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Thermal Conductivities of Some Common Soils in Trinidad

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Abstract: *Thermal conductivity (k) of twelve soils from Trinidad was measured in the field and the laboratory using a portable sensor and probe. The effect on k of compacting three of the soils (a sandy loam, clay loam and clay) using 5, 15 and 25 Proctor hammer blows at water contents which ranged from 5% to 40% was further investigated in the laboratory. Bulk density (ρ_b) achieved during soil compaction was measured to assist in the interpretation of the results. The k measured in the field ranged from 0.90 to 1.55 W m^{-1} $^oC^{-1}$ and was within 0.1 W m^{-1} $^oC^{-1}$ of the corresponding laboratory-measured values for the individual soils. The k of the laboratory-compacted soils, which ranged from 0.5 to 2.00 W m^{-1} $^oC^{-1}$, increased with increasing water contents with maximum ρ_b being reached before the maximum k. The clay soil had lower values of k and ρ_b than the clay loam and the sandy loam soil. Good agreement was found between the field and laboratory measured k as well as the k values predicted using the Campbell model. The results obtained are discussed in relation to pipe laying in Trinidad. Apart from soils with appreciable sand contents, most soils because of their large clay contents would require standard backfills during cable laying.*

Keywords: *Thermal, conductivity, soil, compaction, cable, density*

1. Introduction

Soil thermal properties are required in many areas of engineering, agronomy and soil science. Some engineering interests include the design of underground telecommunication and power transmission cables (Campbell and Bristow, 2002) and underground thermal energy storage and ground source heat pump systems (Spitler et al., 2000). In agronomic practice, seed germination, seedling emergence and establishment are affected by their microclimate, which is influenced by soil thermal properties (Ghuman and Lal, 1985; Abu-Hamdeh, 2000).

The thermal properties of soils have recently received renewed attention 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 generates heat and the resistance to heat flow between the cable and the ambient environment causes the cable temperature to rise. The k of the surrounding soils on which the cables are laid is important as it determines how much heat the cable is able to dissipate and whether or not the temperature rises (Campbell and Bristow, 2002). The ideal soil is one that has high k. A simple solution often utilized is to make conservative assumptions about soil properties and to oversize the cable so that temperature increases are avoided (Campbell and Bristow, 2002). Another solution is to lay cables in a relatively large trench surrounded with a backfill of stabilized soil or sand with high k. Both techniques are expensive, especially where cable lengths of many kilometers are planned. An alternative approach 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 ρ_b and water contents. This, therefore, calls for the determination of the thermal capacity of local soils.

In agriculture, temperature fluctuations are undesirable as they lead to constraints to plant growth. Low soil temperature increases the viscosity of soil water and thus its resistance to heat flow. As a result, there may be poor contact between plant roots and soil particles as the soil water flow is impeded. On the other hand, high soil temperatures can lead to excessive evaporation of soil water. Control of soil temperature is therefore important. It offers the potential to grow crops that require a temperature regime different from the unmanaged environment (van Donk et al., 2004).

Thermal conductivity, k (W m^{-1} K^{-1}) describes the soil's ability to transmit heat (mainly by conduction). It is usually defined as the quantity of heat that flows through a unit area in a unit time under a unit temperature gradient, as described by Fourier's law of heat conduction (Bristow, 2002). A soil with a high k is one in which heat flow occurs at a fast enough rate to ensure that temperature extremes in the soil are avoided. Thus, high conductivity of heat is desirable in most soils (Ekwue et al., 2005). In the tropics, high k allows a soil to rapidly dissipate most of the heat captured from the sun to the cooler sub-surface, and therefore maintain a cooler soil surface.

Thermal conductivity of soils is generally affected by soil texture and structure, and increase with ρ_b and water content (Ghuman and Lal, 1985; Ahu-Hamdeh, 2000; Nakshabandi and Kohnke, 1965). Nakshabandi and Kohnke (1965) observed that the k of soils at the same water content is highest in gravel and sand, intermediate in loam and lowest in clay soils. They found that water variations had a much greater effect on k than ρ_b and grain size.

No previous reported work has fully investigated the thermal properties of many soils in Trinidad. 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 is very timely particularly with 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 objectives of this study were:

i) To quantify the k of twelve major Trinidadian soils both in the field and the laboratory;
ii) To examine the effects of compaction and water content on k for three of these soils representing the range of textural properties;
iii) To assess the adequacy of the well-known Campbell model for estimating k of Trinidadian soils; and
iv) To determine the suitability of the soils for use as backfill material in underground pipe laying.

2. Materials and Methods

2.1 Theoretical Considerations

Twelve soils representing some of the major soils in Trinidad were selected for the field and laboratory study of k (see Figure 1). The first two soils are sandy loams, the third is sandy clay loam, and the next two are clay loams while the remaining seven soils are clays. Soil thermal conductivity, k was measured at the soil surface in the field with the KD2 sensor and probe manufactured by Decagon Devices Inc. (2001). The sensor measures thermal properties and calculates k 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.

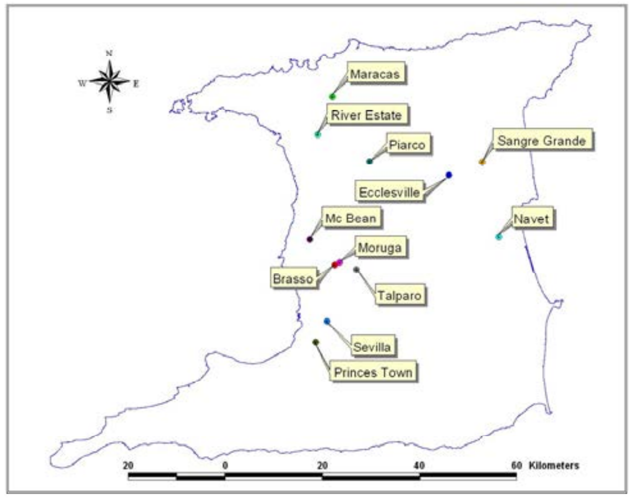

Figure 1. Soil sampling locations in Trinidad

According to the KD2 User's Manual (Decagon Devices, Inc., 2001) when a long, electrically heated probe is introduced into a medium, when time, t(s) is large, the rise in temperature from an initial temperature, T_o at some distance r, (m) from the probe can be approximated as:

$$T - T_o = \frac{q}{4\pi k}\left[\ln(t) - \gamma - \ln\left\{\frac{r^2}{4\alpha}\right\}\right] \quad \text{...Eq.1}$$

Where, T is temperature (°C); q is heat produced per unit length per unit time (W m^{-1}); α is diffusivity (m^2 s^{-1}) and k is thermal conductivity (W m^{-1} $^oC^{-1}$) of the medium while Υ is Euler's constant (0.5772).

The relationship between k and $\Delta T = T - T_0$, shown in Equation 1, is such that ΔT and ln t are linearly related with a slope, m, such that $m = q / 4\pi k$. Linearly regressing ΔT on ln (t) yields a slope, which, after rearranging, gives the k, as:

$$k = q / 4\pi m \quad \text{...Eq.2}$$

Where, q is known from the power supplied to the heater.

The above theory assumes that the long heat source can be treated as an infinitely long heat source; the soil is both homogeneous and isotropic, and that a uniform initial temperature, T_0, is assumed in the soil. These assumptions are not strictly true, but are adequate for accurate thermal property measurements. The manufacturer of the KD2 probe found that it measures k with 5% accuracy. The KD2 probe records the temperature of the medium. During the laboratory tests, the soil temperature range was from 25^{o}C to 27^{o}C. Although k is temperature dependent (Campbell et al., 1994), the narrow range of temperature would ensure that the temperature variations of the medium did not significantly affect the results.

Core cylinders (5.76 cm diameter, 6.72 cm high) were used to collect minimally disturbed soil samples within the top 20 cm depth in the twelve study sites and oven-dried at 105^{o}C in the laboratory to determine the field in-situ ρ_b and water contents (see Table 2) using the method of Blake and Hartage (1986). Also bulk samples were collected from the study sites, air-dried and sieved through 5mm openings and used for laboratory testing. Particle size analysis (as showed in Table 1) was carried out using the hydrometer method (Lambe, 1951). The organic matter in the samples was measured using the method of Walkley and Black (1934).

Table 1. Location, classification, organic matter, and particle size distribution (%) of twelve Trinidadian soils

Soil Series	GPS Location	Classification*	Organic Matter Content (%)	Sand 2-0.05 mm	Silt 0.05-0.002 mm	Clay < 0.002 mm
River Estate	N $10^0$38.312'	Fluventic	0.9	67.30	15.8	16.9
	WO $61^0$25.566'	Eutropepts[1]				
Piarco	N 10^0 35.395'	Aquoxic	1.7	64.90	17	18.1
	WO $61^0$19.699'	Tropuldults[2]				
Moruga	N $10^0$24.525'	Typic	2.6	57.30	15.4	27.3
	WO $61^0$23.151'	Haplustults[3]				
Maracas	N $10^0$42.399'	Orthoxic	4.7	44.70	24.7	30.6
	WO $61^0$23.868'	Tropudults[4]				
Ecclesville	N $10^0$33.861'	Aquentic	1.4	50.00	14.7	35.3
	WO $61^0$10.766 '	Chromuderts[3]				
Mc Bean	N $10^0$33.861'	Typic	0.7	37.30	27.4	35.3
	WO $61^0$10.766 '	Tropudults[3]				
Sangre Grande	N $10^0$35.299'	Aeric	2.2	37.00	11.7	51.3
Talparo	WO $61^0$07.004'	Tropaquepts[3]				
	N $10^0$23.804'	Aquentic	2.7	25.4	28.3	46.3
Brasso	WO $61^0$21.228'	Chromuderts[3]				
	N $10^0$24.263'	Aquentic	4.8	12.30	27.4	60.3
Navet	WO $61^0$23.693'	Chromuderts[3]				
	N $10^0$27.200'	Aeric	4.2	13.30	19.40	67.3
Sevilla	WO $61^0$05.152'	Tropaquepts[3]				
	N $10^0$38.312'	Aquentic	1.1	12.70	20	67.3
Princes Town	WO $61^0$25.566'	Chromuderts[5]				
	N $10^0$15.954'	Aquentic	1.9	17.30	11.4	71.3
	WO $61^0$25.853'	Chromuderts[5]				

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

Table 2. Field water content, ρ_b and measured k in the field and the laboratory

Soil Series	Field water content, % dry mass	Field bulk ddensity, Mg m^{-3}	Thermal conductivity, W m^{-1} ^{o}C^{-1}		
			Field	Lab.	Predicted*
River Estate	21.5	1.38	1.01	0.91	1.09
Piarco	21.1	1.60	1.55	1.52	1.59
Moruga	18.3	1.41	1.24	1.14	1.11
Maracas	14.7	1.59	1.52	1.47	1.42
Ecclesville	17.9	1.55	1.45	1.47	1.40
Mc Bean	14.6	1.57	1.22	1.29	1.31
Sangre Grande	18.3	1.41	1.03	1.05	1.01
Talparo	38.3	1.19	0.87	0.86	0.95
Brasso	34.1	1.31	0.99	1.03	1.12
Navet	50.7	1.15	0.90	0.91	0.86
Sevilla	22.5	1.41	0.99	0.93	1.12
Princes Town	26.3	1.34	0.91	0.91	1.06

Remarks: *Using Campbell (1985) Model

In order to investigate the authenticity of the measurement of k on disturbed soils in the laboratory, the twelve soil samples collected from the field were repacked in three layers in a cylindrical mould, 15.2 cm in diameter and 10.8 cm in height at the same water contents and ρ_b as existed in the field. A standard compression (flypress) machine was used to repack the soils and k was measured at the soil surface using the KD2 sensor and probe (see Table 2).

Three of the twelve soils, offering a range of texture (Piarco sandy loam, Maracas clay loam and Talparo clay), were selected for a more detailed laboratory study to examine the effects of compaction and water content on k. To determine the maximum ρ_b and k after compaction for the three selected soils, the standard Proctor compaction test (Lambe, 1951) was adopted. Details of the experimental procedure used for the compaction test were described by Ekwue and Stone (1994) and Ekwue et al. (2006). For each soil, compaction was done in three layers at different water contents (ranging from 5 to 40%) using 5, 15, and 25 blows from a standard Proctor hammer in cylindrical moulds of 10.2 cm diameter and 11.6 cm height. After compaction, the mold with the soil was weighed to determine the ρ_b, before determining k at the soil surface with the KD2 sensor and probe.

In addition to the field and laboratory measurements, independent estimates of soil k were obtained using the equations developed by Campbell (1985) for comparison with those measured with the KD2 sensor and probe. These estimates were obtained for all the twelve soils used in the field study (see Table 2) as well as for the three selected soils compacted at various densities and water contents in the laboratory.

According to Campbell (1985), soil k can be empirically described using the equation:

$$k = A + B\,\theta_v - (A - D)\exp[-(C\,\theta_v)^E] \qquad \text{....Eq.3}$$

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 (like in the present soils, see Table 1 for soil mineralogy), Campbell (1985) gave the values of the coefficients as:

$$A = 0.65 - 0.78\,\rho_b + 0.60\,\rho_b^2 \qquad \text{....Eq.4}$$

$$B = 1.06\,\rho_b\,\theta_v \qquad \text{....Eq.5}$$

$$C = 1 + 2.6\,m_c^{-0.5} \qquad \text{.....Eq.6}$$

$$D = 0.03 + 0.10\,\rho_b^2 \qquad \text{.....Eq.7}$$

$$E = 4 \qquad \text{.....Eq.8}$$

Where ρ_b is soil dry bulk density (Mg m^{-3}) and m_c is clay mass fraction. For the present study, the exponent of ρ_b in Equation 5 above was changed from 2 to 2.5 as it better reflected the increase in k as ρ_b of the soil increased during compaction.

3. Results and Discussions

3.1 Comparison of measured k in the field and the laboratory

The k measured in the field and the laboratory for the twelve study soils were closely related and varied within 0.1 W m^{-2} ^{o}C^{-1} for each soil (see Figure 2 and Table 2). This result is reassuring and demonstrates that although the structure of the soil in the field and the laboratory may have differed, calibrations obtained in the laboratory can be considered adequate for describing these soils. The values of the slope of the regression line (0.97) and the intercept (0.06) were close to 1.00 and 0.00 respectively indicating that there was no bias in the measurements.

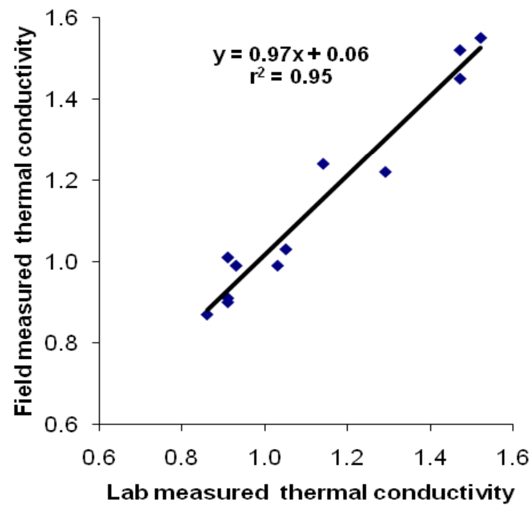

Figure 2. Laboratory measured versus field measured values of thermal conductivity (W m^{-1} ^{o}C^{-1})

3.2 Comparison of predicted and measured values of k

Measured k for all the twelve soils in the field and for the three soils, Piarco sandy loam, Maracas clay loam, and Talparo clay in the laboratory (see Figure 3) was plotted alongside k values based on the model predictions of (Equation 3). Figure 4 shows the results that predicted and measured values were significantly correlated (P = 0.001). The predicted k values were within 0.15 W m^{-2} ^{o}C^{-1} of the values measured in the field (see Table 2). 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 values of ρ_b, water content and clay content are known.

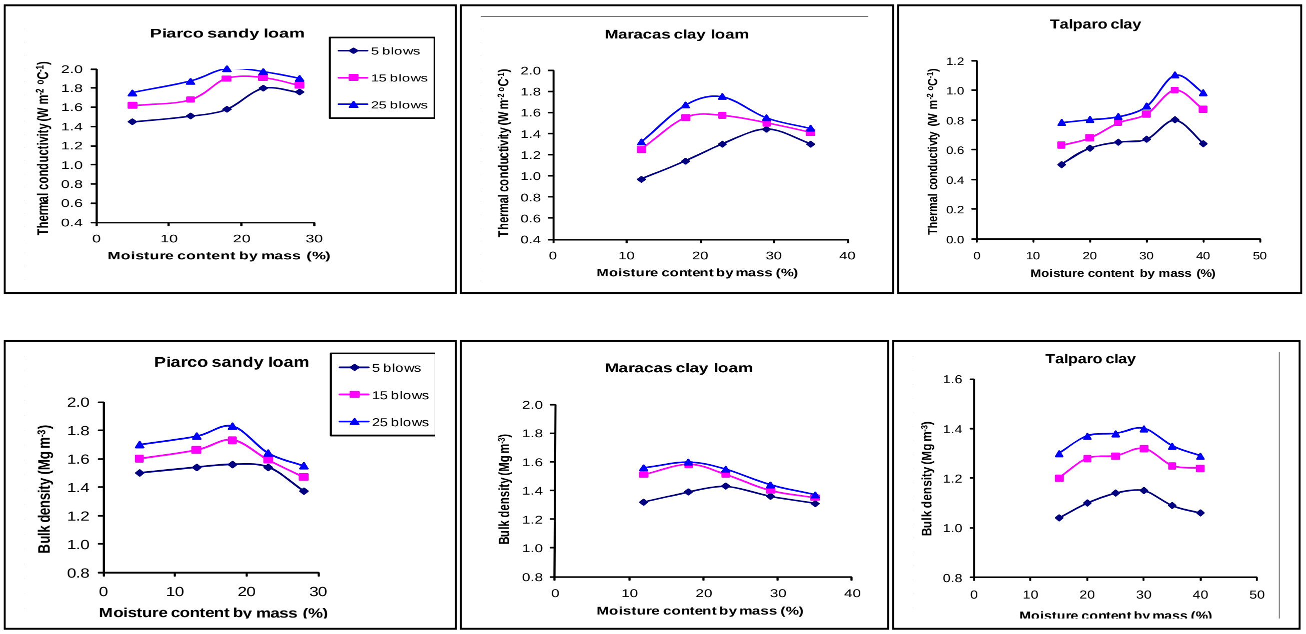

Figure 3. Thermal conductivity and bulk density of three soils each at three compaction levels

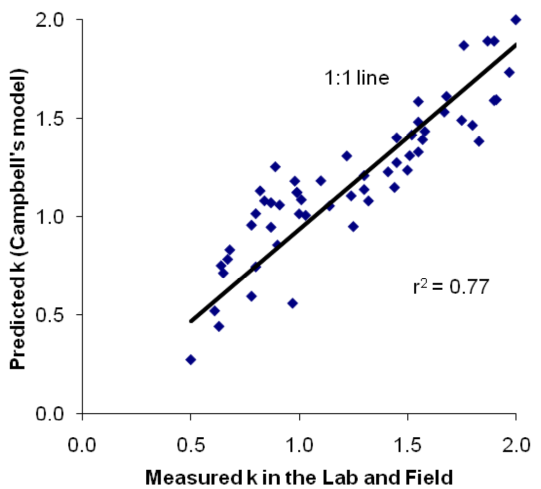

Figure 4. Measured versus predicted thermal conductivity, k (W m^{-2} ^{o}C^{-1})

3.3 Factors affecting k and ρ_b

The plots of k and ρ_b versus water content for the three soils used for the compaction study each compacted with 5, 15 and 25 Proctor compaction blows are shown in Figure 4. For each soil and compaction level, k and ρ_b increased with increase in soil water content until peak values k_{max} and ρ_{max} were reached. After this, as expected, the ρ_b values declined with further increases in water content as is common in soil compaction studies using the Proctor method. This decline in values of k with water content after maximum values were reached is being reported for the first time to the best of the authors' knowledge.

Bulk density ρ_b increased initially as water was added causing slaking and lubrication of the soil lumps, as well as greater soil cohesion. Since k is known to increase with ρ_b and water content (Ghuman and Lal, 1985; Nakshabandi and Kohnke, 1965; Wierenga et al., 1969), it also increased with water content at this stage. Water has a k that is approximately 30 times that of air, but considerably smaller than the soil particles. Consequently, the thickness and the geometric arrangement of the water layer around the particles would increase k (Nakshabandi and Kohnke, 1965). As ρ_b of a given soil increases, the contact between the individual particles becomes more intimate, and results in increases in k (Nakshabandi and Kohnke, 1965). This facilitates greater heat movement through the soil. Figure 5 shows that the linear relationship between k and ρ_b for the three soils with different water contents was highly significant (p = 0.001). This result suggests that when soils are compacted, the relationship between the two parameters is expected to be unique, regardless of soil type, water content and level of compaction effort.

On the wet side of the maximum density, the soil lumps had been slaked, and the excess water caused greater pore water pressures as the compaction continued and the soil became less compactible and the ρ_b declined (Ohu et al., 1989). This caused a decline in k. For each soil and compaction effort, the water content at which ρ_{max} occurred were smaller than those at which k_{max} was obtained.

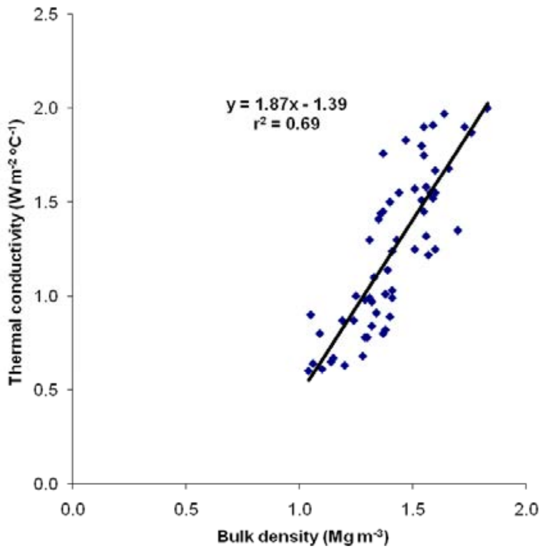

Figure 5. Thermal conductivity versus bulk density for all the soils

After the optimum water content for maximum compaction was reached, although bulk densities declined, water contents still increased. The k values therefore increased slightly after the optimum water content was reached until the effect of reduced ρ_b became more important than the increased water content, leading to the eventual decline in k. This has not been previously reported in previous work. Most past workers on k including Nakshabandi and Kohnke (1965) and Wierenga et al. (1969) found that k increased linearly with water content. However, these past workers kept ρ_b of the soil constant and varied only water content. In this Proctor soil compaction test adopted, both ρ_b and water content of the soil were varied at the same time leading to the decline in k obtained after maximum values were reached.

Table 3 summarizes values of maximum k, k_{max} and maximum ρ_b, ρ_{max} as well as the corresponding values of the water contents at which these maximum values occurred. For a given compaction effort, in all cases, values of ρ_{max} and k_{max} decreased while the corresponding water contents at which they occurred, increased with increasing clay content of the soils. Maximum ρ_b was highest in the Piarco sandy loam followed by the Maracas clay loam and the Talparo clay as expected. This is in agreement with previous research (Ohu et al., 1989; Ayers and Perumpral, 1982) and is due to the higher degree of aggregation in soils with high clay contents. Sandy soils are poorly aggregated and therefore have less pore space, greater ρ_b and better contact between particles than well aggregated soils (Abu-Hamdeh, 2000; Nakshabandi and Kohnke, 1965). Since the Piarco soil with the lowest clay content had the highest ρ_b, it was therefore not surprising that it also had the greatest k.

Table 3. Maximum thermal conductivity and ρ_b of the soils and the corresponding water contents

Soil	Compaction level (Proctor blows)	Maximum thermal conductivity, k_{max} (W m^{-2} $^oC^{-1}$)	Maximum bulk, density, ρ_{max} (Mg m-3)
Piarco sandy loam	5	1.80 (23.0)*	1.58 (19.8)
	15	1.91 (20.0)	1.73 (18.2)
	25	2.00 (18.2)	1.83 (17.2)
Maracas clay loam	5	1.44 (29.0)	1.43 (23.0)
	15	1.57 (20.5)	1.58 (19.0)
	25	1.75 (20.0)	1.60 (18.0)
Talparo clay	5	0.80 (35.0)	1.15 (30.0)
	15	1.00 (35.0)	1.32 (28.5)
	25	1.10 (34.5)	1.40 (28.2)

Remarks: *Values in parenthesis are water contents, dry mass basis (%) at maximum k and maximum ρ_b

As expected, values of ρ_{max} and k_{max} increased with increasing compaction effort. Thermal conductivity increased because of the higher ρ_b created by soil compaction. Moreover, in line with previous work on soil compaction (Hamdani, 1983), the water content corresponding to ρ_{max} decreased with increasing compaction effort. As compaction effort increases, less water is required for lubrication to achieve maximum ρ_b and strength (Hamdani, 1983). This result also applied to k_{max}.

This study has shown that the reaction of soil k to water content is similar in every way to the response of ρ_b, with the only difference being that the optimum water content for maximum ρ_b and compaction occurs earlier than the water content for maximum k. This is a major finding of this study.

4. Application of Results to Underground Cable Laying in Trinidad

As was 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) mentioned that a fluidized thermal backfill that has a thermal conductivity of about 1.33 W m^{-2} $^oC^{-1}$ when dry to 2 W m^{-2} ^{o}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 excavated 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, k is known to reduce considerably. These water contents correspond to typical minimum water contents in the root zone of growing plants.

The equivalent static pressures of the 5, 15 and 25 Proctor compaction blows can be estimated as 175, 404 and 618 kPa respectively using the equation derived by Raghavan and Ohu (1985). Since applied stress due to agricultural traffic on farms seldom exceeds 500 kPa (Gupta and Larson, 1985), the 25 compaction blows represent severe soil compaction. For the soils tested in the field (see Table 2), using the k of the fluidized thermal backfill mentioned above as a standard, only the Piarco sandy loam, Maracas clay loam and the Ecclesville clay loam fell within the 1.33 to 2.00 W m^{-2} ^{o}C^{-1} range where direct ploughing of cables can be allowed. The latter two soils only achieved the recommended k because of their high ρ_b which are more that the maximum of 1.50 Mg m^{-3} that is normally required for adequate plant development (Soane, 1975). For the clay soils, their relatively low k in the field suggests that there is the need of standard backfill materials during underground pipe laying.

The results of the laboratory compaction study showed that no matter the value of ρ_b or water content to which the soils are exposed, while direct ploughing of cables can be allowed for the Piarco sandy loam, the cable laying in the Talparo clay must be accompanied by adequate standard backfill materials (see Figure 3). For the intermediate Maracas clay loam, the 1.33 to 2.00 W m^{-2} ^{o}C^{-1} range of thermal conductivity can only be achieved at high compaction levels or at high water contents. 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 allowed for the excessive soil compaction level of 25 Proctor blows. Based on the results of this study, it is safe to state that standard backfills should be utilised during pipe laying in all the soils used except in the Piarco loam soil where direct ploughing of the cables into a minimum width trench followed by backfilling with excavated local soil can be done.

5. Conclusions

The following conclusions can be drawn based on the results obtained:

1) Laboratory measurements of k for twelve soils in Trinidad were in close agreement with the corresponding field measurements. In the laboratory, k could be accurately measured once ρ_b and water contents similar to those existing in the field are maintained.
2) The k measurements correlated well with predicted values obtained using the Campbell (1985) model popular in the literature. This shows that this model can be used to estimate reliably the thermal conductivity of soils in Trinidad.
3) The k was lower for the clay soil than for the sandy loam and the clay loam soil.
4) A unique linear relationship exists between ρ_b and k for compacted soils. This relationship provides a quick and simple procedure for the prediction of k.
5) When soils are compacted, the water content at which maximum ρ_b occurs is less than that at which maximum k is obtained.
6) Based on field and laboratory measurements of k, most soils apart from those with appreciable sand contents would require standard backfills during underground cable laying.

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References:

Abu-Hamdeh, N.H. (2000), "Effect of tillage treatments on soil thermal conductivity for some Jordanian clay loam and loam soils", *Soil and Tillage Research*, Vol.56, pp.145-151

Ayers, P.D. and Perumpral, J.V. (1982), "Water and density effect on cone index", *Transactions of the American Society of Agricultural Engineers*, Vol.21, pp.1169-1172

Blake, G.R., and Hartage, K.H. (1986), "Particle density", In: Klute, A. (ed.) *Methods of Soil Analysis: Part 1.*, 2nd. Edition, Agronomy Monogram 9, ASA and SSSA, Madison, WI, pp.377-382

Bristow, K.L. (2002), "Thermal conductivity", In: Topp, G.C. and Dane, J.H. (ed.) *Methods of Soil Analysis: Part 4*, Soil Science Society of America Book Series 5. Madison, WI, pp.1209-1226

Campbell, G.S., Jungbauer, J.D., Bidlake, W.R. and Hungerford, R.D. (1994), "Predicting the effect of temperature on soil thermal conductivity", *Soil Science*, Vol.158, pp.307-313

Campbell, G.S. (1985), *Soil Physics with Basic-Transport Models for Soil-Plant Systems*, Elsevier, New York

Campbell, G.S. and Bristow, K.L. (2002), *Soil Thermal Resistivity*, PTD Publications, Chapel Hill, Qld, Australian, pp.46-48

Decagon Devices, Incorporated (2001), *KD2 Thermal Properties Analyzer User's Manual*, Version 1.0. http://www.thermalresistivity.com/KD2man.pdf (2005/02/23).

Ekwue, E.I. and Stone, R.J. (1994), "Effect of peat on the compactibility of some Trinidadian soils", *Journal of Agricultural Engineering Research*, Vol.57, pp.129-136

Ekwue, E.I., Stone, R.J., Maharaj, V.V. and Bhagwat, D. (2005), "Thermal conductivity and diffusivity of four Trinidadian soils as affected by peat content", *Transactions of the American Society of Agricultural Engineers*, Vol.48, pp.1803-1815

Ekwue, E.I., Stone, R.J. and Bhagwat, D. (2006), "Thermal conductivity of some compacted Trinidadian soils as affected by peat content", *Biosystems Engineering*, Vol.94, pp.461-469

Ghuman, B.S. and Lal, R. (1985), "Thermal conductivity, thermal diffusivity and thermal capacity of some Nigerian soils", *Soil Science*, Vol.139, pp.74-80

Gupta, S.C. and Larson, W.E. (1985), "Modeling soil mechanical behaviour during tillage", In: Unger, P.W and van Doren, D.M. (Eds.), *Predicting Tillage Effects on Soil Physical Properties and Processes*, Madison, Wisconsin: ASA Special Publication 44, American Society of Agronomy, pp.151-178

Hamdani, I.H. (1983), "Optimum water content for compacting soils: One point method", *Journal of Irrigation and Drainage Engineering*, Vol.109, No.2, pp.232-237

Lambe T.W. (1951), *Soil Testing for Engineers*, John Wiley, New York

Nakshabandi, G.A. and Kohnke, H. (1965), "Thermal conductivity and diffusivity of soils as related to water tension and other physical properties", *Agricultural Meteorology*, Vol. 2, pp.271-279

Ohu, J.O., Folorunso, O.A., Adeniji, F.A. and Raghavan, G.S.V. (1989), "Critical water content as an index of compactibility of agricultural soils in Borno State of Nigeria", *Soil Technology*, Vol.2, pp.211-219

Raghavan, G.S.V. and Ohu, J.O. (1985), "Prediction of static equivalent pressure of Proctor compaction blows", *Transactions of the ASAE*, Vol.28, pp.1398-1400

Smith, G.D. (1983), *Soil and Land Use Surveys*, No.27, Correlation of the Soils of the Commonwealth Caribbean, Puerto Rico, The Virgin Islands

Spitler, J.D., Yavuzturk, C. and Rees, S.J. (2000), "In situ measurement of ground thermal properties", *Proceedings of Terrastock 2000*, Stuttgart, Vol. 1, pp.165-170

Soane, B.D. (1975), "Studies on some physical properties in relation to cultivation and traffic", *Soil Physical Conditions and Crop Production: MAFF Technical Bulletin*, Vol.29, pp.160-182

Soil Survey Staff (1999), "Soil taxonomy: A basic system for making and interpreting soil surveys", In: *Agriculture Handbook*, 2nd Edition, US Govt Printing Office/USDA, Washington-DC, pp.128-129

van Donk S.J., Tollner, E.W., Steiner, J.L. and Evett, R.S. (2004), "Soil temperature under dormant Bermuda grass mulch: simulation and measurement", *Transactions of the ASAE*, Vol.47, pp.91-98

Walkley, A. and Black, I.A. (1934), "An examination of the effect of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method", *Soil Science*, Vol.37, pp.29-38

Wierenga, P.J., Nelson, D.R. and Hagan, R.M. (1969), "Thermal properties of soil based upon field and laboratory measurements", *Soil Science Society of America Proceedings*, Vol.33, pp.354-360

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