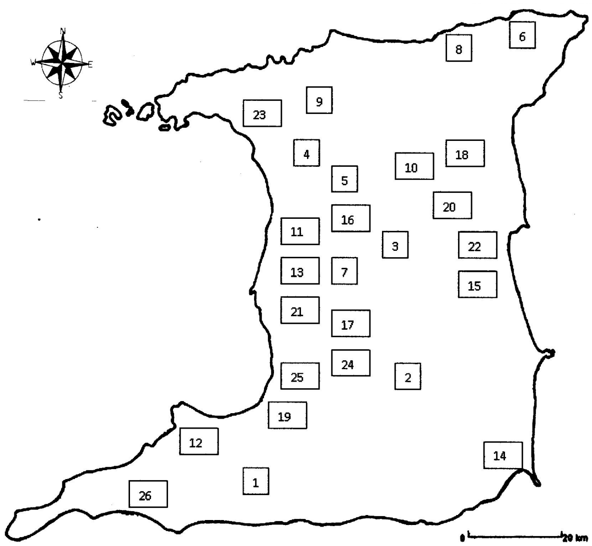
2. Materials and Methods

Twenty six soils representing some of the major agricultural soils in Trinidad were selected for the field and laboratory study of thermal conductivity (see Table 1 and Figure 1). The soils have a wide range of texture including sandy, sandy loam, sandy clay loam, clay loam and clay. Thermal conductivity was measured at existing water contents and bulk densities in the field using the KD2 sensor and probe described below.

Table 1. Classification, organic matter, and particle size distribution (%) of twenty six Trinidadian soils

Soil No.	Soil series	Classification[a]	Organic Matter content, %	Sand 2 – 0.05 mm	Silt 0.05 – 0.002mm	Clay < 0.002 mm	USDA soil textural class
1	Siparia	Typic Haplustults[1]	1.4	54.5	33.5	12.0	Sand
2	Cocal	Typic Quartzipsamments[2]	2.7	81.0	6.0	13.0	Sand
3	Brazil	Umbric Tropaquults[1]	4.8	67.0	20.0	13.0	Sand
4	River Estate	Fluventic Eutropepts[3]	0.9	67.3	15.8	16.9	Sandy loam
5	Piarco	Aquoxic Tropudults[4]	1.7	64.9	17.0	18.1	Sandy loam
6	Grand Riviere	Typic Tropofluverts[3]	1.5	58.0	22.0	20.0	Sandy loam
7	Moruga	Typic Haplustults[5]	2.6	57.3	15.4	27.3	Sandy clay loam
8	Matelot	Orthoxic Tropudults[3]	4.6	50.0	22.0	28.0	Sandy clay loam
9	Maracas	Orthoxic Tropudults[6]	4.7	44.7	24.7	30.6	Clay loam
10	Ecclesville	Aquentic Chromuderts[5]	1.4	50.0	14.7	35.3	Clay loam
11	Mc Bean	Typic Tropudults[5]	0.7	37.3	27.4	35.3	Clay loam
12	Delhi	Typic Tropudults[7]	1.5	39.2	24.8	36.0	Clay loam
13	Freeport	Aeric Tropaqualfs[5]	2.4	30.5	24.5	45.0	Clay
14	Guayagayare	Vertic Tropudalfs[5]	4.8	30.0	25.0	45.0	Clay
15	Plum Mitan	Aquic Tropudalfs[5]	8.8	33.0	21.0	46.0	Clay
16	Cunupia	Aquic Eutropepts[5]	1.7	24.0	30.0	46.0	Clay
17	Talparo	Aquentic Chromuderts[5]	2.7	25.4	28.3	46.3	Clay
18	Sangre Grande	Aeric Tropaquepts[5]	2.2	37.0	11.7	51.3	Clay
19	Debe	Entic Pelluderts[5]	3.4	20.4	23.4	56.2	Clay
20	Tamana	Typic Tropudalfs[7]	7.7	25.0	17.0	58.0	Clay
21	Brasso	Aquentic Chromuderts[7]	4.8	12.3	27.4	60.3	Clay
22	Navet	Aeric Tropaquepts[5]	4.2	13.3	19.4	67.3	Clay
23	Frederick	Vertic Tropaquolls[5]	4.1	6.2	26.5	67.3	Clay
24	Sevilla	Aquentic Chromuderts[7]	1.1	12.7	20.0	67.3	Clay
25	Princes Town	Aquentic Chromuderts[7]	1.9	17.3	11.4	71.3	Clay
26	San Francique	Entic Pelluderts[5]	4.9	4.0	22.5	73.5	Clay

Note: a - Classification according to the Soil Taxonomy System (Soil Survey Staff, 1999).
All values are means of three replicates. Numbers in superscript are soil mineralogy given by Smith (1983) and represent (1) siliceous, (2) uncoated, (3) micaceous, (4) kaolinitic clay, (5) mixed clay mineralogy, (6) clayey oxidic, and (7) montmorillonitic clay



* Notes::Trinidad (Soil numbers are detailed in Table 1. The coordinates are shown in Table 2)

Figure 1. Soil sampling locations for the 26 soils in

Three replicate measurements of thermal conductivity were made within the top 20 cm of each soil. Three replicate soil core samples (collected with core cylinders 5.76 cm diameter and 6.72 cm height) were collected from the study sites and used to determine bulk densities and water contents (see Table 2) that existed in the field using the method of Blake and Hartage (1986). Table 2 also shows the coordinates of the soils. In addition, disturbed samples were collected from the study sites, air-dried and ground to pass a 5-mm sieve. These sieved soil samples were subsequently brought to the same water contents and compacted to the same bulk densities that existed in the field. Laboratory measurements of thermal conductivity were then made using the KD2 probe and sensor. Both field and laboratory measurements were adopted in order to test the authenticity of measuring thermal conductivity in the laboratory using disturbed soil samples.

Particle-size distribution analysis (see Table 1) was performed using the hydrometer method (Lambe, 1951). Organic matter content in the samples was measured using the Walkley and Black (1934) method. Four of the twenty six soils (Siparia sand, Brazil sand, Tamana clay and Frederick clay) were selected for more detailed compaction study designed to examine the effects of bulk density, water content and peat content on these soils. Each soil with zero or with 4% peat contents at different gravimetric water contents (i.e., 5, 12, 17 and 26%) was placed in cylindrical molds of 102 mm diameter and 116 mm height and compacted uniformly to bulk densities of 1.2, 1.3, 1.4, 1.5 and 1.6 Mg m^{-3} using a fly press machine. After compaction, thermal conductivity was determined.

Soil thermal conductivity was measured with a portable thermal properties sensor (KD2) manufactured by Decagon Devices Inc, Pullman, Washington, United States. The sensor measures thermal properties and calculates thermal conductivity by monitoring the dissipation of heat from a line heat source given a known voltage using the equation for radial heat conduction in a homogeneous and isotropic medium. This theory was well described by the KD2 User's Manual by Decagon Devices Incorporated (2006) and Ekwue et al. (2006) and was based on the solution to the heat conduction equation where a heat-pulse is applied instantaneously from a line source (Bristow, 2002).

Apart from the field and laboratory measurements, independent estimates of soil thermal conductivity were obtained for comparison with the KD2 measurements using the equation developed by Campbell (1985). These estimates were obtained for all the twenty six soils used in the field study (Table 1) as well as for the four selected soils with zero peat contents compacted at five bulk densities and four water contents in the laboratory.

Using the Campbell (1985), soil thermal conductivity can be empirically described using the equation:

$$k = A + B\,\theta_v - (A - D)\exp[-(C\,\theta_v)^E] \qquad (1)$$

where: k is soil thermal conductivity (W m^{-1} ^{o}C^{-1}), θ_v is volumetric water content and A, B, C, D and E are soil dependent coefficients. For many mineral soils where the quartz fraction can be neglected (as in the present soils, see Table 1 for soil mineralogy), Campbell (1985) gave the values of the coefficients as:

$$A = 0.65 - 0.78\,\rho_b + 0.60\,\rho_b^{\,2} \qquad (2)$$

$$B = 1.06\,\rho_b\,\theta_v \qquad (3)$$

$$C = 1 + 2.6\,m_c^{-0.5} \qquad (4)$$

$$D = 0.03 + 0.10\,\rho_b^{\,2} \qquad (5)$$

$$E = 4 \qquad (6)$$

Where ρ_b is soil dry bulk density in Mg m^{-3} and m_c is clay mass fraction. For the present study, the exponent of ρ_b in Eqn (2) above was changed from 2 to 2.5 as it better reflected the increase in k as bulk density of the soil increased during compaction.

3. Results and Discussion

3.1 Comparison of measured thermal conductivity in the field and the laboratory

Thermal conductivity measured in the field and the laboratory were closely related and varied within 0.11 W m^{-2} ^{o}C^{-1} for each of the soils (see Table 2 and Figure 2). This result demonstrates that the KD2 sensor is expected to measure soil thermal conductivity accurately in the laboratory once the field water contents and bulk densities are maintained during testing in the laboratory. The coefficient of determination of the comparing equation (see Figure 2) is significant at 0.1% level.

Table 2. Field moisture content, bulk density, soil coordinates and thermal conductivity

Soil No.	Soil series	Field moisture content (% dry mass)	Field density (Mg m^{-3})	Soil Coordinates		Thermal conductivity (W m^{-1} °C^{-1})		
				Latitude (N)	Longitude (W)	Field	Lab	Predicted *
1	Siparia	15.0	1.67	10°08.3′	61°30.0′	1.69	1.58	1.62
2	Cocal	41.0	1.20	10°16.0′	61°10.8′	1.13	1.16	0.99
3	Brazil	13.9	1.25	10°27.2′	61°11.5′	0.73	0.80	0.75
4	River Estate	21.5	1.38	10°38.3′	61°25.6′	1.01	0.91	1.04
5	Piarco	21.1	1.60	10°35.4′	61°19.7′	1.55	1.52	1.54
6	Grand Riviere	21.1	1.33	10°47.0′	61°00.0′	0.78	0.85	0.95
7	Moruga	18.3	1.41	10°24.5′	61°23.2′	1.24	1.14	1.06
8	Matelot	44.1	1.33	10°45.1′	61°07.0′	0.93	0.93	1.12
9	Maracas	14.7	1.59	10°42.2′	61°23.9′	1.52	1.47	1.37
10	Ecclesville	17.9	1.55	10°33.9′	61°10.8′	1.45	1.47	1.36
11	Mc Bean	24.6	1.57	10°28.2′	61°25.9′	1.22	1.29	1.33
12	Delhi	17.1	1.59	10°10.0′	61°36.0′	1.47	1.47	1.44
13	Freeport	18.3	1.58	10°24.5′	61°25.9′	1.27	1.31	1.42
14	Guayagayare	32.4	1.38	10°09.5′	61°06.0′	1.00	1.00	1.20
15	Plum Mitan	23.9	1.40	10°23.5′	61°05.2′	1.18	1.25	1.11
16	Cunupia	18.3	1.58	10°30.1′	61°23.2′	1.45	1.40	1.42
17	Talparo	38.3	1.19	10°23.8′	61°21.2′	0.87	0.86	0.91
18	Sangre Grande	18.3	1.41	10°35.3′	61°07.0′	1.03	1.05	0.97
19	Debe	28.4	1.43	10°12.5′	61°25.0′	1.13	1.21	1.25
20	Tamana	40.6	1.26	10°31.5′	61°06.5′	1.02	1.03	1.09
21	Brasso	34.1	1.31	10°24.3′	61°23.7′	0.99	1.03	1.08
22	Navet	50.7	1.15	10°27.2′	61°05.2′	0.90	0.91	1.02
23	Frederick	32.8	1.23	10°41.3′	61°30.0′	0.84	0.84	0.91
24	Sevilla	32.5	1.41	10°38.3′	61°25.6′	0.99	0.93	1.08
25	Princes Town	36.3	1.34	10°16.0′	61°25.9′	0.91	0.91	1.19
26	San Francique	33.0	1.36	10°04.0′	61°50.0′	1.03	1.09	1.17

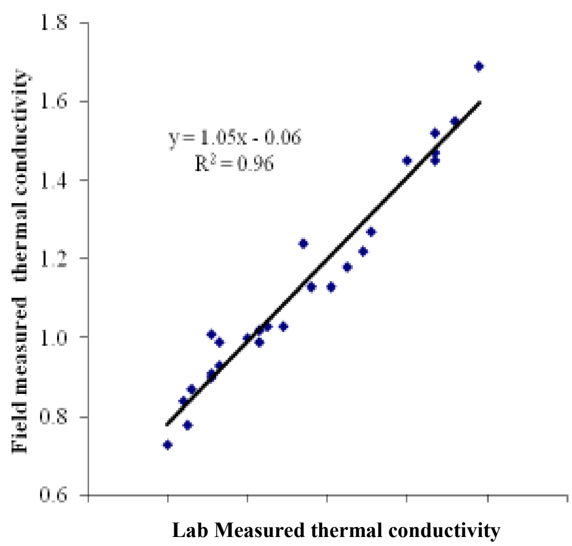


Figure 2. Measured values of thermal conductivity (W m^{-1} °C^{-1}) in the laboratory and the field

The values of the slope of the regression line (1.05) and the intercept (-0.06) were close to 1.00 and 0.00 respectively which demonstrate that there was little or no bias in the measurements. The values of thermal conductivity measured in the field ranged from 0.73 W m^{-2} °C^{-1} in Brazil sand to 1.69 W m^{-2} °C^{-1} in Siparia sand. As mentioned in the introduction section, there are two major options of power cable installation to avoid excessive increases in cable temperature which could shorten cable life. One is the use of designed backfill materials. Campbell and Bristow (2002) observed that a fluidized thermal backfill that has a thermal conductivity which varies from 1.33Wm^{-2} °C^{-1} when dry to 2 W m^{-2} °C^{-1} when wet can be poured in place. The second option is the direct ploughing of the cables into a minimum width trench and backfilling with removed local soil.

Campbell and Bristow (2002) suggested that the engineer should specify the density of a backfill material, and assure, through design and appropriate management, that water content does not fall below 5% water content by volume in sandy soils and 10 or 15% in clay soils. Below these minimum water contents, thermal conductivity is known to decrease considerably. These water contents correspond to typical minimum water contents in the root zone of growing plants. For the soils tested in the field (see Table 2), using the thermal conductivity of the fluidised thermal backfill mentioned above as a standard, only the Siparia sand, Piarco sandy loam, Maracas clay loam, Ecclesville clay loam, Delhi clay loam and the Cunupia clay fell within the 1.33 to 2.00 W m^{-2} °C^{-1} range where direct ploughing of cables can be allowed.

As shown in Table 2, these soils achieved the recommended thermal conductivity because of their high bulk densities which are greater than the maximum of 1.50 Mg m^{-3} that is normally required for adequate plant development (Soane, 1975). For most clay soils, their relatively low thermal conductivities in the field suggest that there is the need for standard backfill materials during underground pipe laying.

3.2 Comparison of predicted and measured values of thermal conductivity

Measured thermal conductivity values were compared with those predicted by Campbell (1985). Results are showed in Table 2 and Figure 3. The predicted and measured values were significantly correlated (R^2= 0.83; P = 0.001). The predicted thermal conductivity values were within 0.20 W m^{-2} $^oC^{-1}$ of the values measured in the field. Abu-Hamdeh (2000) reported that the model of Campbell (1985) accurately predicted the thermal conductivity of some Jordanian soils very closely. This result shows that, although Campbell and Bristow (2002) suggested that thermal conductivities should be measured in-situ, the model of Campbell (1985) would be useful for obtaining estimates of thermal conductivity of mineral soils in Trinidad once their bulk density, water content and clay content are known. This result also agrees with previous studies by Ekwue (2005, 2006, 2011) that the Campbell (1985) model could predict thermal conductivity values accurately.

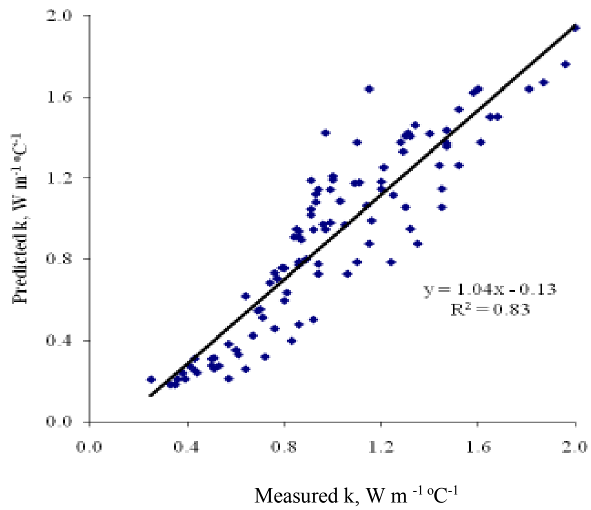


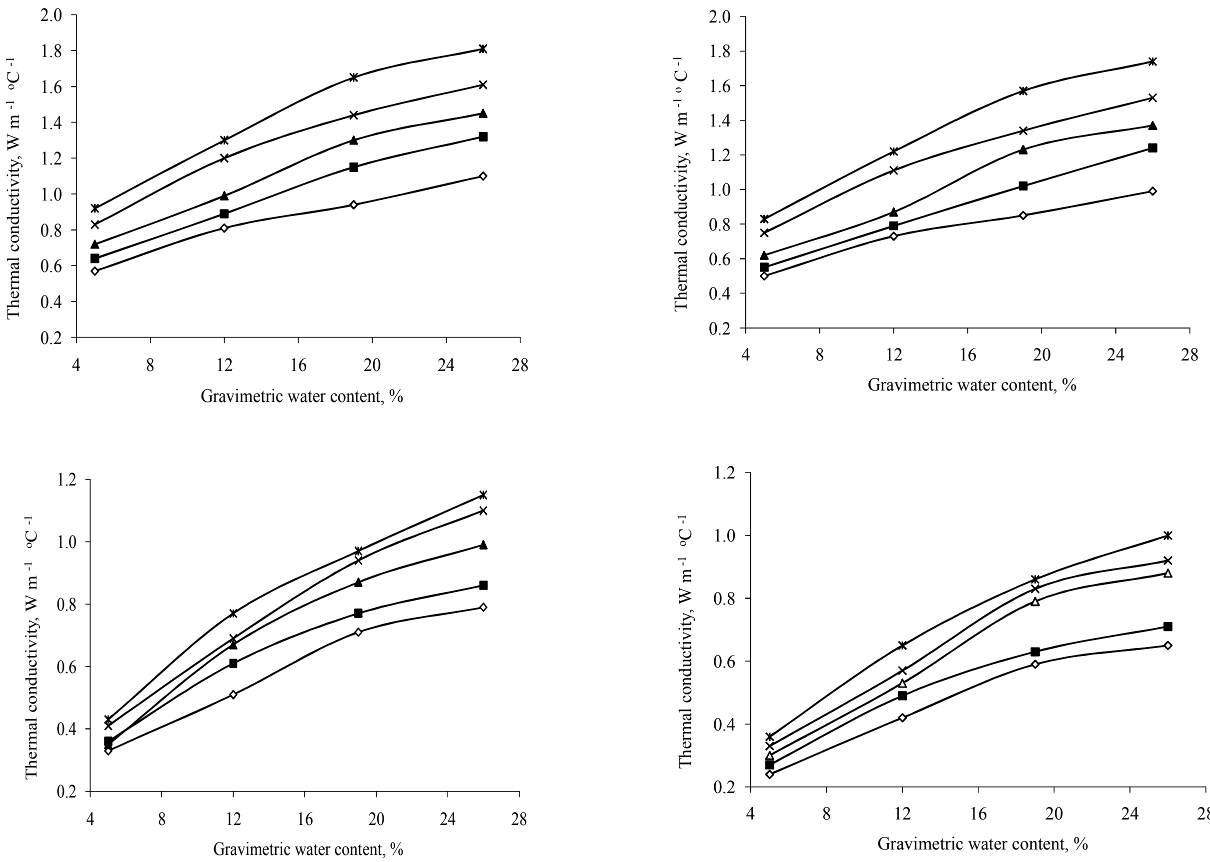
Figure 3. Measured thermal conductivity k versus values predicted by Campbell's model as a function of bulk density, moisture content and clay fraction

3.3 Factors Affecting Thermal Conductivity

Thermal conductivity for the four soils at different peat content and water contents compacted in the laboratory at different bulk densities are shown in Table 3. The plots for two of the soils are shown in Figure 4. Values of thermal conductivity in the compaction study ranged from 0.25 W m^{-2} $^oC^{-1}$ to 2.05W m^{-2} $^oC^{-1}$.

Table 3. Laboratory measured values of thermal conductivity, k (W m^{-2} $^oC^{-1}$) for different soils with or without peat at various moisture contents and bulk densities

Bulk density, Mg m^{-3}	Without Peat (Moisture contents, %)				With 4% Peat content by mass (Moisture contents, %)			
	5	12	19	26	5	12	19	26
Siparia sand								
1.2	0.57	0.81	0.94	1.10	0.50	0.73	0.85	0.99
1.3	0.64	0.89	1.15	1.32	0.55	0.79	1.02	1.24
1.4	0.72	0.99	1.30	1.45	0.62	0.87	1.23	1.37
1.5	0.83	1.20	1.44	1.61	0.75	1.11	1.34	1.53
1.6	0.92	1.30	1.65	1.81	0.83	1.22	1.57	1.74
Brazil Sand								
1.2	0.25	0.64	1.06	1.24	0.29	0.67	0.75	0.86
1.3	0.43	0.86	1.35	1.65	0.57	0.82	1.01	1.23
1.4	0.50	0.96	1.45	1.87	0.63	0.89	1.07	1.31
1.5	0.57	1.11	1.52	1.96	0.72	1.00	1.33	1.60
1.6	0.86	1.32	1.68	2.05	0.86	1.22	1.53	1.84
Tamana clay								
1.2	0.35	0.53	0.70	0.86	0.25	0.55	0.65	0.78
1.3	0.39	0.60	0.76	0.92	0.31	0.59	0.74	0.80
1.4	0.44	0.76	0.97	1.20	0.50	0.85	0.88	0.90
1.5	0.50	0.80	1.00	1.28	0.55	0.85	0.96	0.99
1.6	0.51	0.94	1.34	1.60	0.73	1.06	1.18	1.25
Frederick clay								
1.2	0.33	0.51	0.71	0.79	0.24	0.42	0.63	0.65
1.3	0.36	0.61	0.74	0.86	0.25	0.49	0.63	0.71
1.4	0.38	0.67	0.87	0.99	0.27	0.56	0.79	0.88
1.5	0.41	0.69	0.94	1.10	0.33	0.57	0.85	0.92
1.6	0.43	0.77	0.97	1.15	0.35	0.65	0.86	1.00



(c) Frederick clay – No peat; (d) Frederick clay with 4% peat

Keys:

*◊ 1.2 ; ■ 1.3 ; ▲ 1.4; x 1.5; and * 1.6 Mg m^{-3}*

Figure 4. Influence of moisture content on thermal conductivity of two soils - Siparia sand and Frederick clay at bulk densities

The plots for two of the soils are shown in Figure 4. Values of thermal conductivity in the compaction study ranged from 0.25 W m^{-2} ºC^{-1} to 2.05W m^{-2} ºC^{-1}. As expected, thermal conductivity increased with increasing water content and bulk density but declined with peat content. The "two sandy soils" had higher values of thermal conductivity than the "two clay soils" in line with previous work. From the results of the laboratory compaction study, since the minimum water content expected in the field should be ideally used in the design (Campbell and Bristow, 2002), if this is assumed as 12% water content by mass, then the direct ploughing can only be barely allowed for the excessive soil compaction level of greater than 1.5 Mg m-3 in the sandy soils using the 1.33 to 2.00 Wm^{-2} °C^{-1} range of thermal conductivity. It is apparent that no matter the value of bulk density or water content to which the clay soils are exposed, direct ploughing of cables cannot be allowed. The cable laying in the clay soils must be accompanied by adequate standard backfill materials. Based on the results of this study, standard backfills should be utilised during pipe laying in all the soils used in this study except for highly compacted sandy loam soils, when soil densities are very high.

The mean values of thermal conductivity for all the experimental factors are shown in Table 4. While thermal conductivity increased with water content and bulk density, it declined with peat content and increasing clay content in the soils. The analysis of variance showed that the main effects of all the experimental factors and their first and second order interactions significantly affected soil thermal conductivity. The main effect of water content was the highest followed by soil type, bulk density and peat content in that order. The most important first order interaction was between peat content and water content followed by soil type and water content. However, the interaction effects of the other first-order interactions and the second-order interactions were small compared to the main effects and the mentioned first-order interactions, and only the latter were therefore examined further.

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Table 4. Mean* values of thermal conductivity from the compaction study

Factor level	Mean thermal conductivity (W m-1 °C -1)
Soil type	
Siparia sand	1.09
Brazil sand	1.09
Tamana clay	0.80
Frederick clay	0.66
LSD (P = 0.001)	0.04
Peat Content (%)	
0	0.96
4	0.85
LSD (P = 0.001)	0.03
Moisture content (%)	
5	0.51
12	0.82
19	1.06
26	1.24
LSD (P = 0.001)	0.04
Bulk density (Mg m^{-3})	
1.2	0.66
1.3	0.79
1.4	0.91
1.5	1.01
1.6	1.16
LSD (P = 0.001)	0.04

* - Mean values for each factor were obtained by averaging the measured values over the levels of the other three experimental factors. Number of experimental points is 320 representing a factorial experiment with 4 soil types, 2 peat contents, 4 moisture contents, 5 bulk densities and 2 replications

Water has a thermal conductivity that is approximately 30 times that of air, but considerably smaller than that of the soil particles. Consequently, the thickness and the geometric arrangement of the water layer around the particles increase soil conductivity (Nakshabandi and Kohnke, 1965). As the bulk density of a given soil increases, the contact between the individual particles becomes more intimate, and results in increases in thermal conductivity (Nakshabandi and Kohnke, 1965). This facilitates greater heat movement through the soil. The interaction between the soil water content and soil type (see Figure 5) implies that the increases in thermal conductivity with water content would be more pronounced in sandy soils than in clay soils.

The higher mean values of thermal conductivity of the two sandy soils than the two clay soils were expected. This confirms the previous research by Nakshabandi and Kohnke (1965), Abu-Hamdeh (2000) and Ekwue et al. (2005, 2006) and is due to the greater particle size of sandy soils. The lower thermal conductivity of the clay soils means that they will experience greater surface temperature fluctuations than the sandy soils. The interaction between soil type and water content shows that the effect of soil type on thermal conductivity is more pronounced at higher rather than lower moisture contents (see Figure 5).

Thermal conductivity declined with increasing peat contents and this has been found in previous studies by Abu-Hamdeh and Reeder (2000) and Ekwue et.al. (2005, 2006). The latter authors attributed this to the decline in bulk density resulting from the greater pore space normally obtained when soils are amended with organic matter. They stated that since peat decreased soil bulk density it also decreased the soil thermal conductivity.

However, in this study, for all soils compacted to the same bulk density, soils with peat had lower thermal conductivity than the soils with no peat. This study, therefore, shows that in addition to peat decreasing bulk density, it decreases thermal conductivity because its material has a lower thermal conductivity than mineral soils (see Figure 6). Electricity flowing in a conductor generates heat. The ideal soil used as backfill material for the cables is the one with a high thermal conductivity, so that most of the heat generated can be dissipated (Campbell and Bristow, 2002). This means that soils that contain appreciable organic materials, particularly in form of peat, will not be suitable as backfill material for underground cables.

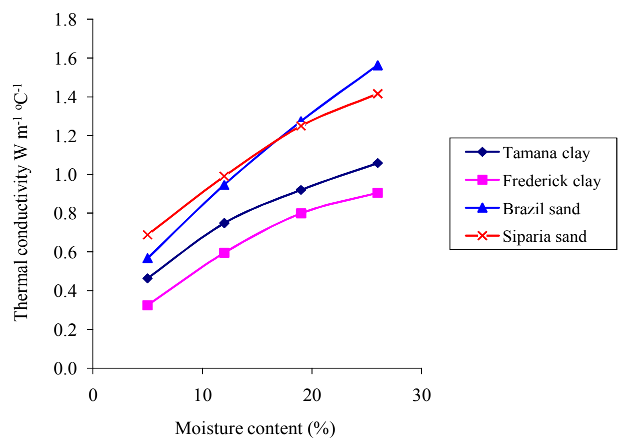

Figure 5. The effect of the interaction between soil type and moisture control on thermal conductivity

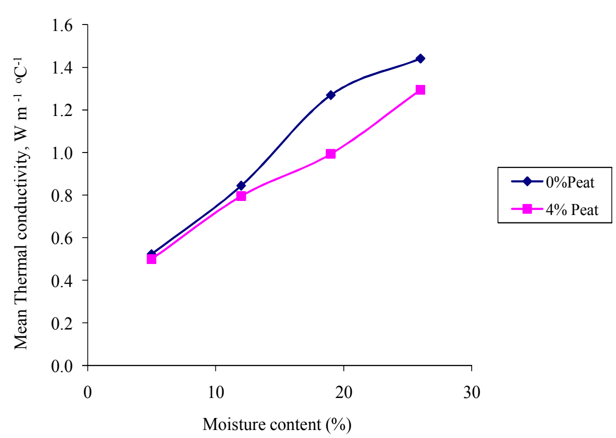

Figure 6. The effect of the interaction between peat control and moisture control on thermal conductivity

In situations where cables must pass through soils with appreciable organic materials, it may be necessary to dig a trench and fill it with large amounts of high thermal conductivity backfill materials such as sand, as explained by Campbell and Bristow (2002). The significant interaction obtained between peat content and water content means that at low soil water contents, the effect of peat content in reducing thermal conductivity would be minimal.

4. Conclusions

The thermal conductivities of 26 Trinidadian soils were measured in the field and in the laboratory. This was accompanied by a detailed laboratory compaction study in which four of the soils were compacted to five bulk densities, with or without peat, and at four moisture contents prior to the measurement of thermal conductivity. Field and laboratory measurements of thermal conductivity were similar for all the 26 soils. These similarities demonstrate that laboratory measurements of thermal conductivity could be used to accurately represent field measurements provided that soil bulk densities and water contents similar to those existing in the field are maintained.

Thermal conductivity increased with increasing bulk density and moisture content, declined with the addition of peat and was lower for clay soils than for sandy soils. The effect of peat in reducing thermal conductivity is achieved both by its role in decreasing soil bulk density and its lower thermal conductivity compared to mineral soils. Thermal conductivity predictions using the popular Campbell model correlated well with their corresponding measured counterparts thereby demonstrating the utility of this model in providing reliable estimates of thermal conductivity of Trinidadian soils. The major implication of this study is that most soils in Trinidad, apart from those with appreciable sand contents, would require standard backfills during underground cable laying. The highlights of the paper include:

i) Laboratory measured thermal conductivities are similar to those measured in the field as long as the density and water contents of soils are similar to those existing in the field.
ii) Campbell (1985) model can be reliably used to estimate the thermal conductivity of soils in Trinidad.
iii) Thermal conductivity values were lower for the clay soils than for the soils with high sand contents.
iv) Peat reduces thermal conductivity by reducing soil bulk material and because of its material which has a low thermal conductivity.
v) Most soils in Trinidad, apart for those with appreciable sand content would require standard landfills during undergraduate electric cable laying.

Future studies could examine the effect of actually laying electric cables in some of the soils with known thermal conductivity and monitoring the rise of temperature of the surrounding soil with time.

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