

Earth System Science Program
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**DETERMINATION OF THE THERMOPHYSICAL
PROPERTIES OF SOIL SAMPLES**



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Introduction

The physical properties of soil affect the transport of water, heat, solutes and oxygen. These, in turn, affect the rate of plant growth and development. The solid phase of soil consists of irregularly shaped fragments of crystalline material and some amorphous gels that may coat the crystals and modify their behavior. The adhering amorphous material may consist of iron and aluminum oxide or organic matter that attaches itself to soil particles and joins them together. The inorganic portion consists of particles having various shapes, sizes and chemical compositions. The organic fraction consists of live active organisms and plant and animal residues in different stages of decomposition. Thus, the amount and kind of surface of the solid phase in soils and the interactions with the solution (liquid) and gaseous phases vary tremendously. In general, the solid phase occupies from 30% to 60% of the total soil volume.

The liquid phase is dynamic because its volume usually varies between 0-50 % in soil. This phase represents the soil water that fills part or all of the open spaces between the particles in the solid phase. These open spaces are called pores. The liquid phase varies in water content, chemical composition, and the freedom with which it is permitted to move. The ionic composition includes inorganic ions {Na, K, Ca, Mg, Cl, NO₃, SO₄, HCO₃} and various organic ions and molecules.

The gaseous phase is also dynamic. It occupies the part of the pore space not occupied by the liquid phase. It consists mostly of N₂, O₂, CO₂ and traces of other gases. The physical relationships between the three phases are affected by both temperature and pressure. The total porosity, f , is defined as

$$(1) \quad f = (V_w + V_g) / V_t$$

where V_w and V_g are the volumes of water and gas in the soil, and V_t is the total volume. The porosity is one of the properties of soils that was measured in the present study.

Initial Measurements

I. Density

The bulk density of a soil sample is not considered a static property. However, particle density is considered to be a static property of a soil having a given mineral composition. Particle densities of mineral soils vary between 2.6 and 2.7 g/cm³ and, for most mineral soils, average 2.65 g/cm³. The bulk density of a soil depends upon the relative amounts of water and air present within the pore space, and

upon the degree of soil compaction. Typical values range from 1.1 - 1.6 g/cm³.

In the present study, samples were taken from four locations at Bledsoe Farm, an agricultural research station near Williamson, Georgia, which is affiliated with the University of Georgia. The samples (all moist at the time of sampling) can be described as follows:

- Tower (T) - Sandy clay, reddish brown color indicative of iron oxide; this soil was taken from beneath a grassy patch at the base of the crank-up tower. (Grass Site 1)
- Loam (L) - Dark brown sandy clay; this soil was taken from a patch about 100 feet east of the tower. This soil appeared to have little, if any, iron oxide content. (Grass Site 2)
- Upper Field (UF) - Reddish brown sandy clay; this clay appeared to have higher iron oxide content. The sample was taken from a field about 400 yards southeast of the tower. (Red Clay Bare Soil Site)
- Field (F) - Reddish, sandy soil, having the highest iron oxide content (laterite type). This soil was taken from a field about 50 feet south of Grass Site 2. (Brown Loam Bare Soil Site)

Bulk soil density was initially determined by digging up samples with a shovel and placing them into 4-inch long sections of 4-inch (inner) diameter PVC sewer pipe. Pictures of



Fig. 1a. Top View of Sample Container.



Fig. 1b. Side View: On Balance.

the sample container are shown above in Figs. 1a and 1b. The dimensions were measured with a set of calipers that were accurate to ± 0.01 inch. The volume of such a cylindrical shell is given by $V = \pi d^2 h/4$, where d is the pipe inner radius and h is the height of the shell. If the diameter and height are measured in inches, and the volume is expressed in cm³, then $V_{\text{cm}^3} = 12.87 d_{\text{in}}^2 h_{\text{in}}$. For a 4 x 4 inch

shell, the volume is approximately 824 cm³.

The bottom of the container was covered by a layer each of fabric and nylon screen, and both were held in place with picture-framing wire, wrapped around the outside of the shell. The weights of the empty and filled shells were determined using a lab balance with a stated accuracy of ± 0.1 grams. The density was then calculated as the mass in grams by the volume in cm³.

The soil samples were then fully saturated with water and weighed. They were placed in a drying oven for at least 24 hours at 105 degrees Celsius and re-weighed. The volume fraction due to water was computed using the density for liquid water for the temperature at which the sample was originally saturated. The following densities were determined for the dry, in-situ and saturated samples, along with the volumetric water content of the saturated sample (porosity):

	Tower	Loam	Upper Field	Field
Dry	1.485	1.429	1.415	1.443
In-Situ	1.572	1.592	-----	-----
Saturated	1.972	1.950	1.878	1.894
V _{water} /V _{soil}	0.329	0.365	0.327	0.312

It will be noted that due to the size of the holes in the cloth/nylon cover on the base of the shell, some of the finer particles of clay were lost when water was added to the samples. In the future, our containment vessel will be lined with small pore (< 1 μm) filter paper to trap such particles.

II. Volumetric Water Content

A second instrumental method for determining the volumetric water content of a given soil type was also employed. We purchased a **ThetaProbe** soil moisture sensor, type ML2x (Delta-T Devices, Ltd., UK - supplied by Dynamax, Inc., Houston, TX). These sensors utilize a high-frequency alternating current (100 MHz) to measure the dielectric constant of the medium, ϵ , which is related to the volumetric water content, T_v ($V_{\text{water}} / V_{\text{soil}}$), in the following manner:

$$(2) \quad \epsilon = a_0 + a_1 T_v$$

where a_0 and a_1 are constants, determined from the data. The output of the probe is a DC voltage which is also related to the dielectric constant in a similar manner:

$$(3) \quad \epsilon = 1.1 + 4.44 V_p$$

where V_p is the voltage produced by the probe. The dielectric constant can be eliminated by setting equations (2) and (3) equal to each other and solving for T_v in terms of V_p . A soil specific calibration can be performed by measuring the voltage in two samples of differing volumetric water content. To

span the maximum usable range of values, a dry sample ($T_v = 0$) and a water-saturated sample were used for calibration purposes. This yields the calibration equation:

$$(4) \quad V_p = V_{dry} + (V_{sat} - V_{dry}) (T / T_{sat})$$

where V_{dry} is the voltage produced by the dry sample, V_{sat} is the voltage produced in the water saturated sample, and T_{sat} is the measured volumetric water content of the water saturated sample.

Reasonable accuracies can be obtained when studying common mineral soil samples by using a generic, non-specific calibration suggested by the manufacturer. The following values $\{a_0 = 1.6, a_1 = 8.4\}$ are employed in (2). This leads to the following calibration equation.

$$(5) \quad T_v = 0.529 * V_p - 0.060$$

Using (5) for the four samples (3 measurement points per sample) of soil, results in the following.

Location	Wet Volts	Dry Volts	Water Content
Tower	.841 ± .027	.065 ± .002	.395 ± 0.022
Loam	.839 ± .067	.059 ± .001	.384 ± 0.037
Upper Field	.885 ± .014	.068 ± .002	.408 ± 0.012
Field	.914 ± .009	.060 ± .005	.424 ± 0.032

It will be noted that the agreement between the voltages of the dry samples and the generic offset from equation (5), namely 0.060 volts, is quite good.

III. Heat Capacity

The measurement of heat capacity, C , requires a calorimeter. A number of experimental designs were tried which involved styrofoam containers and plastic, insulated food coolers. They were either mechanically too difficult to work with or lost too much heat during the measurement period. The design that was finally adopted (shown to the right in Fig. 2) employed an ordinary one pint, silvered-glass Thermos bottle filler, held up by a plastic shell, cut to the appropriate height. The top of the Thermos bottle was capped with a large cork. The cork had two holes bored into it: one to hold a NIST-certified (± 0.1 C) centigrade thermometer and the other to hold a wooden stirring rod equipped with a home-made thin aluminum mixing blade.

The calibration constant for the calorimeter was determined from several experiments; each involved filling the calorimeter with a known amount of water (about 250-300 grams in both cases) at room temperature, then adding a known amount of warm water. During a measurement the stirring rod was turned manually. After mixing, the solution reached its final temperature in less than one minute, and it held that temperature to within 0.1? C for a minimum of three to four minutes before any cooling of the mixture was noted. Both the room temperature and warm water were added to the calorimeter from a plastic, 1-liter jug. The amount of water added was determined by weighing the bottle before and after it was emptied into the calorimeter. Fig. 2. The Calorimeter.

The dried soil samples (approximately 100 grams) were crumbled into a pyrex beaker and heated in a digitally-controlled oven which was set for 90? C. The calorimeter was filled with water at room temperature and allowed to stabilize in temperature. The heated soil sample was then added to the calorimeter, and the final temperature was noted. The heat capacity was then calculated. The following results were obtained for the four Bledsoe Farm samples.

Location	Heat Capacity (Cal/g-°C)
Tower	.324
Loam	.316
Upper Field	.272
Field	.228

Difficulties Encountered

I. ThetaProbe

A problem developed during the initial experiments with the ThetaProbe that need resolution. When the soil samples were dried, it became very difficult to get the probe tips to penetrate all the way into the sample. As a result, the samples were usually saturated in order to loosen the dirt, then the ThetaProbe was inserted into them. Removal of the probe left a hole pattern, which was then filled by using nails of the appropriate length and diameter (see Fig. 1a). The nails would prevent the holes from closing as the samples were dried. It was usually necessary to use a large pair of pliers to remove the nails from a totally dry soil sample before the Probe could be inserted into the holes.

II. Density and Soil Volume Changes

An important factor had to be considered when interpreting the soil density measurements. While reviewing techniques used by others, no mention was made of soil volume changes which occur during the process of adding or removing water from the soil samples. When the samples under study were dried, there was a significant contraction of the sample in every dimension. The soil separated from the wall of the container entirely and could be pushed out of the containment vessel and handled. The surface contracted as well. Instead of appearing cylindrical, the plug of soil appeared more like a conic section with its top sheared away. For one sample the bottom diameter was 3.88 inches, while the diameter at the top was 3.63 inches. The height of the plug decreased from 4 inches to 3.72 inches. It was estimated that the total volume decreased from 830 cm³ to approximately 675 cm³. Normally this would not be troublesome, but it is noteworthy that other research groups made no mention of such shrinkage.

In thinking about this problem, it was noted that there is difference in the way a soil sample in a plastic container behaves while drying and the way an arbitrary section of soil situated in a large, continuous plot of ground behaves. The in-situ sample is surrounded by soil on all sides. It can not simply “unstick” from the sides of its “container.” When bare soil (no vegetation) dries, the surface often cracks. The surface is the only part of the soil that is not bounded by more soil. Thus an isolated sample in the lab might be expected to behave differently under drying conditions than a sample that resides in a continuous soil environment. One way to resolve this problem is to dig up a totally dry sample of soil and compare its density to that of a sample that has been dried in the lab.

The manner in which samples are currently packed makes this difficult. Slipping the PVC casing around a wet sample of soil is not difficult. Doing this on a dry sample is virtually impossible because the sample is so hard. This problem should be solved by use of a new sample coring device which was recently purchased and is described later in the report.

III. Calorimeter

It is relatively easy to measure the heat capacity of dry samples using the method described above. It is not so easy when the sample contains appreciable amounts of water. The samples are heated to 90°C before being placed in the calorimeter. On the other hand, in a wet sample unknown amounts of water would be boiled off during the heating process. The sample could be weighed prior to placing it in the calorimeter, but this would introduce an unknown amount of cooling.

The problem can be overcome by chilling the sample instead of heating it. This would keep the equilibrium vapor pressure of water relatively low. The calorimeter doesn't require a heated sample. It only requires that there be a difference in temperature between the water in the calorimeter and the sample. A series of measurements is planned in which wet soils are placed in a beaker that is immersed in an ice bath. These chilled samples will be added to the calorimeter, and the heat capacity will be computed in a similar manner as before. The heat capacity of wet soil is expected to approximately obey the following relation:

$$(6) \quad \rho_{\text{mix}} C_{\text{mix}} = (1-f) \rho_{\text{dry}} C_{\text{dry}} + \rho_w C_w T_w$$

where ρ refers to density, C to heat capacity, and T to actual volumetric water content. The subscripts "mix," "dry," and "w" refer to the wet sample, the dry sample and water. The quantity f is the saturation volumetric water content (porosity) from (1).

Measurements to be Made in Near Future

I. New Soil Collection Method

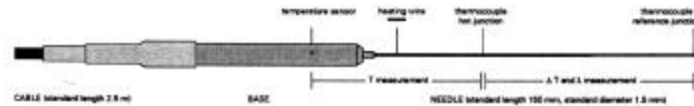
A special coring tool has been purchased for collecting undisturbed soil samples. The auger head is designed to hold a plastic liner that is 2 inches in diameter and 4 inches long. The liner can be removed from the tool after the sample is taken and sealed off with two plastic end caps. The sample size is smaller than that currently in use, which will make storage and sample preparation easier. The uniform liner dimensions will also result in a more consistent sample size.

II. Thermal Conductivity

We recently purchased three **TP02 Non-Steady State Thermal Conductivity Probes** from Hukseflux Thermal Sensors in the Netherlands. A picture of the sensor is shown below in Fig. 3. A schematic diagram of the sensor is shown in Fig. 4.



Fig. 3. TP02 Non-Steady State Thermal Conductivity Probe.



TP02 Non-Steady-State Probe consists of a needle with 2 thermocouple junctions (one of which acts as a reference) and a heating wire. It is inserted into the medium that is investigated. In the base, a temperature sensor is mounted. Advantages of this design: an optimal accuracy independent of the medium temperature, a minimal sensitivity to thermal gradients, a high sensor stability and the possibility to use normal cables and connectors.

Fig. 4. Schematic Diagram of Thermal Conductivity Sensor.

The unit consists of a needle which encloses an electrical resistance heating wire and two thermocouple junctions, one of which acts as a reference junction. The probe creates a heat pulse at the hot junction which propagates into the surrounding medium. The duration of the heat pulse is several minutes, and during this time the medium heats in the radial direction from the axis of the probe. After tens of seconds the transient heating of the medium becomes linear with the logarithm of time. It is in this linear region that the measurement of thermal conductivity is made, wherein the temperature rise (i.e., the temperature difference between the heated region of the medium and the unheated region), ΔT , is related to time in the following manner (Lachenbruch, 1957; Jaeger, 1958):

$$(7) \quad \Delta T \propto (Q/4 \pi k) (\ln(t) + B)$$

where Q is the heater power, determined from the current supplied to the heating element of known resistance, k is the thermal conductivity, t is time, and B is a constant. Note that ΔT in Carslaw and

Jaeger (1959) and Jaeger (1958) is simply denoted as T because the initial temperature is zero.

By measuring the temperature rise at two points in time, B is eliminated, and the thermal conductivity can be calculated (Buettner, 1955; Jaeger, 1956; Lachenbruch, 1957; Von Herzen and Maxwell, 1959) by the following expression.

$$(1) \quad \alpha = \frac{Q}{4 \rho C (\Delta T) \ln(t_2/t_1)}$$

Having experimental values for the density, heat capacity and thermal conductivity of a soil sample allows the thermal diffusivity to be calculated via:

$$(2) \quad \alpha = \frac{k}{\rho C}$$

where α is the thermal diffusivity, C is the heat capacity, and ρ is the density.

In the solution to the simple one-dimensional heat conduction equation, assuming a periodic boundary condition on temperature at the surface leads to the following:

$$(3) \quad \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \quad \text{with}$$

$$(4) \quad T(0,t) = T_m + A \sin[(2\pi/P)t].$$

The solution to (10) under (11) leads to:

$$(12) \quad T(z,t) = T_m + A e^{-z/d} \sin[(2\pi/P)(t - t_m) - z/d]$$

where P is the period of the surface wave (24 hours), $T=T(z,t)$, z is depth beneath the surface, t is time, T_m , t_m and A are constants, and d is the damping depth, given by $(\alpha P/\pi)^{1/2}$. Using data for the soil temperature at least two depths, the thermal diffusivity can be estimated either from the phase lag between the temperature waves at each depth, or from the decrease in amplitude of the temperatures at each level. The present study has access to such temperature profiles and will be able to compare the estimates of thermal diffusivity from (11) to the values determined directly in the lab using the expression in (8).

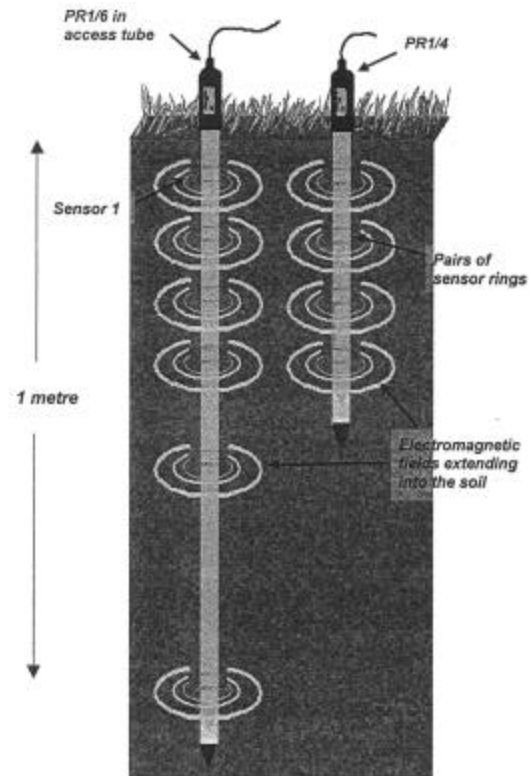
III. Volumetric Water Content as a Function of Depth

A Delta-T Devices type PR1 water content profile probe has recently been purchased. It measures the volumetric water content of soil in a manner similar to the ThetaProbe.

It is a linear device that extends 0.5 meters into the ground. It measures the volumetric water content at several depths along the length of the probe. This unit will be used in conjunction with concurrent measurements of soil temperature at the same depths.

IV. Soil Matric Potential

Another useful probe that has been purchased is the Delta-T Devices EQ2 Equitensiometer for measuring soil matric potential, i.e. the negative pressure (or suction) required to extract water from between the soil particles. It provides a measure of plant-water stress. The EQ2 consists of a ThetaProbe with measuring rods that are embedded in a porous material (the equilibrium body). The material has a known, stable relationship between water content and matric potential. When the probe is inserted into the soil, the matric potential within the equilibrium body rapidly equilibrates to that of the surrounding soil. The water content is determined by the ThetaProbe and is converted into the matric potential using the calibration curve supplied with the device.



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