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Thermal Properties of High Water Content Materials

Abstract: Fundamental thermal properties of various high water content materials were determined using a number of thermal testing methods. Tests were conducted on peat soils, solid wastes, industrial sludge, and bentonite slurries. Thermal conductivity, heat capacity, and thermal diffusivity were determined. The thermal conductivity of the materials was determined using a needle probe method. The volumetric heat capacity of the materials was determined using a dual probe method. These values were used together to obtain thermal diffusivity. Analytical methods are also used to determine heat capacity and thermal diffusivity. The theory for determination of thermal parameters using the various methods is presented. Experimental methods were determined to be effective at measuring thermal properties of high water content materials. Thermal parameters are dependent on material composition and structure. Heat capacity and thermal diffusivity are greatly affected by water content because of the high heat capacity of water compared with air and solids. A comparison is made between experimental and analytical methods used to determine thermal parameters. Good agreement was observed between experimental and analytical methods. Results of thermal tests have applications in the prediction of heat transfer through soils, sludges, and wastes.

Keywords: thermal properties, peat, bentonite slurry, thermal conductivity, thermal diffusivity, heat capacity, specific heat, solid waste, sludge

Introduction

Heat transfer in high water content materials is caused by both natural and manmade thermal gradients. Natural thermal gradients are caused by seasonal temperature Cycles, waste decomposition, and geothermal activity. Man-made thermal gradients are Produced by manufacturing and energy producing facilities, soft ground improvement methods (including thermal precompression of peat and soil freezing), and environmental remediation techniques (including thermal bioremediation and soil vitrification). Analysis of thermal properties of high water content materials including

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organic soils and wastes is required to determine temperatures near heat sources, assess efficiency of ground improvement techniques, and optimize operation of landfills as bioreactors.

Thermal properties of various high water content materials were determined in this study. Probe methods (needle probe thermal conductivity method and specific heat dual probe method) were used. A description of applicable thermal properties, theory of the probe methods, and results of laboratory and field measurements are presented. A comparison of methods for determining thermal properties is also presented.

Background

The two major parameters needed to quantify heat transfer are the rate of *heat* flow through a medium (thermal conductivity, k_t), and the ease with which a medium can be heated (mass heat capacity, *c*, or volumetric heat capacity, C). Mass heat capacity is also known as specific heat. The effectiveness at which a medium gains heat content (thermal diffusivity, a) is a composite parameter of k_t and *C* (Andersland and Ladanyi 1994). Thermal conductivity can be defined as the amount of heat passing through a unit *area* over a unit time under the effect of a unit thermal gradient. Heat capacity can be defined *as* the amount of heat required to change the temperature of a material by one degree Kelvin. This can be quantified on a unit-mass or a unit-volume basis. A low heat capacity corresponds to a relatively large temperature change for a given amount of heat application. Thermal diffusivity is defined as the quotient of thermal conductivity, k_b and volumetric heat capacity, *C* (Equation 1). Volumetric heat capacity, *C*, is the product of mass heat capacity, *c* and density of material, *p*.

$$\alpha = \frac{k_t}{C} = \frac{k_t}{c\rho} \quad (1)$$

where:
α = thermal diffusivity (m^2/s)
k_t = thermal conductivity ($W/m\cdot°C$)
C = volumetric heat capacity ($kJ/m^3\cdot°C$)
c = mass heat capacity ($kJ/kg\cdot°C$)
ρ = mass density (kg/m^3)

Thermal diffusivity is a composite parameter that indicates how fast temperature change occurs in a material subjected to a thermal gradient. A material that has a high thermal diffusivity experiences an increase in temperature faster than a complementary material that has a low thermal diffusivity (Andersland and Anderson 1978). Table 1 shows the thermal properties of various materials that make up soil. The difference in the thermal properties of the materials in Table 1 indicate the importance of soil composition on the thermal properties of soils.

Thermal properties of soil are dependent on material composition, fabric or packing arrangement, water content, and temperature. For a porous material at a given dry density, thermal conductivity increases with increasing moisture content. For a given moisture content, thermal conductivity increases with increasing dry density. The composition of porous material also has an effect on the magnitude of the thermal conductivity (e.g. organic vs. inorganic constituents, Table 1). Thermal conductivity increases with increasing temperature. Reasons for this include an increase in the thermal conductivity of the individual components of the porous material, an increase in moisture migration, and improvement of particle contact bonds with increasing temperature (Farouki 1981).

[Insert Table 1]

The fundamental thermal properties (thermal conductivity, heat capacity, and thermal diffusivity) can be determined using probe devices. Thermal conductivity is determined using a single probe method and heat capacity and thermal diffusivity are determined using a dual probe method. ASTM Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure (D 5334) involves placing a thermal needle probe into the soil and monitoring the transient heating effects. The probe has both heating and temperature sensing capabilities. The heat energy applied to the soil is monitored by means of a voltage application through a calibrated resistor. The temperature is measured with a thermocouple positioned at the midpoint of the probe. By comparing the amount of heat energy applied to the needle to the resulting temperature increase, the amount of heat transferred to the surrounding material can be deduced.

The thermal needle probe method has proven to be a reliable and straightforward means of obtaining the thermal conductivity of soils. Mitchell and Kao (1978) concluded that the thermal needle probe was the most effective means of determining thermal conductivity of soils. The thermal needle probe has been adapted for field (Slusarchuk and Foulger 1973, Goodrich 1986). For field applications, the diameter and length of the probe are increased. The aspect ratio of length to diameter of a common laboratory probe is 95 (120 mm length, 1.27 mm diameter). The aspect ratio of the field probe is 35 (330 mm length, 9.5 mm diameter).

The dual probe method has been developed for an accurate determination of heat capacity of soils (Bristow et al. 1994). An apparatus which consists of two closely spaced, small probes is used in this method. One of the probes provides a short duration heat pulse and the other probe monitors temperature at a nearby location. By monitoring the maximum temperature rise at a known distance from the heat source, the heat capacity of the material can be determined. The dual probe method allows for direct calculations of thermal diffusivity and volumetric heat capacity. Using these values and the density of the material, the thermal conductivity can be calculated.

Experimental Methods for Determination of Thermal Properties

Thermal conductivity is determined using ASTM D 5334. Volumetric heat capacity is determined using the Dual Probe Method (Bristow et al. 1993, 1994). Thermal diffusivity is determined using the results of these two tests. The methods and theory required to determine thermal parameters using these tests is briefly described.

Needle Probe Method

The needle thermal conductivity probe consists of a stainless steel tube (hypodermic needle) that contains a heating element and a thermocouple which are both connected to a datalogger. Specifications of the probe used in the test program are: length: 120 mm; diameter: 1.27 mm; resistance: 151 ohms (resistance includes reference resistor); resistivity: 1141 ohm/m; heating voltage: 4.4 V (supplies approximately 1W/m). A schematic of the thermal conductivity probe used in the test program is presented in Figure 1.

[Insert Figure 1]

The test is conducted by applying a heating current to the probe and monitoring temperature at the midpoint of the probe for a duration of 1-2 minutes. The interpretation of the needle probe method is based in the theory of an infinite line source of heat within an infinite homogeneous medium. The rate of temperature rise along the linear heat source is monitored. The temperature at any radius, *r*, from the linear heat source is given by Carslaw and Jaeger (1959) as:

$$T = \frac{q}{4\pi k_t} E_i\left(-\frac{r^2}{4\alpha t}\right) \qquad (2)$$

where:
T = temperature (°C)
q = power input (W/m)
k_t = thermal conductivity (W/m·°C)
E_i = exponential integral
r = radial distance from line heat source (m)
α = thermal diffusivity (m²/s)
t = time (s)

For small values of the last term (small *r*, large *t*), the exponential integral can be approximated by a logarithm function (Slusarchuk and Foulger 1973). A straight line is obtained when this function is plotted as temperature rise vs. logarithm of time for a given distance from the heat source. The slope of this line represents thermal conductivity of the material and is calculated as follows:

$$k_t = \frac{q}{4\pi(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \qquad (3)$$

where:

k_t = thermal conductivity (W/m·°C)
q = power input (W/m)
T_1 = temperature (°C) at time, t_1 (s)
T_2 = temperature (°C) at time, t_2 (s)

Typical experimental test results for the needle probe method are presented in Figure 2. The linear portion of the data in Figure 2 represents the steady state portion of the test. Data obtained before the linear portion of the curve represents transient conditions of the probe itself heating and should be neglected for curve-fitting procedures. Data beyond the linear portion results from edge and end effects and should also be neglected. A shallow slope of the line indicates that the heat produced along the length of the probe is transferred more effectively into the surrounding medium resulting in a high thermal conductivity (Hanson 1996).

[Insert Figure 2]

Dual Probe Method

The Dual Probe Method is used for the determination of heat capacity. The apparatus consists of two small stainless steel tubes of the same diameter and length, placed parallel to each other at a spacing of approximately 6 mm. The length of the probes is 30 mm and the diameter is 0.90 mm. One probe contains a heating element and the other probe contains a thermocouple. The heater has a resistivity of 1141.5 52/m. The thermocouple is made of Copper-Constantan (Type T). A schematic of the dual probe used in the test program is presented in Figure 3.

[Insert Figure 3]

Power is supplied to the heating probe for an 8 second heating interval. The power supplied to the heating probe and resulting temperature rise at the sensing probe is monitored for 80 seconds. Maximum temperature rise and power input are used to compute heat capacity using Equation 4 (Campbell et al. 1991). The magnitude of the peak temperature change is inversely proportional to heat capacity.

$$C = \rho c = \frac{q}{e \pi r_m^2 \Delta T_m} \quad (4)$$

where:

ρ = mass density (kg/m^3)
c = mass heat capacity (kJ/kg·°C)
q = power supplied to probe (W/m)
C = volumetric heat capacity (kJ/m^3·°C)
e = base of the system of natural logarithms
r_m = fixed distance from heating probe (probe spacing) (m)
ΔT_m = maximum temperature rise (°C)

Typical response of the specific heat dual probe is presented in Figure 4. Both the magnitude of the peak and the time required to reach the peak temperature indicate the thermal behavior of the material being tested.

[Insert Figure 4]

Indirect Methods for Determination of Thermal Properties

Indirect and analytical methods can be used to estimate thermal properties. Heat capacity can be approximated by summing components of composite materials. Also, ground temperature data with depth can be used, together with an idealized analytical solution, to approximate thermal diffusivity of subsurface materials.

Theory for Summing Components of Heat Capacity

Common values for heat capacity for various materials are presented by Andersland and Ladanyi (1994), Carslaw and Jaeger (1959), and De Vries (1966). The heat capacity of a composite material can be calculated by the summation of the individual components of volumetric heat capacity (Equation 5). Values from Table 1, together with weight-volume relationships, can be used to approximate heat capacity of soils and slurries. Equation 5 can be adapted to reflect other constituents of geomaterials (Andersland and Ladanyi 1994). The accuracy of equation 5 is limited by the accuracy of weight-volume relationships and the volumetric heat capacity of the various constituents of the material. Errors in these parameters will be reflected in the overall volumetric heat capacity determined using Equation 5.

$$\rho C \cong \rho_w C_w \theta + \rho_b C_m \quad (5)$$

where:

ρ = overall mass density (kg/m^3)
C = overall volumetric heat capacity (kJ/m^3·°C)
ρ_w = mass density of water (kg/m^3)
C_w = volumetric heat capacity of water (kJ/m^3·°C)
θ = volumetric water content
ρ_b = bulk density of soil minerals (kg/m^3)
C_m = volumetric heat capacity of soil minerals (kJ/m^3·°C)

Approximation of Thermal Diffusivity from Field Temperatures

Thermal diffusivity of soils can be estimated by monitoring amplitude decrement and phase lag of the ground surface temperature wave with depth. Infinite half-space conductive heat transfer theories are used to back calculate values of thermal diffusivity (Lundy 1981). Uniform soil conditions are assumed between two depths of temperature measurements. A schematic plot of temperature vs. time at two depths is presented in Figure 5. Equation 6 is used to estimate thermal diffusivity based on amplitude decrement.

[Insert Figure 5]

$$A_x = A_s e^{-x\sqrt{\frac{\pi}{365\alpha}}} \quad (6)$$

where:

A_x = amplitude of ground temperature wave at x (°C)
A_s = amplitude of ground temperature wave at surface (°C)
x = depth below surface (m)
α = thermal diffusivity (m^2/day)
e = base of the system of natural logarithms

Phase lag measurements of the seasonal ground temperature wave can also be used to estimate the thermal diffusivity in the field (Lundy 1981). At various depths, the peak of the temperature wave will occur at different times due phase lag of the wave. This phase lag can be used to calculate thermal diffusivity using Equation 7. Annual peak to peak temperatures are used to determine phase lag.

$$L = \frac{1}{2}\sqrt{\frac{365}{\pi\alpha}} \quad (7)$$

where:

L = time lag (days)
α = thermal diffusivity (m^2/day)

Materials Tested for Thermal Property Determination

Thermal property testing was conducted on high water content organic soils, municipal solid waste, industrial sludge, and bentonite slurries. The organic soils were obtained from a National Science Foundation/Federal Highway Administration Thermal Precompression field test site in Middleton, Wisconsin (Hanson 1995). The municipal solid waste and industrial sludge were obtained from Sauk Trail Hills Landfill in Canton, Michigan. Bentonite slurries (both chip and powder) were prepared in the laboratory at various water contents.

The two organic soils tested for this program are a fibrous peat and a sedimentary peat. The physical properties of the two soils are presented in Table 2.

[Insert Table 2]

Peat samples were obtained using 75 mm diameter Shelby tubes. The brown fibrous peat consists of porous fibers interwoven in a horizontal plane that results in a structurally anisotropic fabric (Fox 1992). The individual fibers of the fibrous peat are characterized by roots and limbs. A block sample of fibrous peat was also used for thermal property testing. The greenish-brown sedimentary peat is characterized by highly decomposed plant remains which resemble grass and leaves. Fibers of sedimentary peat are much softer and more easily torn apart than the fibers of fibrous peat. The sedimentary peat is more uniformly decomposed in appearance and consistency than the fibrous peat. The fabric of both pests is affected by layering in the horizontal plane.

The municipal solid waste (MSW) is quite variable in nature depending on waste Stream and sampling location. Field tests were conducted to include the macro-effects and spatial variability of the MSW. Main components of the MSW include paper, food, clothing, organic yard waste materials, and shredded wood daily cover material. Water contents of the MSW tested ranged from 16% to 38%.

The industrial sludge is a waste product of the automobile industry and has gravimetric moisture content, w = 50%, bulk specific gravity, G, = 1.6, and pH = 12.5. The consistency of the sludge is primarily granular with some separate highly plastic (tar-like) components.

The bentonite mixtures were made using Wyoming bentonite. The powder and chips were obtained from Bariod Drilling Fluids, Inc ®.[4] The bentonite slurry from powder was prepared by mixing water with 2%, 5%, and 10% bentonite by weight. The bentonite powder slurries were prepared in 20 L containers. The bentonite chips were approximately 6

[4] Baroid Drilling Fluids, Inc., Denver, Colorado.

mm diameter angular particles. The bentonite chips/water mixture was prepared to model a seal used for backfilling a borehole at a water content of 50%. The bentonite chips were placed dry in a 5 L cylinder and allowed to hydrate for 30 days before testing. The resulting mixture had a unit weight of approximately 14 kN/m^3. The specific gravity of the bentonite chips and bentonite powder was 2.6.

Results and Discussion

Thermal conductivity and volumetric heat capacity were determined using the needle probe method and dual probe method, respectively. The results of the thermal probe testing program are presented in Table 3. The variable structure and composition of the materials result in scatter in the thermal property data. The uncertainty in thermal conductivity and heat capacity are reported as Two-Sigma error corresponding to a 95% confidence interval (Table 3). Any uncertainty in thermal conductivity and heat capacity affect the calculation of thermal diffusivity. The uncertainty in thermal diffusivity was calculated using an adaptation of Taylor's Theorem on the propagation of uncertainty (Beckwith and Marangoni 1990). The uncertainty of the thermal diffusivity, a can be expressed as is shown in Equation 8.

$$u_\alpha = \sqrt{\left(u_{k_t}\frac{\partial \alpha}{\partial k_t}\right)^2 + \left(u_C\frac{\partial \alpha}{\partial C}\right)^2} \qquad (8)$$

where:

u_α = the overall uncertainty in thermal diffusivity
$u_{k'}$ = discrete uncertainty in thermal conductivity, k_t
u_C = discrete uncertainty in volumetric heat capacity, C

The results of the tests indicate that the thermal conductivity of peat is lower than the thermal conductivity of typical soils (sands and silts). The large void ratios of the organic soils prevent effective transfer of heat through the soil. The fibrous peat has a higher thermal conductivity than the sedimentary peat. This can be attributed to the . presence of a structural skeleton in the fibrous peat. The heat capacity of the peats is higher than that of sands and silts. The high water content of peats controls the heating process.

A block sample of fibrous peat was used to investigate the spatial variability of thermal parameters. The size of the block was approximately 250 mm x 300 mm x 500 mm. Thermal probes were inserted both vertically and horizontally into the block sample. The values obtained from the block sample were all in good agreement. All thermal parameters determined from the block sample were within the range of values obtained from the Shelby tube samples. No evidence of anisotropic behavior was apparent from the block sample tests. The testing of the block sample also indicated that scaling effects between Shelby tube samples and block samples were negligible. The variability associated with placement of the probes within the larger block sample was similar to the variability of results from Shelby tube samples.

The thermal properties of the MSW are the most variable of any of the materials tested. This is due to the nonuniform composition of the waste materials. Most values of thermal conductivity measured for the MSW were quite low and compared to values for air. This is due to the large void ratio of the waste materials that is occupied by air.

[Insert Table 3]

Variation was observed in the thermal properties of the industrial sludge can be attributed to high spatial variability and the presence of distinct immiscible phases in the material. Results were dependent on placement of the probes within the material. The sludge was less conductive than the peats and slurries. The sludge had a relatively low thermal diffusivity.

The thermal properties of the three typical bentonite slurries (2%, 5%, and 10% solids content) were determined. The thermal properties of the 5% solids and 10% solids bentonite slurries are similar. Results from the 2% solids bentonite slurry are inconsistent With the other results and are not reported in Table 3. Convective heat transfer in the low solids content slurry may be responsible for the inconsistent trends.

The bentonite chips/water mixture, at a substantially higher solids content, has a higher thermal conductivity than the slurries. The high solids content of the bentonite chips/water mixture allows for more effective heat transfer than the bentonite powder slumes. The bentonite chips/water mixture, however, is less conductive than silts and sands due to the relatively low dry density.

Thermal diffusivity is a composite parameter of thermal conductivity and heat capacity. Results of the tests indicate that of these materials, inorganic soils (including bentonite chips/water mixture) have the highest thermal diffusivity. The lowest values of thermal diffusivity were obtained for the MSW and industrial sludge. The highest water content materials (peats and bentonite slurries) had diffusivity values approaching that for water.

Problems were encountered in using the probes in the field. The most important problem was interference of large particles during insertion of the probes. Many trials were required to successfully insert the thermal conductivity probe into the ground. Proper placement of the specific heat dual probe (maintaining a constant distance between the probes) was difficult due to the interference of materials within the waste.

Comparison of Thermal Properties Test Methods

A comparison was made between the experimental and indirect methods used to determine thermal parameters. An analysis was conducted to compare volumetric heat capacity determined using the dual probe method to the determination using summation of components of the materials and published values of heat capacity of the material components. In the summation method, water content, organic content, and degree of saturation were used in the estimation of heat capacity. A summary of this comparison is presented in Table 4. The volumetric heat capacity for fibrous peat, sedimentary peat, and bentonite slurries are in good agreement with those measured using the dual probe. This is due to the high volumetric water content of these materials. Discrepancy exists between the two methods due to structural variability (predominant in the peats and bentonite chips/water mixture) and potential for convective flow (in the relatively low viscosity bentonite slurries). Comparisons for MSW and industrial sludge are not included in Table 4 because published values of volumetric heat capacity are not available for all the components of these materials.

[Insert Table 4]

Thermal diffusivity was determined using experimental methods and inferred from theoretical amplitude decrement and phase lag of the ground surface temperature wave with depth. The maximum seasonal amplitude was monitored at various depths at the Middleton field site. Temperatures at various depths (1.5 m, 3.2 m, and 4.5 m) were recorded for 5 years at an unheated reference site and used for this analysis. Damping envelopes were graphically fit around the ground temperature data to estimate temperature decrement with depth. The maximum amplitude analysis is presented in Figure 6 (Hanson 1996).

Temperature data collected at the three depths at the field site are shown on this graph. The maximum temperature fluctuation amplitudes at the various depths are identified using this graph. The two peat layers are combined for this analysis because of limited temperature data with depth. Experimental values of thermal diffusivity are obtained from the probe methods. Experimental values for the two peats are averaged. Table 5 summarizes the comparison of analytical prediction of thermal diffusivity to experimental results. The analytical results were obtained using Equations 6 and 7. Good agreement is observed between analytical prediction and the thermal probe methods. A benefit of the analytical method is that a larger volume of material is represented, thus including macro-effects of the soil structure. However, drawbacks of the method include the necessity for long-term temperature monitoring and complications due to extreme seasonal weather conditions and layering of different soils.

[Insert Figure 6]

[Insert Table 5]

Conclusions

The needle probe thermal conductivity method and specific heat dual probe method are effective techniques for determining thermal properties of high water content materials. High water content materials are inherently spatially variable and ranges of parameters are possible within a material type. Thermal parameters are affected by material composition and structure. Heat capacity and thermal diffusivity are greatly affected by water content because of the high heat capacity of water compared to air and solids.

The results of the testing program indicate that the thermal conductivity of peat is lower than the thermal conductivity of typical soils (sands and silts). The large void ratios of the peats prevent the effective transfer of heat through the soil. The heat capacity of the peats is higher than that of sands and silts. This is due to the high water content of these materials. The high water content of peats controls the thermal parameters.

The thermal properties of the MSW are the most variable of any of the materials tested. This is due to the nonuniform composition of the waste materials. Most values of thermal conductivity measured for the MSW were quite low and compared to values for air. This is due to the large void ratio of the waste materials that is occupied by air. A large

variation in heat capacity was also observed for the MSW. Variation was observed in the thermal conductivity of the industrial sludge that can be attributed to high spatial variability and the presence of distinct immiscible phases in the material. Heat capacity of the sludge compares to published values for organic soil materials.

The two bentonite slurries (5% and 10% solids content) displayed similar results. The bentonite slurries have a thermal conductivity similar to the peats and a heat capacity similar to water. The bentonite chips/water mixture that contains a substantially higher solids content has a higher thermal conductivity than the slurries and peats. The bentonite chips/water mixture allows for more effective heat transfer. The bentonite chips/water mixture, however, is less conductive than silts and sands. The heat capacity of the bentonite chips/water mixture was similar to the heat capacity of soil.

Results of the tests indicate that of these materials, inorganic soils (including bentonite chips/water mixture) have the highest thermal diffusivity. The lowest values of thermal diffusivity were obtained for the MSW and industrial sludge. The highest water content materials (peats and bentonite slurries) had diffusivity values approaching values associated with water.

Similar results were obtained for thermal diffusivity determined using analytical methods (summing components, phase lag, and amplitude decrement) and experimental methods (needle and dual probe methods).

Indirect methods for determining thermal diffusivity compare well to experimental methods. The methods using field temperature data provide assessment of a large volume of material and in-situ conditions. However, for most applications, these methods may not be practical due to complications in the analysis and due to the extensive ground temperature monitoring required. Summing components of volumetric heat capacity is a simple method; however, it requires identification of material components and knowledge of the volumetric heat capacity of the individual components.

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Table 1 - *Thermal Properties for Various Soil Constituents*

Material	Density ρ (kg/m^3)	Heat Capacity c (kJ/kg·°C)	Thermal Conductivity k_t (W/m·°C)	Thermal Diffusivity α (m^2/s x10^{-7})	Source[a]
Many Soil Minerals*	2600	0.73	2.90	15	(2)
Water	981	4.19	0.60	1.42	(2)
Soil Organic Matter*	1275	1.93	0.25	1.0	(2)
Air	1.2	1.00	0.03	0.210	(1)

* Approximate average values

[a] (1) Lunardini 1985; (2) De Vries 1966

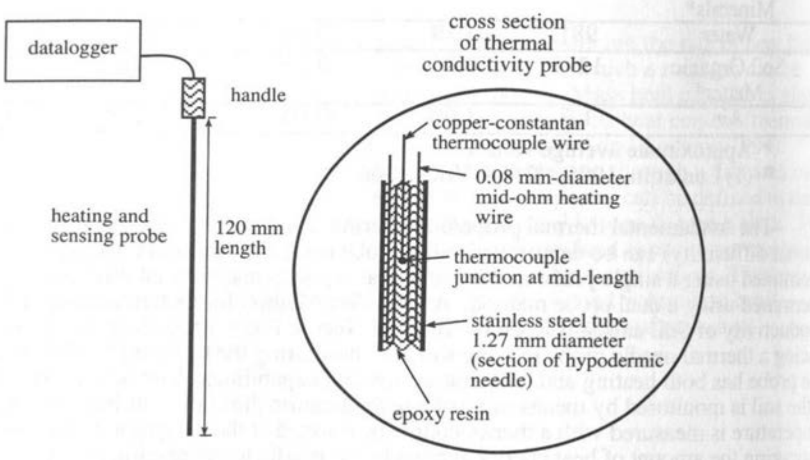

Figure 1 - *Schematic of Thermal Conductivity Probe*

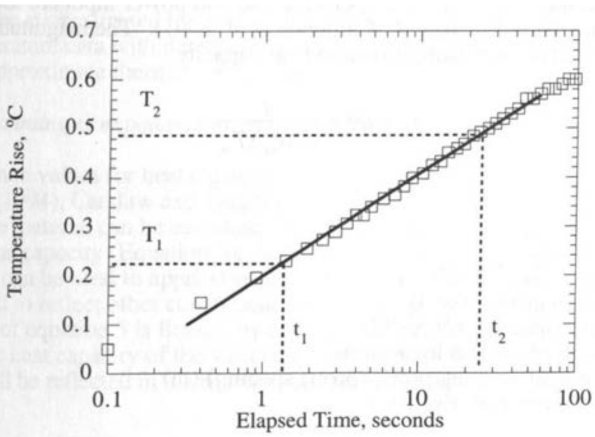

Figure 2 - *Typical Response of Thermal Conductivity Probe*

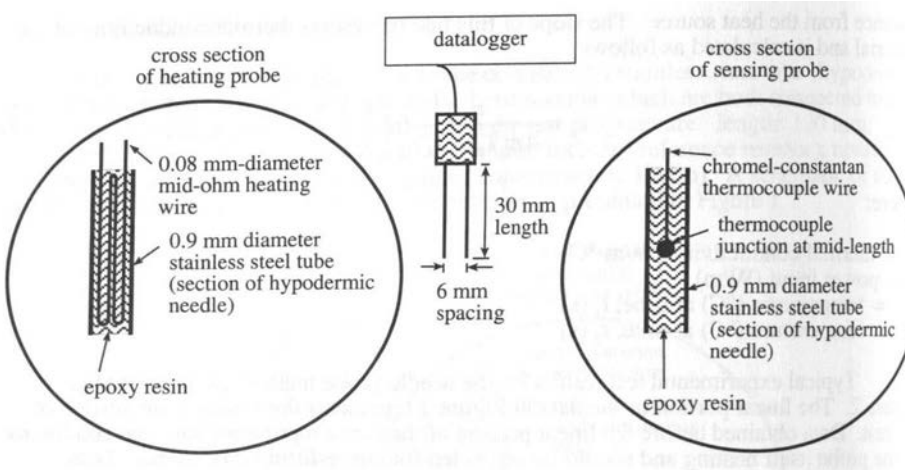

Figure 3 - *Schematic of Specific Heat Dual Probe*

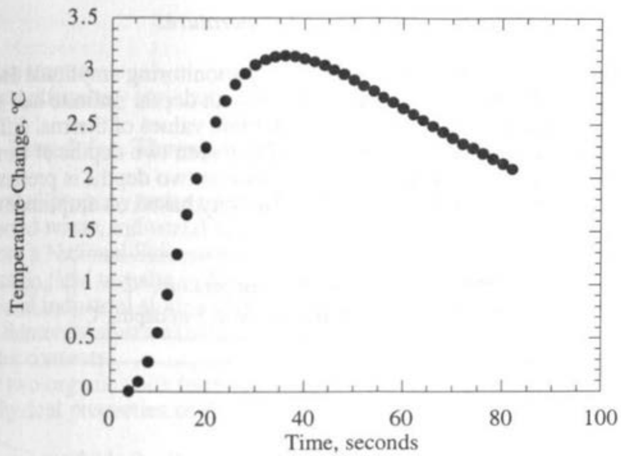

Figure 4 - *Typical Response of Specific Heat Dual Probe*

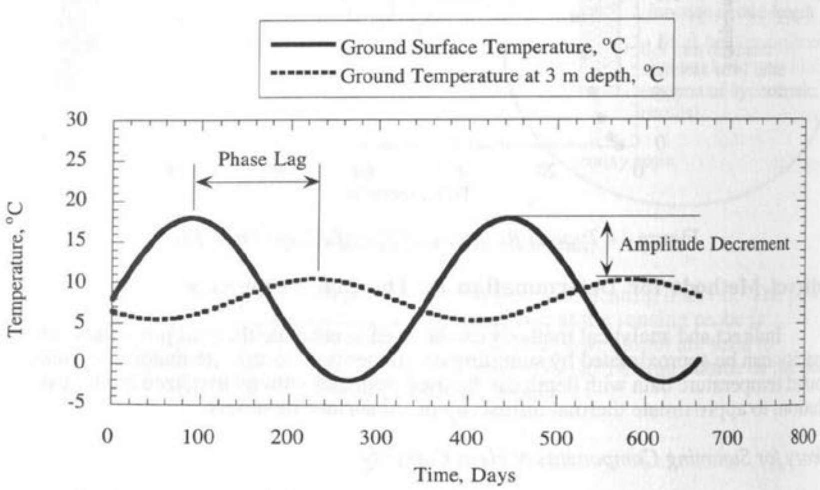

Figure 5 - *Schematic Plot of Phase Lag and Amplitude Decrement*

Table 2 - *Properties of Fibrous and Sedimentary Peat*

Physical Property	Fibrous Peat	Sedimentary Peat
Specific Gravity[1]	1.7	1.7
Initial Void Ratio	10 ± 2	7.4 ± 1
Water Content[2]	500-700%	430-520%
Organic Content[2]	88-95%	58-65%
Fiber Content[3]	30-60%	20-30%
Wet Unit Weight (kN/m^3)	10 ± 0.4	10.3 ± 0.2
Dry Unit Weight (kN/m^3)	1.25-1.88	1.6-2.0
Von Post Classification[4]	H3	H6
pH[5]	5.04 ± 0.02	6.06 ± 0.03

[1] ASTM Test Method for Specific Gravity of Soils (D 845)
[2] ASTM Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils (D 2974)
[3] ASTM Test Method for the Laboratory Determination of the Fiber Content of Peat Samples by Dry Mass (D 1997)
[4] ASTM Test Method for Estimating the Degree of Humification of Peat and Other Organic Soils (Visual/Manual Method) (D 5715)
[5] ASTM Test Method for pH of Peat Materials (D 2976)

Table 3 - *Thermal Properties from Experimental Program*

Soil Type	Thermal Conductivity (W/m·°C)	Heat Capacity (MJ/m^3·°C)	Thermal Diffusivity ($m^2/s \times 10^{-7}$)
Fibrous Peat	0.71 ± 0.3	3.9 ± 0.4	1.8 ± 0.2
Sedimentary Peat	0.57 ± 0.1	3.7 ± 0.2	1.5 ± 0.1
MSW	0.01-0.7	0.8-10	0.2-0.7
Industrial Sludge	0.4 ± 0.2	2.4 ± 0.2	0.22 ± 0.1
Bentonite Slurry, 10% solids	0.75 ± 0.1	4.3 ± 0.1	1.9 ± 0.2
Bentonite Slurry, 5% solids	0.72 ± 0.2	3.6 ± 0.1	1.9 ± 0.2
Bentonite Chips/Water Mixture	0.95 ± 0.1	2.5 ± 0.3	4.0 ± 0.5
Silt Topsoil*	1.3 ± 0.1	2.5 ± 0.1	5.3 ± 0.2
Sand Fill*	1.4 ± 0.25	1.8 ± 0.3	7.8 ± 1.0

*values provided for reference; (Hanson 1996)

Table 4 - *Comparison of Volumetric Heat Capacity Determinations*

Material	Dual Probe (MJ/m^3·°C)	Summing Components (MJ/m^3·°C)
Fibrous Peat	3.9 ± 0.4	3.8
Sedimentary Peat	3.7 ± 0.2	3.8
Bentonite Slurry, 10% solids	4.3 ± 0.1	3.8
Bentonite Slurry, 5% solids	3.6 ± 0.1	4.0
Bentonite Chips/Water Mixture	2.5 ± 0.3	1.8

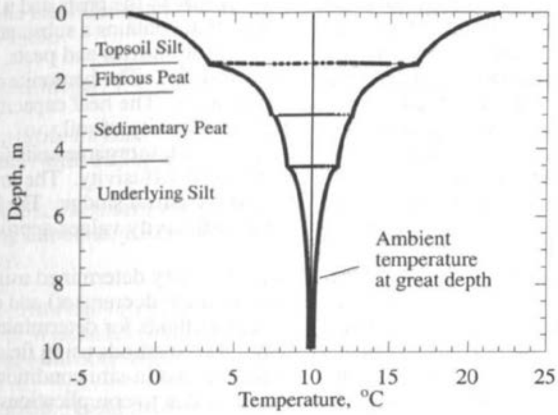

Figure 6 - *Estimation of Approximate Damping Envelope*

Table 5 - *Thermal Diffusivity of Peat*

Method	Thermal Diffusivity ($m^2/s \times 10^{-7}$)
Laboratory thermal probes	1.7 ± 0.8
Inferred from amplitude decrement	1.5 - 2.9
Inferred from phase lag	1.3 - 1.9