EVALUATION OF SOIL PROPERTIES AND THEIR CORRELATION WITH SOIL THERMAL PROPERTIES FOR FIVE OKLAHOMA MESONETWORK SITES

By

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PREFACE

This report contains the descriptions as well as measured soil properties for five sites in Oklahoma. Soil samples were taken from each site and analyzed for basic soil mechanics properties. These samples were then recompacted at varying moisture content values to determine soil thermal property variation. This research was financed by the Electric Power Research Institute (EPRI).

I wish to express my gratitude to both the South Central Chapter of the Association of Drilled Shaft Contractors and the Civil and Environmental Engineering Department at Oklahoma State University for giving me financial assistance in the form of scholarships.

I am especially grateful to Dr. Donald R. Snethen for all of his support and guidance during this project and my graduate studies here at Oklahoma State University.

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CHAPTER I

INTRODUCTION

Scope of the Research

This research was sponsored by the Electric Power Research Institute (EPRI). The project was originally planned to include 20 sites across Oklahoma, all of which were a part of the Oklahoma Mesonetwork. However, because funds for the research were withdrawn by EPRI, only five sites were used as a data base for this thesis. The five sites include Stillwater, Chickasha, Ada, Fairview, and McAlester.

The Oklahoma Mesonetwork consists of 110 automated observing stations that continuously monitor a number of important weather and soil parameters. These stations are distributed across the state, with at least one site located in each of Oklahoma's 77 counties. Data are observed every 5 minutes at each station and then relayed every 15 minutes to a central processing site located on the University of Oklahoma campus. The Mesonetwork was developed through the cooperative efforts of Oklahoma State University and the University of Oklahoma. The Mesonetwork system offered a great opportunity to measure thermal properties of soil on a continuing basis in the field along with continuous climatic data monitoring.

The five sites used for the research were chosen on the basis of soil type and climatic condition. The idea was to get a wide range of both soil type and climatic condition for the thermal property study. The project involved both field and laboratory work. The first step in the research was to install the required equipment at the selected Mesonetwork sites. The equipment included: thermistors, heat flux plates, soil moisture probe access tubes, a thermal property analyzer probe, and a 4 x

16 relay multiplexer and enclosure. The field work also included the collection of disturbed and undisturbed soil samples for the laboratory study.

The soil samples collected in the field were tested for basic engineering properties. The soil properties measured included natural dry density, natural water content, percent minus the No. 200 sieve, grain size analysis, natural soil suction, and Atterberg limits. Using these soil properties, an idealized profile was developed for each site. The soil samples for from the same profile were then combined to form a representative soil layer sample for additional testing. Stillwater, Chickasha, and Fairview profiles were defined using three soil layers, while Ada and McAlester profiles were defined using two soil layers.

A thermal property testing program was conducted on the different soil layers at each site. A molding dry density was selected for each soil layer based on the average dry density value obtained from the soil samples in their respective soil layers. Specimens were then compacted using the specified molding dry density for each soil layer at varied moisture content values using Harvard miniature compaction equipment. A laboratory thermal probe and thermal property analyzer were used to measure thermal resistivity values for each of the layers at all five sites.

Chapter II reviews the literature on the many factors that influence thermal properties of soil and different thermal property measurement techniques. Chapter III discusses field instrumentation installation and soil sampling procedures. Chapter IV discusses the soil properties found for each site. Chapter V describes the laboratory thermal property testing program. Chapter VI correlates the soil properties and the laboratory thermal property testing program results. Chapter VII states the conclusions of the research and recommends some areas for further research.

CHAPTER II

REVIEW OF LITERATURE

Introduction

Subsurface heat exchange systems, such as ground source heat pumps and underground electrical transmission cables, rely on dissipating heat to the surrounding soil. Therefore, soil thermal properties of the surrounding soil are important parameters in the design of these systems. If the rate of heat generated by a heat pump or electrical cable is greater than that dissipated to the surrounding soil, temperature may increase to an unacceptable level, which may cause the heat pump or cable to break down. For this reason, the design of heat exchange systems is usually very conservative. Conservative design is acceptable if the only concern is the performance of the heat pump or electrical cable. However, when the cost of the system must be considered, there is the need for more realistic design procedures.

Thermal Properties of Soils

Thermal Conductivity/Resistivity

The thermal conductivity of a soil is defined as the rate at which heat energy flows across a unit area of the soil due to a unit temperature gradient (2). The thermal resistivity of a soil is the reciprocal of the thermal conductivity. The term conductivity is used because, in soil, heat is transferred mainly by conduction (7).

Thermal Diffusivity

Thermal diffusivity is the ratio of thermal conductivity to the volumetric heat capacity of a soil. The volumetric heat capacity of a soil is the heat energy required to raise the temperature of the soil by one degree Celsius (2). Thermal diffusivity measures the ability of a soil to absorb and conduct heat over a short period of time (7). This parameter is important where cyclic loadings of heat will occur. Thermal resistivity, on the other hand, is important for long term loadings.

Mechanisms of Heat Transfer in Soils

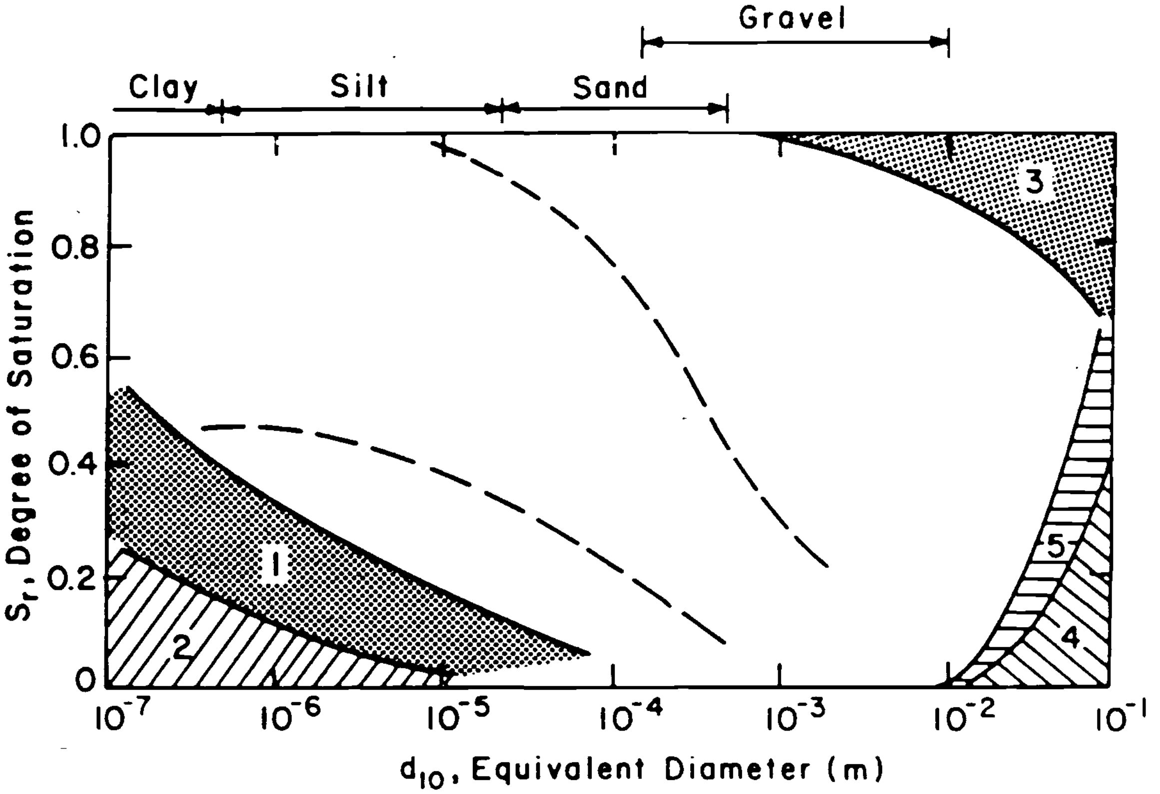
Figure 1 shows the conditions under which the various mechanisms of heat transfer may have a significant influence in the field. This figure shows how soil texture and degree of saturation influence heat transfer.

Heat Conduction

Heat can be transferred in soils by conduction, convection, radiation, and the evaporation-condensation process (2). However, the primary method of heat transfer in soil is conduction. Heat conduction in soil occurs through all the components of a soil system, i. e., through the soil solids, the soil water, and the soil voids (7). Heat conduction through the soil solids occurs by increased atomic vibrations in the soil particles. Heat conduction through the soil air and soil water occurs by molecules colliding together, which results in an increase in kinetic energy. The amount of heat transferred by true conduction increases as the soil dry density increases and as its degree of saturation increases.

Convection

Heat transfer, due to convection, involves the energy exchange between a surface and an adjacent fluid (13). Heat transfer in soil by convection can be carried out by free (natural) convection or forced convection. Free convection occurs when a warmer (or cooler) fluid next to a solid boundary causes circulation because of the density difference resulting from the temperature variation throughout a region of the fluid (13). The higher the fluid temperature, the lower its density will be. Convection through the air or water in soils is usually negligible (2). In order for free convection in soil to become apparent, the pores must be several millimeters across. Therefore, noticeable free convection will not occur in a fine grained soil. However, if this fine



1—Thermal redistribution of moisture
2—Vapor diffusion due to moisture gradients
3—Free convection in water
4—Free convection in air
5—Heat radiation

Note: Unmarked area is heat transfer by conduction. Dashed lines are typical grain size distribution curves for coarse-grained (upper) and fine-grained (lower) samples.

Figure 1. Mechanisms of Heat Transfer (2)

grained soil contains cracks or fissures then free convection may be apparent. Free convection becomes more apparent as the grain size of the soil becomes larger.

Forced convection occurs when currents of air or water are forced to move through the pores of soils by pressure differences (2). Forced convection in the field can be caused by groundwater flow and wind action.

Radiation

Radiant heat transfer is different from conduction and convection because it does not require a medium for its propagation (13). Radiation occurs across air spaces by heat energy propagation as electromagnetic waves (2). In radiation, the amount of heat transfer depends upon both the temperature difference between two bodies and the temperature level. In soils, radiation is usually considered a negligible contribution to heat transfer.

Evaporation-Condensation Process

If a soil is unsaturated, then an increase in temperature can cause water in some areas to evaporate. This water that evaporated will then condense at locations of lower vapor pressure (2). When the water evaporates, it absorbs a latent heat of vaporization corresponding to the temperature of the water (13). When the water condenses, it gives up this latent heat, resulting in heat transfer. Region 1 of Figure 1 gives a rough indication of the condition under which the process of evaporation-condensation may have a noticeable effect.

Primary Factors Influencing Thermal Resistivity

Soil is a three-phase medium containing solids (inorganic and/or organic), liquids (water), and gases (air) (8). The primary factors that influence the thermal resistivity of a soil include: (1) soil composition, (2) soil density, (3) soil moisture content, and (4) soil suction.

Soil Composition

Soil can be classified as either coarse-grained or fine-grained. Fine-grained soils are sometimes referred to as cohesive soils because of their particles' cohesive characteristics. Cohesive soils are usually made up of silt and/or clay particles. Cohesion is attributed to true cohesion and apparent cohesion. True cohesion is the intermolecular attraction of soil particles for each other throughout the soil mass (4). Apparent cohesion is the binding of the soil mass together by the action of the surface tension forces of the soil moisture. Silt and clay particles are small enough to pass through a U.S. Bureau of Standard No. 200 sieve which has an opening of 0.0029 in. Any soil particle that does not pass the U.S. Bureau of Standard No. 200 sieve is considered coarse-grained. Any soil particle that does not pass the U.S. No. 4 sieve is considered gravel. Soil that lies between the No. 4 and No. 200 sieves is considered sand.

The thermal resistivity of a soil depends on the soil structure and the component material of the soil (10). The primary method of heat flow in soil is through solid grain contact (2). For this reason, the thermal characteristics of a soil are also dependent on mineralogy, soil grain shape, soil particle microstructure, bonding and organic content (7). Table 1 lists some average resistivity values for some soil constituents and allied materials. Since the thermal resistivity of air is much larger than any of the other soil constituents including water, the density and degree of saturation play a big role in the thermal resistivity of a soil. Table 2 lists a range of thermal resistivity values for different soil types based on the Unified Soil Classification System. Cohesive soils and peaty soils exhibit higher thermal resistivity values than granular soils.

Another consideration that has to do with soil composition is the ability of a soil to hold water. Fine-grained soils have the ability to hold more water than coarse-grained soils because of surface chemistry effects. Clay particles contain an adsorbed water layer (diffuse double layer) which can help to reduce the thermal resistivity.

TABLE 1

AVERAGE RESISTIVITY VALUES FOR SOME SOIL CONSTITUENTS AND ALLIED MATERIALS (7)

Material	Thermal Resistivity (°C–cm/watt)
Quartz	7.9
Quartz	14.9
Quartz, Random Orientation	11.0
Quartz Glass	79.0
Granite	26-58
$CaCO_3$	26.3
Marble	34-48
Limestone, Dense	45
Ice	45
Sandstone	50
Dolomite	58
Slate	67
Water	165
Mica	170
Pine Wood	265
Pine Wood	608
Organic Material Wet	400
Organic Material Dry	700
Air	4000

TABLE 2

RANGE OF THERMAL RESISTIVITY VALUES FOR DIFFERENT SOIL TYPES (8)

Soil Description	Unified Classification Symbol	Range of Thermal Resistivity (°C–cm/watt)
Silty Clay	CL	85–105
Silty Clay With Organic Matter	CH/OH	120–140
Clayey Silt	ML	85–105
Silt	ML	90–110
Sandy Clay	CL	85–95
Sandy Silt	ML	85–95
Clean Uniform Sand	SP	60–80
Fine to Coarse Sand	SP	75–95
Silty Sand	SM	70–90
Silty Sand and Gravel	SW/SM	65–85
Clayey Sand	SC	80–90
Interbedded Sand and Clay	SP/CL	85–95

Soil Density

An increase in the dry density of a soil (decrease in void ratio) leads to a decrease in the thermal resistivity (8). This is due to three factors: (1) more solid matter per unit soil volume, (2) less pore air or pore water per unit soil volume, and (3) better heat transfer across the contacts (2). The solid particles in a dry soil form a system of series and parallel paths with each other and with the air-filled voids between them (8). The presence of air with its high thermal resistivity greatly increases the overall thermal resistivity of the soil as compared with its soil components for two reasons: (1) part of the heat path must go through the high resistivity air, in parallel with the low thermal resistivity solid material instead of being all through the low thermal resistivity solid material; and (2) the air makes for poor contact between the solid particles introducing the high thermal resistivity air paths in series with the low thermal resistivity paths through the solid particles. Therefore, if the density is increased (total void volume reduced) the contact between the solid particles is improved. This improvement in the contact between solid particles results in a decrease in the overall thermal resistivity of the soil material.

Another benefit from increasing the density of a soil mass is the decrease in permeability. This lower permeability acts to decrease the movement of moisture (8). Ideally, optimum thermal density is characterized by a large amount of solid material per unit volume and a permeability sufficiently great to allow for moisture restoration. If the permeability is too small to allow for moisture restoration, then the soil may become dry and unstable.

Soil Moisture Content

The moisture content of a soil (by weight) is the ratio of water weight in a soil to dry weight of soil expressed as a percentage. Considering the difference in thermal resistivity between water and air, it becomes important to take into account the degree of saturation and moisture content of a soil system. Figures 2 and 3 show the

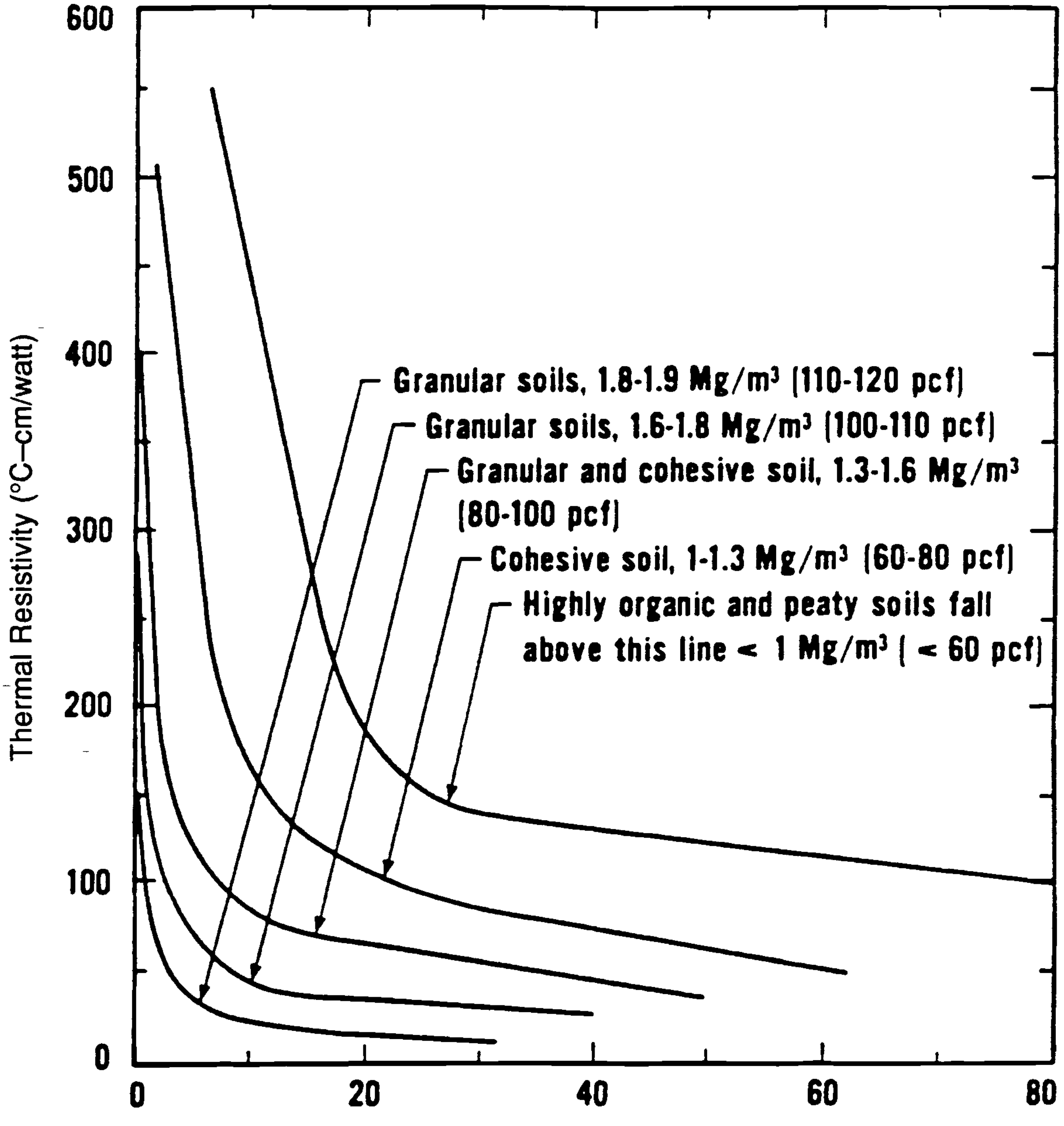


Figure 2. Effect of Soil Type, Dry Density, and Moisture Content on Thermal Resistivity of Soils (9)

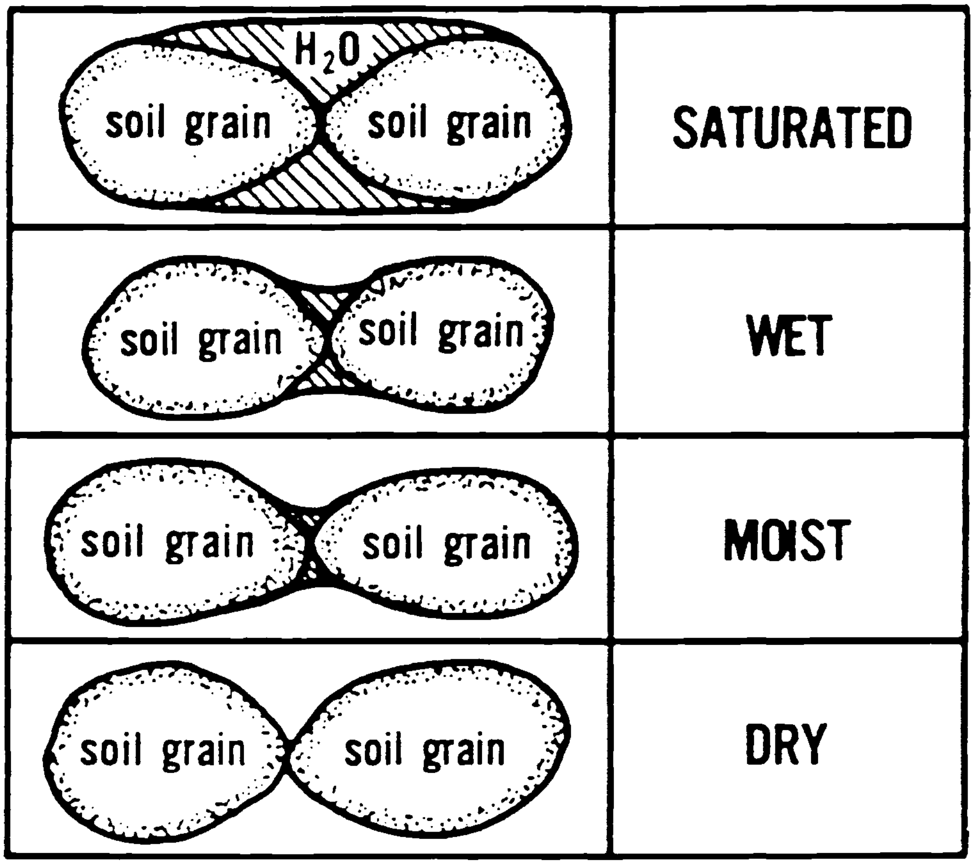


Figure 3. Influence of Soil Moisture on Heat Flow Path (8)

importance of soil moisture to the thermal resistivity of soil. Salomone (8) explains the influence of soil moisture content as follows: "As moisture is added to the soil as a thin film around the soil particles, a path for the flow of heat which bridges the air gaps between the solid particles is provided. By increasing the effective contact areas between particles these films greatly reduce the thermal resistivity of the soil." When the moisture condition in the soil approaches the wet condition shown in Figure 3, the effective contact area no longer increases with increasing moisture content. Therefore, the large decrease in thermal resistivity that is associated with a soil going from the dry to wet conditions is not evident when additional moisture is added to saturate the soil mass. This trend is shown by Figure 2.

Moisture migration is also an important consideration when designing subsurface heat exchange systems. As heat is dissipated from a system into the soil, moisture migrates away from the heat source. If the moisture is not replenished, then the soil moisture content may fall below the critical moisture value, causing thermal instability (11). The critical moisture content (shown in Figure 4) is defined as the point on the resistivity–moisture content plot at which a small reduction in moisture content results in a significant increase in the thermal resistivity (7). Soils with a moisture content above the critical moisture content are thermally stable. Soils with a moisture content below the critical moisture content are thermally unstable. Radhakrishna et al. (6) came up with several basic conclusions about thermal instability: (1) thermal instability is caused by sustained moisture migration along a thermal gradient, (2) such sustained moisture migration occurs for all soils below some critical moisture content below which vapor permeability increases to a point that vapor outflow exceeds liquid inflow, causing progressive drying, and (3) the rate of drying for soils below the critical moisture content depends on the thermal gradient and soil properties. However, thermal instability will eventually manifest itself for any significant thermal gradient. Naturally, the water content of a soil is directly related to climate. Any time the

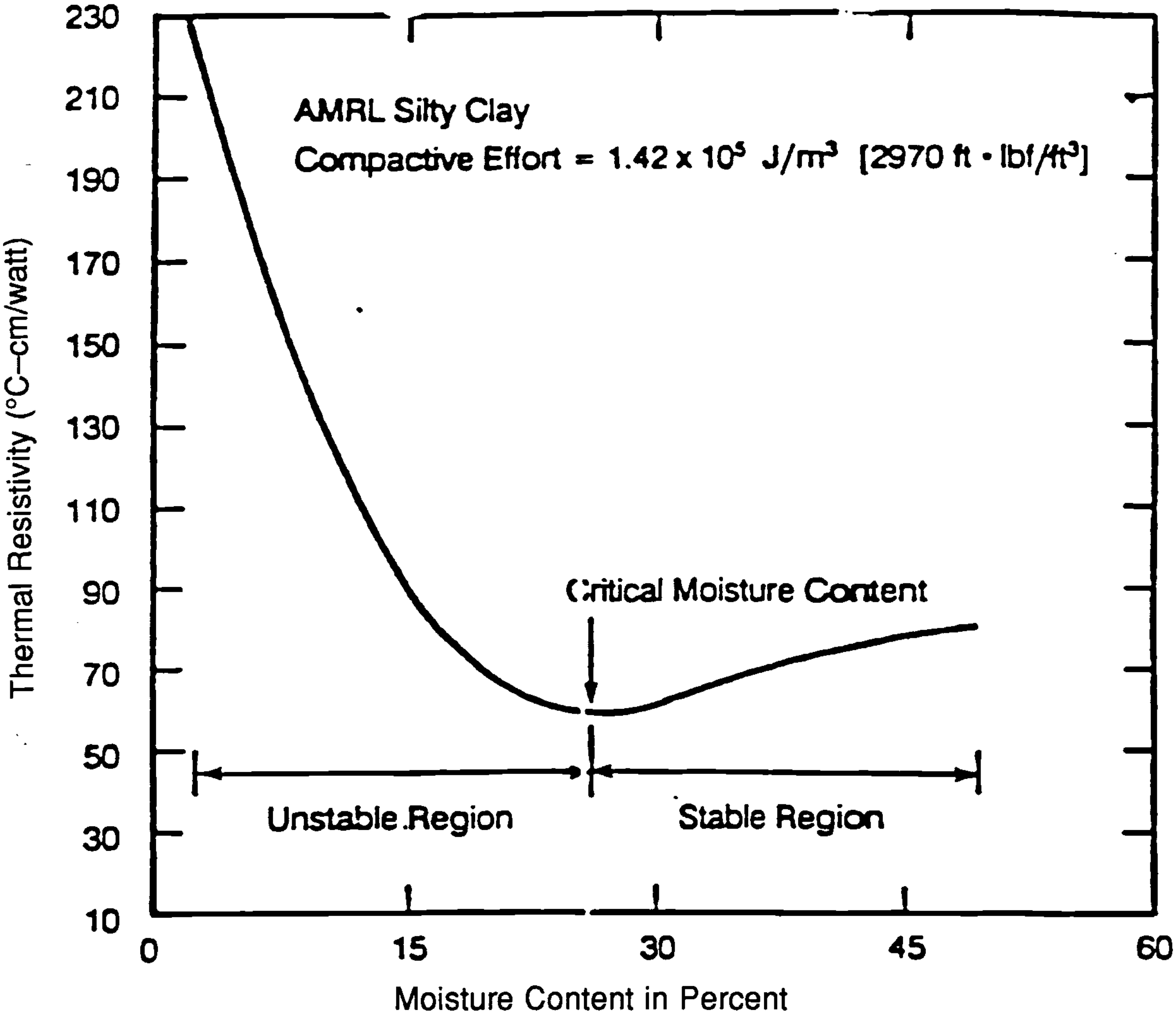


Figure 4. Variation of Thermal Resistivity With Moisture Content (11)

critical moisture content is an important parameter in design, it would be advisable to know the effects of climate on the natural water content.

In a soil mass where the temperature is above freezing, the water in the soil may be divided into "held" moisture and "free" moisture (2). The free water can be removed or can migrate by hydrostatic pressure. The held water may not be removed in this manner because of the complex forces that attract it to the surface of the soil particles. These forces are intermolecular, electrical, magnetic and gravitational. Some of the held water may be chemically combined in the surfaces or adsorbed onto them and some may be held at the particle contact points or in the capillary pores (2). The intensity with which a soil attracts water is called soil suction.

Soil Suction

Soil suction is the attractive force that soils exert on water caused by surface chemistry effects, osmotic effects and capillarity. For partially saturated soils, the suction consists of matrix suction and osmotic suction (11). The matrix suction is caused by capillarity and particle surface adsorption in a soil. The osmotic suction is dependent upon the concentration of soluble salts in the soil water. Total soil suction is the sum of the matrix suction and osmotic suction.

The adsorbed water layer on clay particles is directly related to soil suction. This adsorbed water layer is sometimes referred to as a diffuse double layer. The properties of this adsorbed layer are different from those of ordinary free water.. Figure 5 shows some diffuse electric double layer relationships. The part of the adsorbed layer near the surface of the clay particle can be pictured as being oriented due to the effect of the electric field of the charged soil particle on the water dipoles (2). The formation of the adsorbed layer has been visualized as one whereby free water breaks its hydrogen bonds and passes into a higher energy state, undergoing orientation and compression in the electric force field of the surface (2).

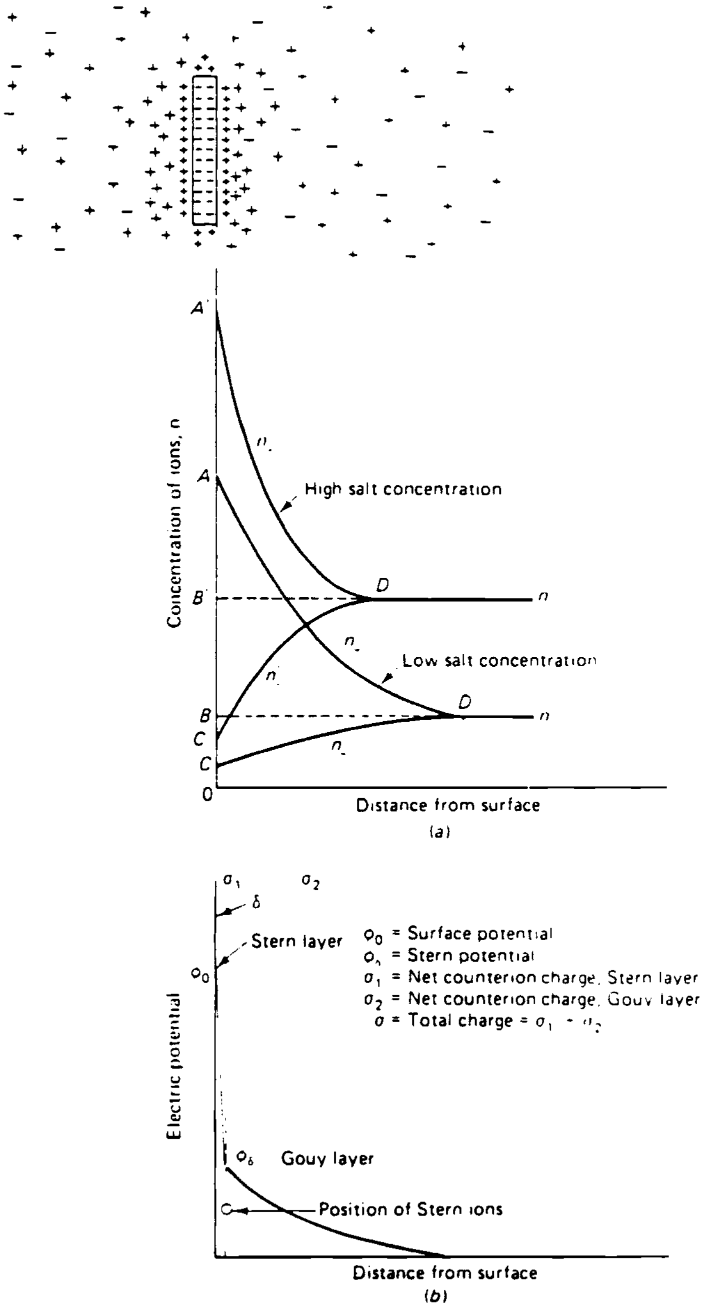


Figure 5. Diffuse Double Layer Relationships (2)

Other Factors Influencing Thermal Resistivity

The thermal resistivity of a soil is also affected by some secondary factors, namely: (1) soil structure, (2) temperature, (3) size and shape of soil particles, (4) ions and other solutes, (5) effects of additives, and (6) organic matter.

Soil Structure

The soil structure for fine-grained soils differs from that of coarse-grained soils. Coarse-grained soils contain a granular contacting skeleton with solid to solid contact and a small proportion of fines that does not interfere with the contact between grains (2). Fine-grained soils have water films between the particles. Fine-grained soils usually consist of aggregations of particles in their natural state. The aggregate may be platy, blocky, prismatic or granular. If this natural soil structure is broken up and finely fragmented, then more air gaps may be introduced which causes an increase in thermal resistivity.

Temperature

The thermal resistivity of a soil may vary considerably with temperature. For this reason, when soil thermal properties are measured, average values are taken over a specified temperature range.

For soils reaching the freezing point, thermal resistivity is highly dependent upon degree of saturation. Below a certain critical moisture content the thermal resistivity increases as the temperature is lowered (2). This is due to the fact that when some of the adsorbed water converts to ice there may be an increase in the effective thermal resistivity of the soil. In other words, the thermal bridge provided by the adsorbed water layer is impaired. However, if the soil water content is high prior to freezing, more ice will be formed. Therefore, the decrease in thermal resistivity of the ice overrides any increase in the soil's thermal resistivity due to lost unfrozen (strongly adsorbed) water (2).

For unfrozen soils, rising temperatures will drive away moisture. This loss of moisture will tend to increase the thermal resistivity of the soil. The temperature also effects the overall thermal resistivity of the soil because the thermal resistivity of each individual soil constituent may be temperature dependent (7). Figure 6 shows the temperature dependence of the thermal resistivity of dry quartz sand and water.

Properties of Soil Solids

The surface area of the soil solids can influence the overall soil thermal resistivity. The specific surface area or the surface area per volume is much larger for clay than for sand. The larger the specific surface area for a soil particle, then the more adsorbed water there will be. The clay mineral montmorillonite, which has a particularly large specific surface area, usually has more adsorbed water that is not mobile (2). Kaolinite clay has a low specific surface area with little adsorbed water. Illite has a capacity for adsorbing water which is between montmorillonite and kaolinite. A purely coarse-grained soil will have a much smaller specific surface area than a purely fine-grained soil. As discussed previously, the amount of adsorbed water has a definite effect on the thermal resistivity of a soil.

The solid constituents of a soil can have different values of thermal resistivity. Inorganic soils are composed of various minerals whose thermal resistivity varies with temperature and also with direction of heat flow (2). Coarse-grained soils can be composed of quartz and/or other minerals such as plagioclase feldspar and pyroxene. The fine-grained portion of a soil can contain the minerals kaolinite, illite, montmorillonite, and/or feldspar, mica, quartz, calcite, or other minerals in the silt or clay size range.

Ions and Other Solutes

Ions and other solutes present in soils may have various direct or indirect influences on the thermal properties of the soils (2). If cations are present in the diffuse double layer of a soil particle, then the water structure is disrupted causing

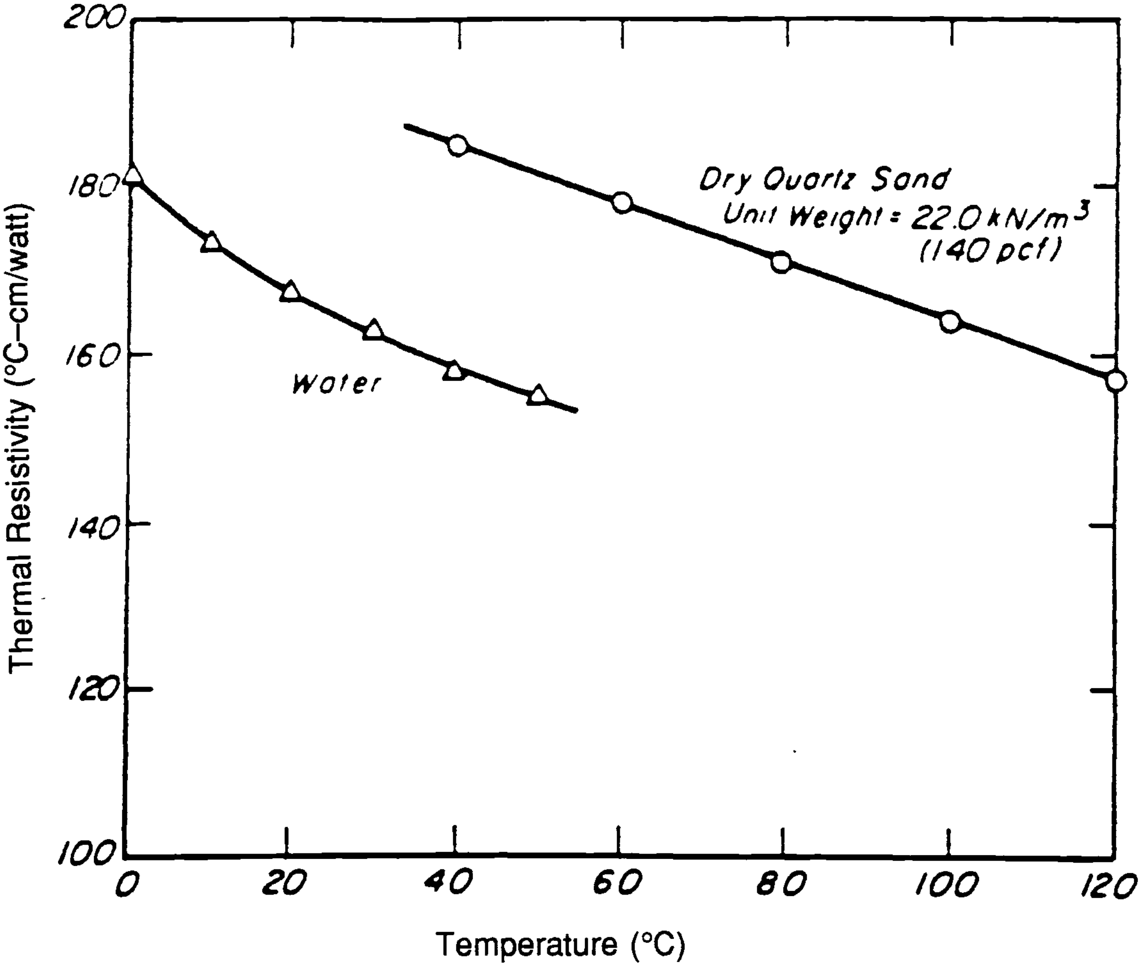


Figure 6. Temperature Dependence of Thermal Resistivity of Dry Quartz Sand and Water (1)

hydrogen bonds to break down. This causes the water dipoles to orient themselves around the cations which results in densification as compared to water not influenced by cations. This densification results in less freedom of movement of the dipoles. Therefore, the adsorbed water becomes capable of absorbing less thermal energy which results in a higher thermal resistivity.

Ions and salts have a greater influence on fine-grained soils than coarse-grained soils because of the higher specific surface areas and surface chemistry effects. Exchangeable cations provide bonds that contribute to the strength of clays and may influence heat transfer from particle to particle (2). Clays may have a flocculated or dispersed structure. Marine clays tend to have a flocculated structure. Fresh water clays tend to have a dispersed type structure. Flocculated marine clays contain large, dense aggregates of particles with large voids between the aggregates (2). Clays with a dispersed structure contain small, more porous aggregates that are uniformly dispersed with small voids between them. Therefore, dispersed clays exhibit a more ordered structure than flocculated clays on a macroscopic level. The more ordered the clay structure is, then the lower the overall thermal resistivity is most likely going to be.

Ions can also affect the thermal properties of a soil by ionic substitution in the mineral particle (2). These ions substitute themselves in a crystal lattice and act as scattering centers which leads to an increase in thermal resistivity.

Effects of Additives

Soils are treated with additives for several different purposes. Different substances can be used to modify a soil by reducing plasticity, reducing amount of swelling, increasing its strength, waterproofing it and/or acting as a binder to improve its thermal conductivity.

Lime or cement can be added to soil to improve workability, increase strength, and reduce plasticity. The reactions of both cement and lime with soil and water act to bind the particles together, producing aggregations of smaller particles that act as one larger particle. These reactions can also act to reduce the thermal resistivity of a soil.

Organic Matter

The thermal resistivity of peat is higher than other soil types. This is mostly dependent on the moisture content, with the fractional solids volume having only a small effect (10). Figures 7 and 8 illustrate the average thermal conductivity of peat as a function of its water content and dry density for the frozen and unfrozen conditions, respectively.

Decaying organic matter in soils produces humus. Humus interacts with clay particles, causing dispersion or aggregation, depending on the chemical makeup of the soil (2). The adsorbed water layer is distorted by the large organic molecules of the humus.

Organic matter in a soil reduces the density which increases the overall thermal resistivity of the soil.

Measurement of Thermal Resistivity

Thermal properties of soils may be measured in situ or in the laboratory. The thermal resistivity of a soil may be needed for several different situations, including analysis of heat dissipation from buried electrical cables, prediction of depth of frost penetration in soils, insulation and heat transfer analyses related to tanks, pipelines, and underground storage chambers, and moisture migration under thermal gradients (5). The thermal resistivity and diffusivity of a soil can be measured by steady state methods or by transient methods. In steady state methods, a temperature gradient is applied to the soil and then a period of time is elapsed before measurements are taken to ensure that the soil is in a steady state. In transient methods, the temperature of the soil varies with time. Transient methods are usually easier to perform and require less time than steady state methods.

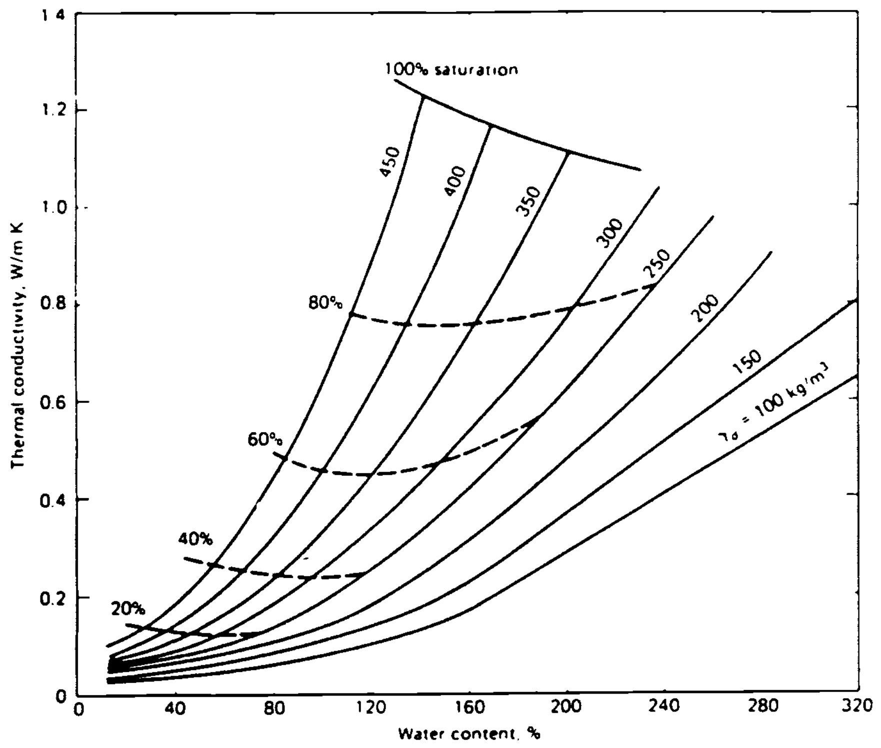


Figure 7. Average Thermal Conductivity of Frozen Peat as a Function of Water Content and Dry Density (2)

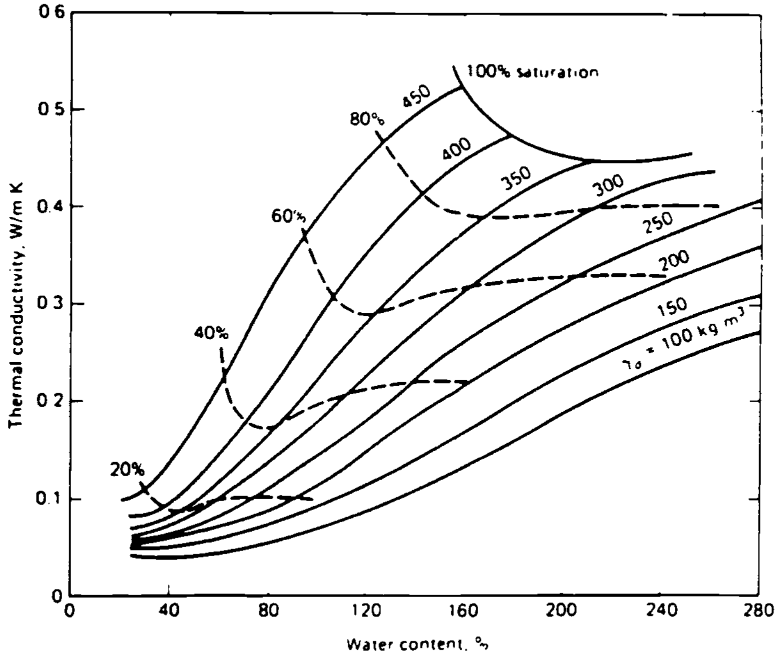


Figure 8. Average Thermal Conductivity of Unfrozen Peat as a Function of Water Content and Dry Density (2)

Guarded Hot Plate Test

The guarded hot plate (GHP) test is a steady state method. The GHP test has been standardized by the American Society for Testing and Materials (ASTM). It is capable of measurements in the range of -50 to +250°F. Farouki (2) explains the GHP test as follows: Two identical test specimens are placed above and below a flat-plate main heater unit which is surrounded by an outer guard heater. The guard eliminates horizontal heat losses and causes heat from the main heater to flow vertically up or down through the test specimens. Liquid-cooled heat sinks are placed adjacent to the outer surfaces of the specimens. A certain temperature drop Δt is thereby obtained across each specimen of thickness Δx. The thermal conductivity of the specimen material is calculated from the equation:

$$k = \frac{Q}{A}\frac{\Delta x}{\Delta t}$$

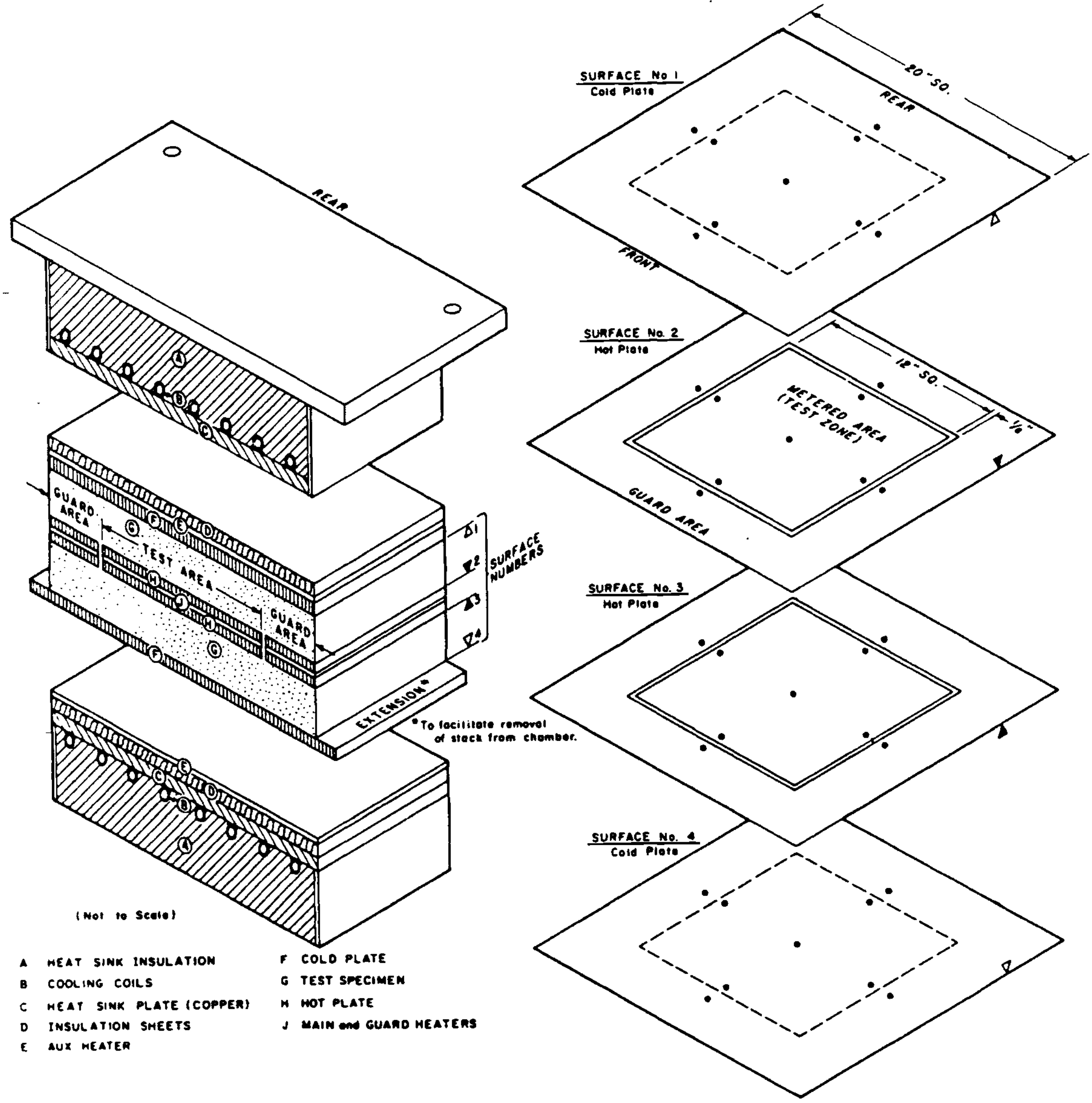
where Q is the time rate of heat flow, and A is the test area of the specimen. The GHP test method is time consuming, and water migration may occur during the test (5). Figure 9 illustrates the guarded hot plate apparatus.

Heat Flux Meter

The heat flux meter (HFM) is also a steady state method. The HFM measures the thermal resistivity of a soil in situ by measuring the temperatures at two points in the soil and the heat flowing between these points (2). The important criterion for a heat flux meter is the ratio of the thermal conductivity of the meter to the soil surrounding it. The HFM should be designed to give values of this ratio above unity for the soil types expected.

Thermal Probe Method

The thermal probe method (TPM) is a transient method which can be done rapidly for soils in the laboratory or in situ. The TPM is based on the measurement of the rate of temperature rise along a line heat source within an infinite, homogeneous medium (5). The probe is inserted into the soil, causing as little disturbance as possible to



a. Stack assembly cross section. *b. Thermocouple locations in plate surfaces.*

Figure 9. Guarded Hot Plate Apparatus (2)

insure good contact between the soil and the probe. The probe consists of a thermal energy producing unit (heater) and a temperature sensing element (thermocouple or thermistor). The logarithm of time versus temperature plot results in a straight line. The slope of this line can be used to calculate the thermal conductivity according to this equation (2):

$$k = (q / (4 * \pi * (T2 - T1))) * \ln (t2/t1)$$

where:

q = constant rate of heat per unit length of probe;
$T1$ = temperature value at time $t1$;
$T2$ = temperature value at time $t2$; and
k = thermal conductivity.

The TPM has a great advantage over steady state methods because the thermal resistivity can be computed directly from the test data without knowing the heat capacity of the soil (5). The TPM also has an advantage over steady state methods because it is simple and measurements can be taken in a short time period. Figure 10 represents a typical thermal probe.

Thermal Shock Method

Shannon and Wells (12) developed this transient method to measure the thermal diffusivity of a soil specimen by applying a sudden temperature change to the boundaries of a cylindrical sample and observing the resulting temperature change at its center. The temperature change was brought about by placing a warm sample (40°C±) into a colder water bath (20°C±) (5). The thermal resistivity of the soil sample is computed from the measured diffusivity, assuming a specific heat value. Mitchell and Kao (5) state that this method has two primary disadvantages: (1) the assumption of a specific heat value can induce an error, i.e. a separate measurement of specific heat is required for best results; and (2) the time factor curve for temperature change at the center of a cylinder of diameter D and height 2D presented by others

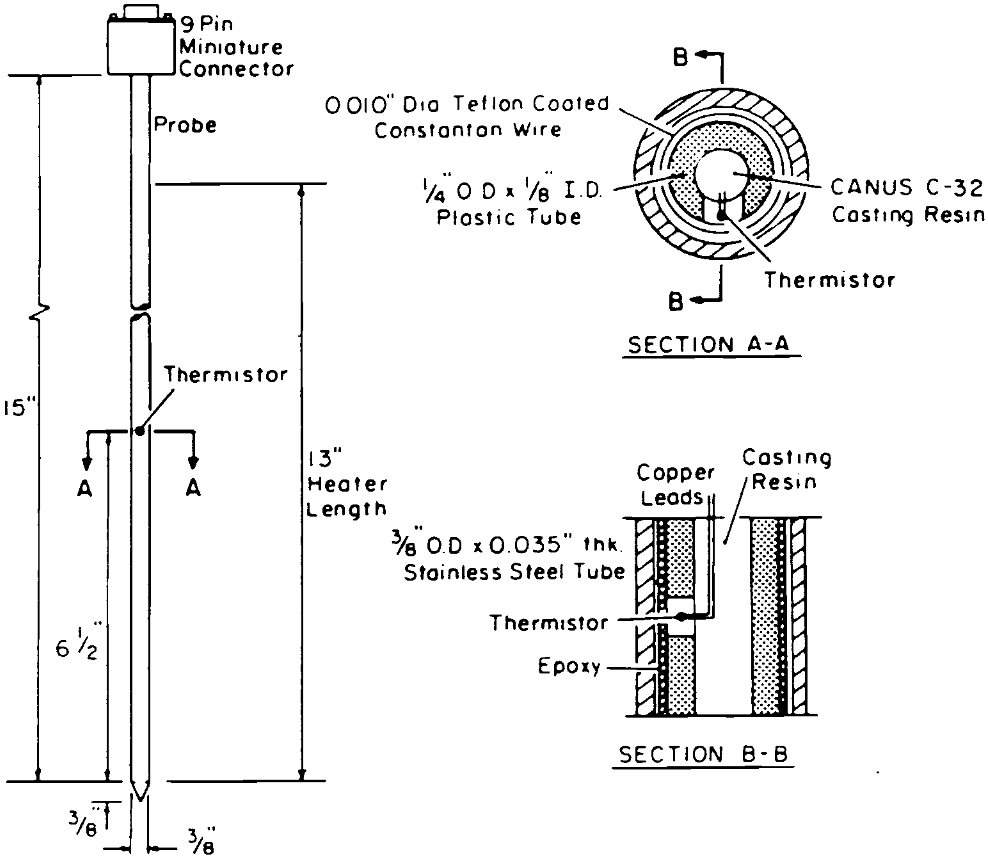


Figure 10. Typical Thermal Probe (2)

was found to be in error by about 20%. This method is only applicable in the laboratory.

Thermal Property Analyzer

Introduction

The Electric Power Research Institute (EPRI) embarked on a research program to develop a microprocessor controlled portable Thermal Property Analyzer (TPA) based on the thermal probe method that was suitable for both laboratory and field applications. The EPRI TPA was developed by Ontario Hydro under an EPRI contract (1). Geotherm Incorporated has since developed an updated version of the EPRI TPA. The Geotherm instrument emulates the Ontario Hydro instrument but offers simplified operation, automatic data storage through both hard copy and computer diskette, and built-in off-line data plotting and analysis routines.

Equipment Description

Geotherm Incorporated (3) describes the TPA as follows: "The Geotherm TPA is a micro-computer controlled system that provides programmable power to thermal probes, reads temperature sensors, probe current and voltage, and computes in real time the thermal resistivity and diffusivity for each active sensor input. The unit consists of a programmable 10-amp, 60-volt power supply, a 12-channel data acquisition system and Toshiba microcomputer. The entire system is software controlled. The only operator controls are the main power switch, and a power supply reset button. A nominal 110-volt AC power source is required. Power requirements are approximately 60 watts above the probe power requirements."

Field and Laboratory Measurement Techniques

The TPA can be used for field or laboratory applications. In the laboratory, six samples can be monitored at one time by using 10 cm long probes. The laboratory probes are inserted into the samples by hand with or without a pre-drilled hole. If a predrilled hole is necessary, a drill bit that is slightly smaller in diameter than the probe should be used to ensure good probe-soil thermal contact. The probe must not be moved during a test because this would result in distortion of the thermal field and would invalidate the data. The samples used for the laboratory testing program can be either undisturbed samples taken from the field or recompacted soil specimens.

Field thermal property measurements can also be taken using the TPA and larger field probes. Field probes have been used in 1- and 2-meter lengths and diameters of 6 and 10 mm (7). The probe must be inserted carefully to ensure good probe-soil thermal contact and minimal disturbance of the natural soil. Usually, some type of a guiding mechanism and a predrilled hole are necessary to keep the probe in line and minimize hole distortion. As with the laboratory probes, a slightly undersized drill bit should be used when drilling the pilot hole.

Summary

The determination of soil thermal properties is a complex phenomenon primarily influenced by soil composition, density, moisture content, and moisture migration. All soils have a relationship between moisture content and thermal resistivity. However, each soil has its own critical moisture content value which determines when that soil will become thermally unstable.

The thermal resistivity of a soil can be measured by steady state methods or transient methods. The thermal probe along with the TPA is the best method for measuring the thermal resistivity of soil. The TPA is relatively simple to use and can obtain measurements in a short time period both in the field and in the laboratory.

CHAPTER III

FIELD METHOD AND PROCEDURES

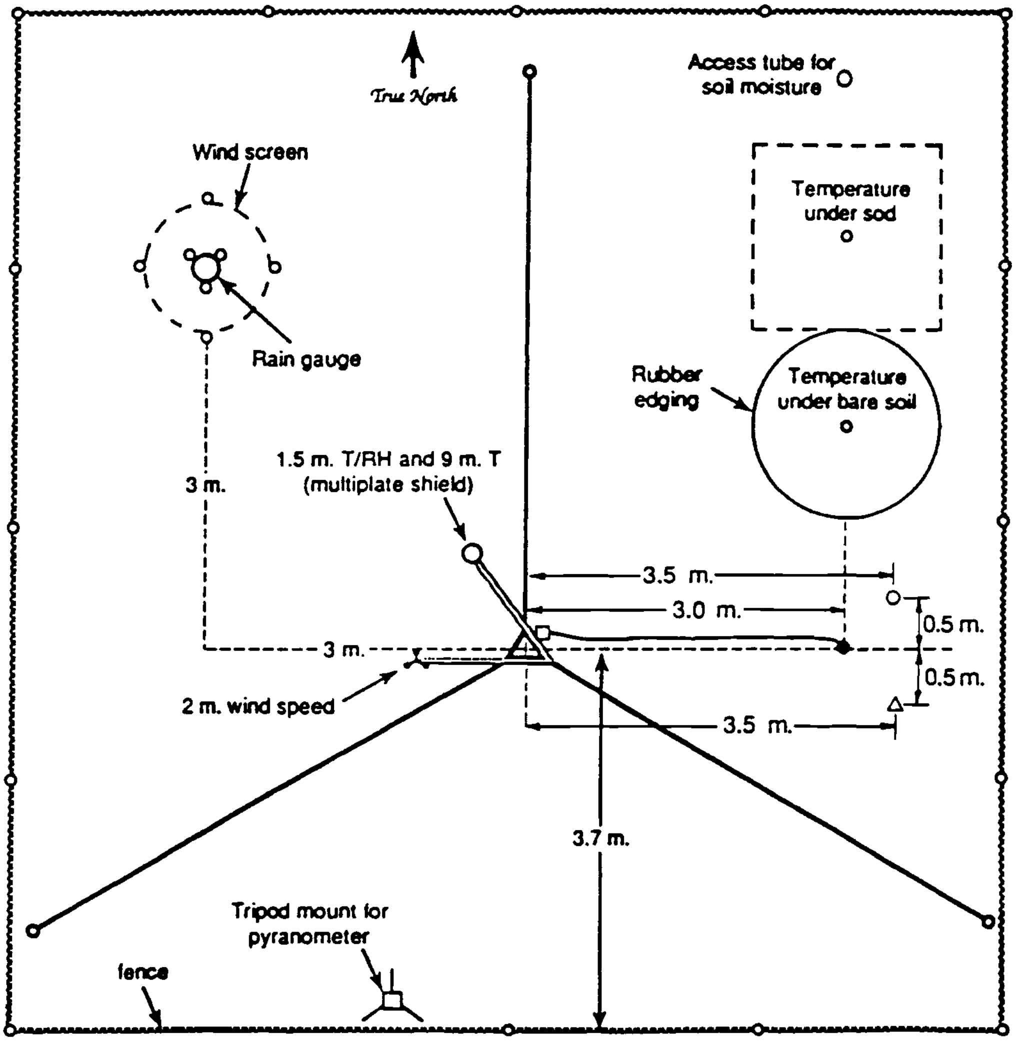
Site Selection Process

The EPRI/OSU project sites were selected at Oklahoma Mesonetwork sites. The Oklahoma Mesonetwork is a statewide automated climate monitoring network developed through the cooperative efforts of Oklahoma State University (OSU) and the University of Oklahoma (OU). The Oklahoma Mesonetwork contains a total of 110 sites that gather a range of meteorological data. EPRI/OSU originally planned to install their instruments at 20 of the Oklahoma Mesonetwork sites. Using the Mesonetwork sites allowed soil thermal property data to be taken concurrently with meteorological data. Since the Oklahoma Mesonetwork sites were scattered across Oklahoma, there would be no problem in finding sites with varying soil and climate conditions.

The first five sites chosen for the EPRI/OSU research project were located in Stillwater, Chickasha, Ada, Fairview, and McAlester. The balance of the EPRI/OSU project sites were cancelled because of funding problems at EPRI.

Instrument Installation

The instruments installed at the EPRI/OSU project sites include thermistors, heat flux plates, soil moisture probe access tube, thermal property analyzer probe, and a 4 x 16 relay multiplexer and enclosure. Figure 11 shows a diagram of a typical EPRI/OSU site instrumentation installation. The thermistors and heat flux plate were placed 3.0 meters east of the tower. The polyvinyl chloride (PVC) access tube for the



EPRI/OSU MESONET STUDY: PHASE II

Legend for Instrument Installation

- ● Thermistors and Heat Flux Plate Boring
- ○ PVC Access Tube for Soil Moisture Probe
- △ Thermal Property Analyzer Probe
- □ 4x16 Relay Multiplexer and Enclosure
- ⟝ Electric Wire and Protective Conduit

Figure 11. Diagram of a Typical EPRI/OSU Site

soil moisture probe was placed 0.5 meters north and 3.5 meters east of the tower. The 4 x 16 relay multiplexer and enclosure were connected to the tower.

Thermistor and Heat Flux Plates

Figure 12 shows the thermistor and heat flux plate installation. The thermistors were used to measure the soil temperature. The heat flux plate was used to measure the soil heat flux. Soil heat flux is the amount of heat flowing in the soil per unit area per unit time. The steps involved in the installations are as follows:

1. The hole was hand augered to a depth of 60 cm, keeping the excavated soil in order, so that the last soil taken out of the hole will be the first to go back into the hole.
2. A depth template and nails were used to establish the proper depths and start the holes for the thermistors. The thermistors were then installed, to their full length, in the prestarted holes.
3. The depth template and cutting tool were used to excavate a slot for the heat flux plate. The heat flux plate was then installed and the soil was replaced around the wires and adjacent to the heat flux plate.
4. The wires were draped to the bottom of the hole and fixed in place with a small amount of the soil cuttings. The wires were then banded together and fed into the conduit. The conduit was installed in a shallow slot (i. e. even with the ground surface) between the boring and the multiplexer and anchored with wire hooks on one-meter intervals.
5. The boring was then backfilled with the cuttings, placing the last soil out in the boring first. The cuttings were then densified by flooding and gently compacting the soil. The conduit was then covered with any extra cuttings.

PVC Access Tube

Figure 13 shows the installation of the PVC access tube for the soil moisture probe and the soil sampling procedure. The PVC tube was used for insertion of the soil

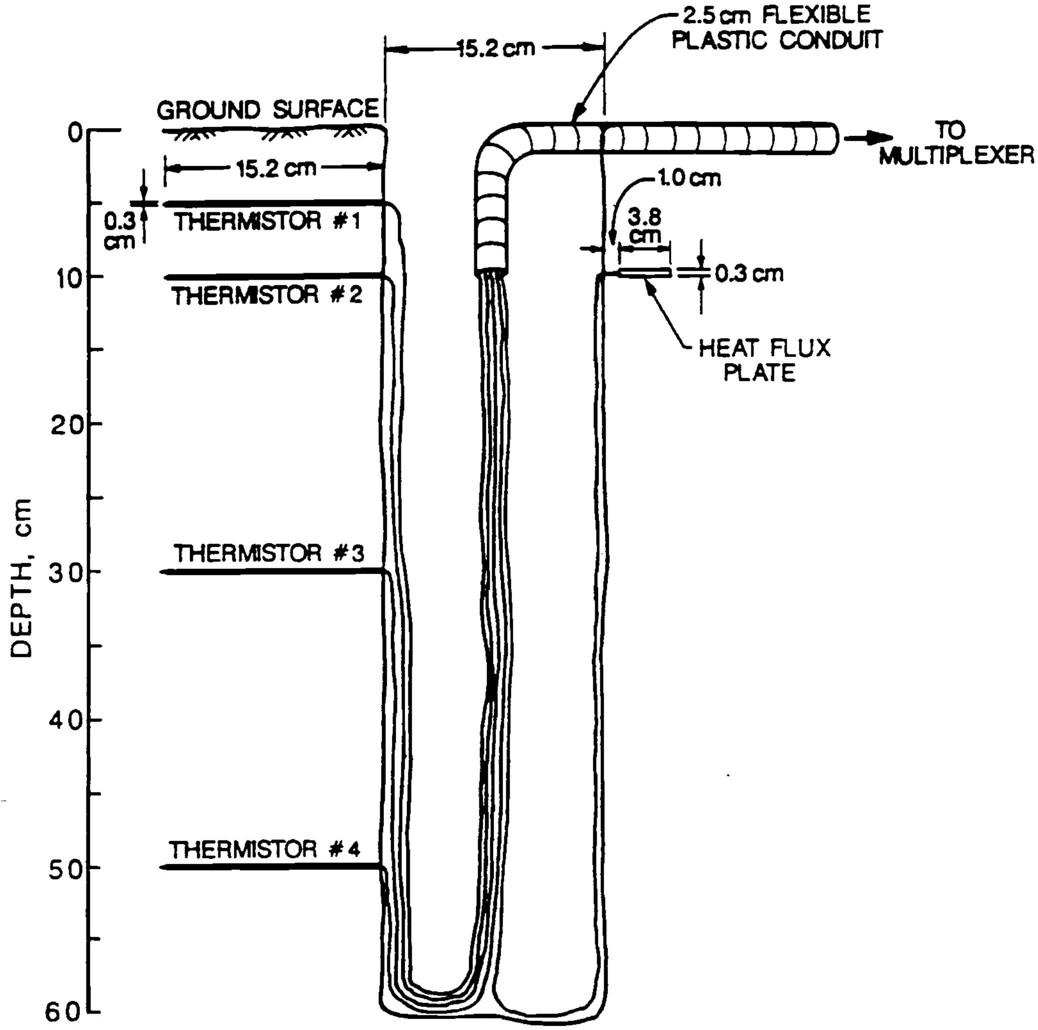


Figure 12. Thermistor and Heat Flux Plate Installation

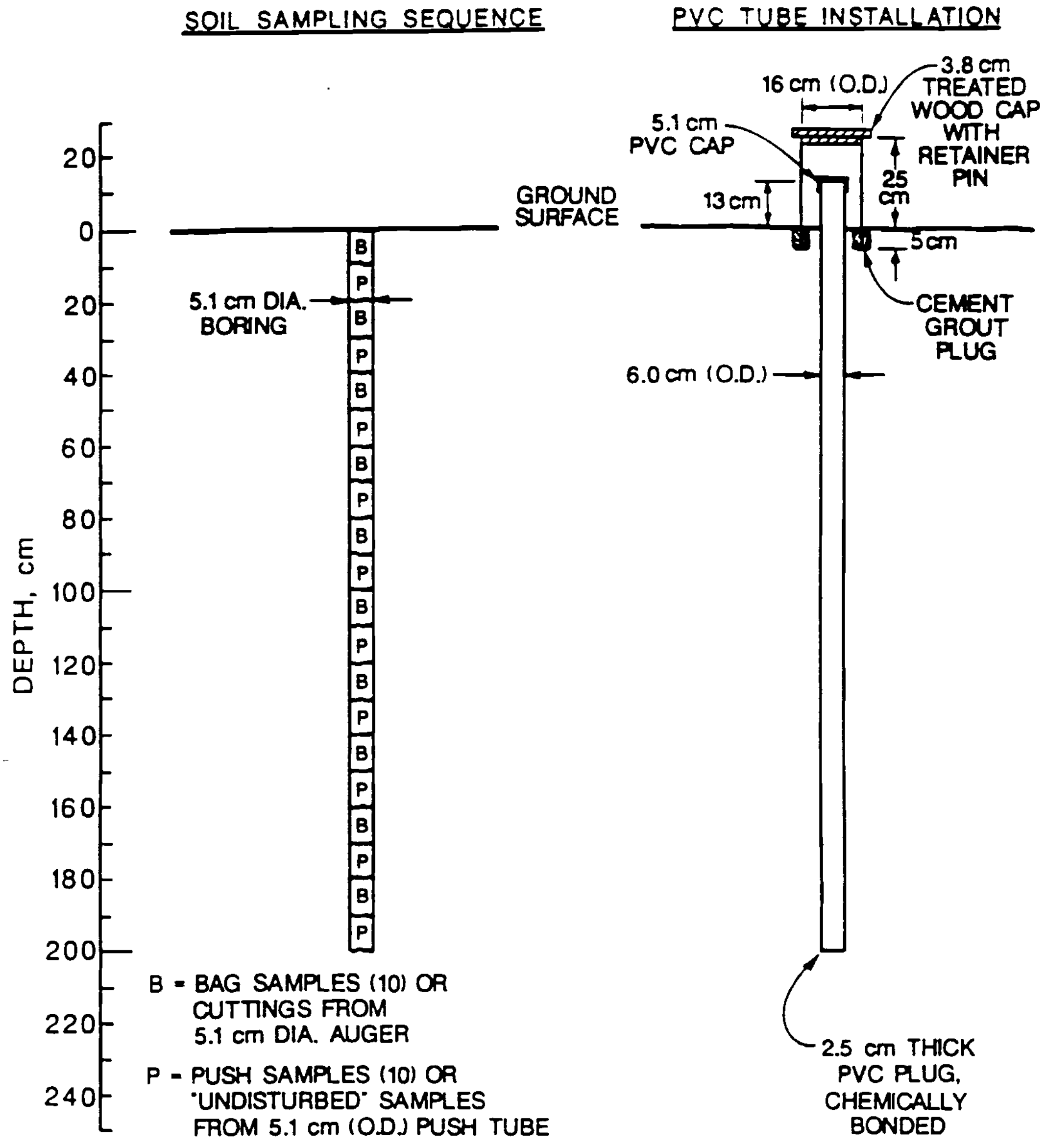


Figure 13. Soil Sampling Procedure and PVC Access Tube Installation

moisture probe to measure moisture content with depth and time.. The steps involved in the installation of the PVC access tube are as follows:

1. A vertical boring was extended 200 cm using a 5.1 cm (o. d.) hand auger and a 5.1 cm (o. d.) hand-operated push-tube sampler. Samples were taken on 10 cm intervals.
2. The hole was then reamed with a 6.0 cm (o. d.) reamer. Cuttings from the hole were placed in a plastic bag whjich was marked to correspond to the site locations and the upper and lower cuttings.
3. The 6.0 cm (o. d.) PVC tube was then installed to a depth of 200 cm.
4. A small 16-cm diameter trench was cut around the 6.0 cm (o. d.) PVC tube. A 16-cm (o. d.) by 30.5 cm long PVC tube was then placed in the trench around the 6.0-cm (o. d.) PVC tube. Excess soil was compacted around the PVC tube to secure it.
5. A PVC cap was placed on the 6.0-cm (o. d.) tube and a wooden cap was placed on the larger tube.

Thermal Property Analyzer Probe

Figure 14 represents the installation of the TPA probe. The TPA probe was used to measure soil thermal resistivity. These properties were measured on an intermittent basis for correlation with the Oklahoma Mesonetwork climatic data. The steps involved in the installation are as follows:

1. The drill frame was set up to insert the pilot probe into the ground.
2. The pilot probe was then drilled into the ground.
3. The pilot probe was then withdrawn and replaced with the TPA probe using the same procedure as with the pilot probe. The TPA probe was rotated into the ground until the terminal box was level with the ground surface.
4. A trench, with a diameter of 16 cm, was cut around the TPA probe so that the terminal box was adjacent to one side of the trench. A 16-cm (o. d.) by 30.5-

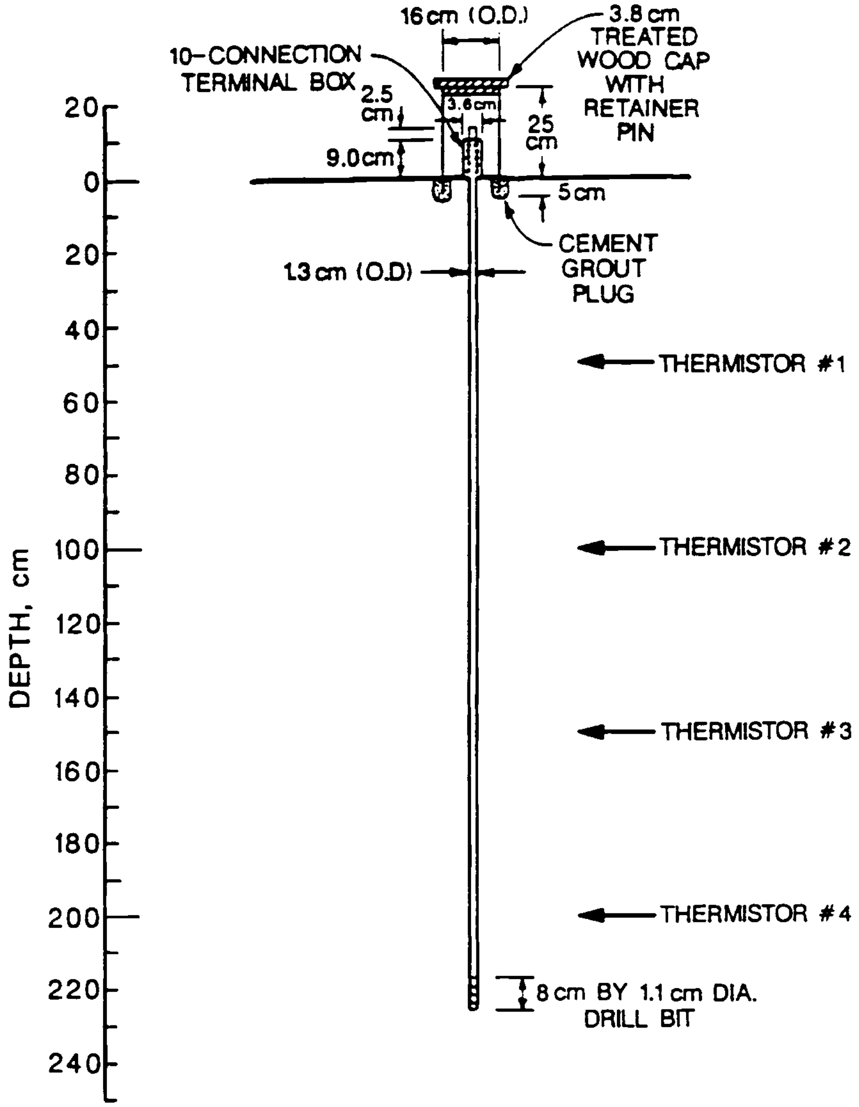


Figure 14. Thermal Property Analyzer Probe Installation

cm long PVC pipe was then placed in the trench and secured by compacting soil around the edges.

Soil Sampling Procedures

Samples were taken using both a hand auger (disturbed samples) and a push-tube (undisturbed samples) sampler. Samples were taken to a depth of 200 cm, during the installation of the soil moisture probe access tube, at each of the five EPRI/OSU sites. Both disturbed and undisturbed samples were taken at 10-cm intervals. A total of 20 samples (disturbed and undisturbed) were taken from each site (see Figure 13).

Disturbed Samples

The hand auger was advanced into the ground while rotating it to collect 10 cm of soil. The soil was placed in a plastic zip-lock bag. The bag was marked with the name of the site and the depth of which the soil sample was taken. The bag was then sealed to preserve natural moisture conditions and placed inside a thermal chest. A minimum of 10 disturbed samples were taken from each site, depending on soil conditions. More disturbed samples were taken if it was impossible to take an undisturbed sample.

Undisturbed Samples

The push tube sampler was pushed into the ground to obtain an undisturbed sample approximately 10 cm in length, where soil conditions allowed. This sample was divided into two equal parts. One part was placed in a plastic zip-lock bag and marked with the name of the site and depth at which the sample was taken. The other part was placed in a small circular plastic container for measurement of natural soil suction. Two pieces of plastic mesh were placed on top of the soil specimen and two pieces of filter paper (Whatman No. 42) were placed on top of the plastic mesh. The circular plastic container was then sealed and the containers with the specimen inside were placed in a thermal chest.

Field Data

The thermal resistivity was measured in the field using the installed thermal probes and a TPA. Measurements were taken on a monthly basis from March 1993 to June 1993 for each of the five sites. The Ada, Fairview, and McAlester sites were not measured in March. The McAlester site was also not measured in May. The results of the field thermal resistivity testing are shown in Table 3. The results show very little change in the in-situ thermal resistivity for all five of the sites over the time period of the measurements. The thermistors represent different depths at which the measurements were taken at each site.

TABLE 3

FIELD THERMAL RESISTIVITY DATA

Site	Thermistor	Thermal Resistivity (°C–cm/W)			
		March 1993	April 1993	May 1993	June 1993
Stillwater	1	61	60	59	62
	2	49	49	49	51
	3	44	43	45	45
	4	40	40	39	42
Chickasha	1	58	58	56	58
	2	65	66	66	66
	3	58	53	53	52
	4	65	64	64	64
Ada	1		44	46	43
	2		36	39	38
	3		48	49	50
	4		42	42	42
Fairview	1		66	65	66
	2		59	62	61
	3		53	51	51
	4		58	58	57
McAlester	1		39		39
	2		44		43
	3		40		41
	4		40		40

Thermistor 1 = 50 cm.
Thermistor 2 = 100 cm.
Thermistor 3 = 150 cm.
Thermistor 4 = 200 cm.

CHAPTER IV

SOIL PROPERTIES

Introduction

After the samples were collected from each site, laboratory tests were run to determine soil properties. Soils were classified as either coarse-grained or fine-grained. The lab tests that were run depended on the type of soil sample and whether the soil was fine-grained or coarse-grained.

Disturbed Samples

The properties measured on coarse-grained disturbed samples included description, natural moisture content, and sieve analysis. The properties measured on fine-grained disturbed samples included description, natural moisture content, percent minus the U. S. number 200 sieve and Atterberg limits.

Undisturbed Samples

The properties measured on fine-grained undisturbed samples included natural moisture content, wet density, dry density, and natural soil suction.

Description of Samples

All samples were described using the visual manual procedure defined in ASTM D 2488 when they were obtained in the field. The characteristics used in the description procedure include: color, moisture, consistency, and soil type. Tables 5 through 9 in Appendix A contain the descriptions for the Stillwater, Chickasha, Ada, Fairview, and McAlester sites.

Percent Minus U.S. No. 200 Sieve

The percent minus the U.S. No. 200 sieve was determined for each disturbed sample to classify the soil as either coarse-grained or fine-grained. The Unified Soil Classification System (USCS) was used for this determination. According to the USCS, if more than 50% passes the U.S. No. 200 sieve then the soil is fine-grained. Tables 10 through 14 in Appendix B show the percent passing the U.S. No. 200 sieve at each disturbed sampling depth for each of the five sites.

Grain Size Analysis

A mechanical grain size analysis was run on each of the samples classified as coarse-grained. The sieves used for the grain size analyses include the U.S. Nos. 4, 10, 40, 100, and 200. Tables 15 through 26 in Appendix C show the grain size analyses at the noted depths for each site.

Natural Moisture Content

The natural moisture content, defined as the ratio of weight of water in a given volume of soil to the weight of the soil particles in that same volume, was determined for both the disturbed and undisturbed samples. The samples were dried in an oven at 105°C ±5° which is consistent with standard procedures.

Wet and Dry Density

The in situ wet density of the undisturbed samples was calculated by dividing the total wet weight of the sample by the total volume of the sample. The in situ dry density was calculated by dividing the oven dried weight of the soil sample by the total volume of the sample before drying. Densities for some of the coarse-grained samples were not obtained due to the fact that they did not contain enough fine-grained soil to hold the soil samples intact for testing. Figures 15 through 19 in Appendix D show profiles of wet density, dry density, and natural moisture content from undisturbed samples.

Natural Soil Suction

Total soil suction was determined for every undisturbed soil specimen using the filter paper method (ASTM D 5298). Two filter papers were placed on top of the soil specimen with two pieces of plastic mesh between the filter papers and the soil specimen. The filter papers, plastic mesh, and soil specimen were then placed in an airtight container for seven days to allow sufficient time for vapor pressure of porewater in the specimen, vapor pressure of porewater in the filter paper, and partial vapor pressure of water in the air inside the container to reach equilibrium. The airtight containers were then placed inside an insulated chest to maintain a nearly constant temperature. After the seven-day equilibration period, the filter papers were removed and dried in an oven separately to determine the mass of water in each filter paper. The total suction was then calculated using a calibration curve for Whatman No. 42 filter paper. Figures 20 through 24 in Appendix E show natural soil suction and natural water content with depth for each of the five sites.

Atterberg Limits

Both the liquid limit and plastic limit were determined for each disturbed fine-grained sample according to ASTM D423 and D424. Figures 25 through 29 in Appendix F show Atterberg limits and natural moisture content for the disturbed samples at each of the five sites.

CHAPTER V

LABORATORY THERMAL PROPERTY TESTING PROGRAM

Introduction

Each EPRI/OSU site soil profile was divided into different soil layers using soil descriptions, water contents, grain size distribution, dry densities, and Atterberg limits. An average water content and dry density were determined for each soil layer at each site. The average water content and dry density were used to determine the molding conditions for their soil specimens used in the laboratory thermal property testing program. The selected soil layers, average water contents, and dry densities for each of the five sites were as follows:

Sites	Water Content (%)	Dry Density (pcf)
Stillwater:		
Layer 1: 5–60 cm	21.6	98.1
Layer 2: 60–140 cm	18.0	102.2
Layer 3: 140–200 cm	15.2	108.1
Chickasha:		
Layer 1: 0–40 cm	19.3	97.9
Layer 2: 40–100 cm	21.2	98.5
Layer 3: 100–200 cm	25.0	91.9
Ada:		
Layer 1: 0–80 cm	16.2	110.1
Layer 2: 80–200 cm	18.3	105.7
Fairview:		
Layer 1 : 0–60 cm	16.4	102.8
Layer 2 : 60–120 cm	14.6	108.2
Layer 3 :120–200 cm	20.1	100.6
McAlester:		
Layer 1: 0–80 cm	18.1	99.2
Layer 2: 80–200 cm	15.0	103.0

Process Description

Five different water content values were chosen for each layer at each site to obtain a range of moisture conditions during thermal property testing. The molding water contents were varied in increments of 1%, usually 2 or 3 points below the average water content and the others above the average. Harvard miniature compaction equipment was used to mold the soil specimens for laboratory thermal property testing. Before the soil specimens were molded, the soil sample was oven dried and broken down by mortar and pestle to minus the U.S. No. 40 sieve. Tables 27 through 31 in Appendix G give the molding conditions for each of the five sites. For most of the soil layers, the water contents were chosen so that the average in situ water content of the layer would lie in the middle of the range chosen. However, some of the soil layers had an average in situ water content that was too wet for proper compaction. For these situations, a water content range was chosen dry enough to correctly compact the soil using Harvard miniature compaction equipment.

The dry density during molding of the samples was maintained as close to the average value, previously described, as possible. The weighing of soil and water was closely monitored to maintain a constant density for each of the specimens tested for a given layer.

After the specimens were compacted, the thermal resistivity was determined using laboratory thermal probes and the TPA. Plots of thermal resistivity versus water content were developed from these values. The critical moisture content for each soil layer was determined by using the intersection of tangents to the legs of the curve. A best fit curve was drawn by hand through all of the data points. Both the stable and unstable portions of the curve were shown whenever possible. A tangent line was then drawn to both the stable and unstable portions of the curve. The intersection of these two points was chosen as the critical moisture content.

After the specimens were tested for thermal resistivity, total soil suction measurements were taken. The same procedure was used for the recompacted samples as was used for the undisturbed samples. After the suction tests were completed, the samples were oven dried to obtain the actual water contents.

Results

Figures 30 through 42 in Appendix H contain plots of thermal resistivity versus water content for the recompacted samples. Figures 43 through 56 in Appendix I contain plots of total soil suction versus water content for the recompacted samples.

CHAPTER VI

DISCUSSION OF SOIL PROPERTIES AND RESULTS OF THERMAL PROPERTY TESTS

Stillwater Site

The Stillwater site was broken down into three soil layers. The first layer (0 to 60 cm) consisted primarily of sandy, silty clay. The second layer (60 to 140 cm) consisted of silty clay. The third layer (140 to 200 cm) consisted primarily of sandy clay. The coarse-grained fraction of the soil increased with increasing depth. The in situ dry density below 100 cm deep was greater than the dry density above 100 cm. The natural water content gradually decreased to a depth of about 180 cm, where it started to increase slightly.

Layer 1 (0 to 60 cm)

Figure 30 shows the thermal resistivity versus molding water content for Layer 1 at the Stillwater site. The critical moisture content was approximately 17.2% at a thermal resistivity of approximately 300°C-cm/W. Thus, according to this curve the soil becomes unstable at a moisture content below approximately 17.2%. The base thermal resistivity of the soil was approximately 175°C-cm/W.

As stated in the literature review, the primary factors that influence the thermal resistivity of a soil include: (1) soil composition, (2) soil density, (3) soil moisture content, and (4) soil suction. This layer was primarily a sandy, silty clay. From the Atterberg limit data, this soil plotted above the "A" line as a lean clay (CL) according to the USCS. This soil layer contained very little coarse-grained material with about 85% passing the No. 200 sieve.

Layer 2 (60 to 140 cm)

The critical moisture content was not apparent from the data for this Layer (Figure 31). Most likely, the critical moisture content occurred below a water content of 15% for this soil and density condition. The thermal resistivity was larger for Layer 2 than Layer 1. The soil went from a sandy, silty clay for Layer 1 to a silty clay for Layer 2. Layer 2 had a higher plasticity index than Layer 1. The critical moisture content ("knee" of the thermal resistivity versus water content curve) becomes harder to define as a soil becomes more cohesive. More data points at lower moisture contents would have helped to define the critical moisture content. Layer 2 contained more coarse-grained material, with about 74% passing the No. 200 sieve. The soil suction from the lab samples was slightly larger for Layer 2 than Layer 1 over the same water content ranges. Even though Layer 2 contained more coarse-grained material than Layer 1, it had a higher thermal resistivity. Therefore, the soil's cohesive characteristics had a larger effect on its thermal resistivity than its grain size distribution when comparing these two soil layers.

Layer 3 (140 to 200 cm)

The thermal resistivity versus water content curve (Figure 32) was very similar to Layer 1. However, the critical moisture content was less apparent for Layer 3. Layer 3 was predominantly a sandy clay. From the Atterberg limit data, this soil layer plotted above the "A" line as a lean clay (CL) very near where the soil in Layer 1 plotted. The critical moisture content was approximately 13.5% at a thermal resistivity of approximately 175 °C-cm/W. Layer 3 contained more coarse-grained material than both Layers 1 and 2 with approximately 57% passing the No. 200 sieve. The molding dry density was 108.1 pcf. The increase in coarse-grained particles along with the increase density material was most likely the reason for the reduction in the thermal resistivity.

At water contents greater than the critical moisture content, the thermal resistivity gradually increased. The cause of this was probably a reduction in density of the samples. As the preparation water content increased for the samples, efficient compaction became very difficult due to pumping.

Chickasha Site

The Chickasha site was broken down into three soil layers. Layer 1 was primarily a silty clay. The top of Layer 1 contained some gravel which was discarded. Layer 2 consisted of clay to silty clay. Layer 3 contained mostly silty fine sand and clayey fine sand. The in situ density increased with depth to 120 cm then decreased. The plasticity index was found to be greater for the soil above 100 cm than below 100 cm (Figure 26).

Layer 1 (0 to 40 cm)

Figure 33 shows the thermal resistivity versus molding water content curve for Layer 1. The critical moisture content was approximately 18.1% with a thermal resistivity of 300°C-cm/W. The resistivity leveled off in the stable region at approximately 200°C-cm/W.

This layer was a dark brown silty clay. The first 20 cm of this layer contained gray crusher run gravel which was discarded and not used in the soil testing. From the Atterberg limit data, this soil plotted above the "A" line as a lean clay (CL).

Layer 2 (40 to 100 cm)

Figure 34 shows the thermal resistivity versus molding water content curve for Layer 2. The critical moisture content was approximately 20.1% with a thermal resistivity of 140°C-cm/W.

This layer was a reddish brown silty clay. From the Atterberg limit data, this soil plotted above the "A" line as a lean clay (CL). This soil layer had a higher plasticity index than any of the previously discussed soil layers. This layer was more fine-grained with around 93% passing the No. 200 sieve. The presence of less coarse-grained material in this soil layer as compared to Layer 1 was part of the reason this layer became unstable at a higher water content. The soil suction was higher for this layer than for Layer 1. This was consistent with the fact that the plasticity index was larger.

Layer 3 (100 to 200 cm)

Figure 35 shows the thermal resistivity versus molding water content curve for Layer 3 at Chickasha. The critical moisture content was approximately 19.9%. The base thermal resistivity was approximately 160°C-cm/W.

This layer varied from a silty fine sand to a fine sandy clay. From the Atterberg limit data, this soil plotted above the "A" line as a lean clay (CL). This soil plotted very near the CL-ML area which probably means that a large portion of the fine-grained material was silt. This soil layer was predominantly fine-grained with about 81% passing the No. 200 sieve.

Ada Site

The Ada site was divided into two soil layers. Layer 1 was primarily clayey sand. Layer 2 consisted primarily of sandy clay.

Layer 1 (0 to 80 cm)

Figure 36 shows the thermal resistivity versus water content curve for Layer 1 at the Ada site. The curve was entirely above the critical moisture content (i.e. beyond the "knee"). The base thermal resistivity value was approximately 160°C-cm/W. According to the USCS, this soil was coarse-grained with approximately 47% passing the No. 200 sieve.

Layer 2 (80 to 200 cm)

Figure 37 represents Layer 2 at the Ada site. This curve was also completely above the critical moisture content. The soil changed from coarse-grained to fine-grained from Layer 1 to Layer 2. There was a slight drop in base thermal resistivity for

Layer 2 as compared to Layer 1 over similar water content ranges. The material in Layer 2 was very similar to Layer 1 with approximately 54% passing the No. 200 sieve. The molding dry density was 105.7 pcf. The soil suction was larger for Layer 1 than for Layer 2 over the same water content ranges. This was contrary to what was expected since Layer 2 was fine-grained material and Layer 1 was coarse-grained material. Either capillarity had a greater effect on Layer 1 or the mineralogy of the fines present was more active than the fines in Layer 2.

Layer 1 contained more coarse-grained material than Layer 2 and a higher molding dry density. However, the thermal resistivity was greater for Layer 1. The data points for Layer 1 were more scattered than the data points for Layer 2. This may be caused by inefficient compaction due to the presence of more coarse-grained material.

Fairview Site

The Fairview site was divided into three soil layers. Layer 1 consisted primarily of clayey silt. Layer 2 consisted primarily of silty clay with some pockets of sand. Layer 3 was primarily silty sand with some clay showing up between 180 and 200 cm. The in situ density was constant down to 80 cm, increased down to 120 cm, and then decreased steadily down to 200 cm. The natural water content was steady down to 120 cm and then gradually increased from that point down.

Layer 1 (0 to 60 cm)

Figure 38 represents the thermal resistivity versus water content curve for Layer 1. The curve was completely in the thermally stable region. The range of resistivity values for this soil across the specified water content range was about 200 to 400°C-cm/W. Layer 1 consisted primarily of a dark brown, clayey silt. From the Atterberg limit data, this soil plotted just above the "A" line in the CL-ML section. This was consistent with the field description of clayey silt for this layer. This soil layer contained very little coarse-grained material with about 88% passing the No. 200 sieve.

Layer 2 (60 to 120 cm)

Figure 39 shows the thermal resistivity versus molding water content curve for Layer 2. The critical moisture content was approximately 13.6% at a thermal resistivity of approximately 200°C-cm/W. The thermal resistivity leveled off in the stable region at approximately 140°C-cm/W.

Layer 2 was predominantly a reddish brown, silty clay. According to Table 2, a silt had a range of thermal resistivity of 90 to 110°C-cm/W and a silty clay had a range of 85-105. This indicated that if a soil contains silt and clay, then the soil with a higher silt content would have a higher thermal resistivity. The molding density was higher for Layer 2 than for Layer 1, which could be another reason for the drop in resistivity from Layer 1 to Layer 2.

This soil layer contained more coarse-grained material than Layer 1 with approximately 78% passing the No. 200 sieve. This was another reason for the drop in thermal resistivity for Layer 2 as compared to Layer 1. The soil suction for laboratory samples of Layer 2 was slightly higher than the soil suction for Layer 1. This was consistent with the increase in clay content for Layer 2 as compared to Layer 1.

Layer 3 (120 to 200 cm)

Figure 40 shows the thermal resistivity versus molding water content curve for Layer 3. The critical moisture content was approximately 9.1% at thermal resistivity of approximately 650°C-cm/W. The thermal resistivity leveled off in the stable region at approximately 550°C-cm/W. Layer 3 was described as reddish brown, silty sand in the field. However, after testing the samples, the soil layer actually contained more fine-grained material than coarse-grained with approximately 61% passing the No. 200 sieve. The presence of more coarse-grained material usually means lower thermal resistivity values. However, the molding density for Layer 3 was lower than for both Layers 1 and 2. The low molding density had more of an effect on the thermal resistivity than soil type. From the Atterberg limit data, this soil plotted at the top to middle of the CL-ML section.

McAlester Site

The McAlester site was broken down into two soil layers. The first layer (0 to 80 cm) consisted of sand and sandy clay. The top 30 cm was primarily sand and the bottom 50 cm was primarily sandy clay. The second layer (80 to 200 cm) consisted of clayey sand or sandstone. The soft sandstone layer was located between 100 and 160 cm. The in situ dry density decreased from 40 cm to 60 cm, gradually increased to 180 cm and then decreased to 200 cm. The natural water content increased sharply from 40 to 50 cm, decreased gradually to 100 cm and then remained fairly constant to 200 cm.

Layer 1 (0 to 80 cm)

Figure 41 shows the thermal resistivity versus molding water content curve for Layer 1 at the McAlester site. The critical moisture content was approximately 11.6% at a thermal resistivity of approximately 400°C-cm/W. The thermal resistivity leveled off in the stable region at around 300°C-cm/W.

The percent passing the No. 200 sieve was only determined for 40 to 70 cm samples. It was found to be approximately 58% passing the No. 200 sieve. The molding dry density for Layer 1 was 99.2 pcf.

Layer 2 (80 to 200 cm)

Figure 42 shows the thermal resistivity versus molding water content curve for Layer 2. The critical moisture content was approximately 11.0% at a thermal resistivity of approximately 300°C-cm/W. At water contents greater than the critical moisture content, the thermal resistivity gradually increased. The cause of this was a reduction in compacted density of the samples due to the difficulty in compacting at higher water contents.

Layer 2 was a coarse-grained material with approximately 29% passing the No. 200 sieve. The molding density was larger for Layer 2 than for Layer 1. Both of these soil characteristics support the fact that the critical moisture content lowered and occurred at a lower base thermal resistivity for Layer 1 compared to Layer 2.

Effects of Plasticity on Thermal Resistivity

Figure 56 shows a plot of plasticity index versus liquid limit for each layer at each site with the corresponding thermal resistivity values shown (see Appendix J). There was a general trend of increasing base thermal resistivity upward and to the right toward the "A" line. However, two points on the chart do not follow the trend. They are the data points for Layer 1 at the Fairview site (300°C-cm/W at a liquid limit of 26 and plasticity index of 7) and Layer 2 at the Fairview site (140°C-cm/W at a liquid limit of 45 and plasticity index of 22). Layer 1 is predominantly a clayey silt and Layer 2 is predominantly a silty clay.

Field Versus Laboratory Data

The thermal resistivity values taken in the field using the 200 cm thermal probes and the TPA are shown in Table 3. The Stillwater site field values show a decreasing trend from top to bottom of the probe. This was consistent with the fact that the in situ density and the amount of coarse-grained material increased with depth at the Stillwater site.

The Chickasha site field values were relatively constant with depth. This was consistent with the fact that the amount of fine-grained material versus coarse-grained also stays relatively constant with depth. The in situ density was smaller at 200 cm than at 150 cm. This was consistent with the larger field thermal resistivity value at 200 cm versus 150 cm.

The Ada site field values are relatively consistent with depth. The in situ density and natural moisture content were also very consistent with depth.

The Fairview site field values show higher values at the 50, 100, and 200 cm thermistors and a lower value at the 150 cm thermistor. This was consistent with the fact that a layer of coarser grained soil existed between roughly 100 and 170 cm.

The McAlester site field values were similar to the Ada site values except that they are a little lower on average. This was consistent with the fact that the soil at this site was very sandy. The 100 cm thermistor showed the highest value out of the four thermistors. This was consistent with the fact that the in situ density is smaller at 100 cm than 50, 150, or 200 cm.

The base thermal resistivity values for the laboratory samples using the laboratory thermal probes were considerably higher than the in situ resistivity values using the field thermal probes for each of the five sites. The difference in field values versus laboratory values ranged from 100 to 500°C-cm/W.

Possible reasons for the difference in field and laboratory values include: (1) scale effects, (2) remolded versus undisturbed testing, and (3) installation procedure of the probes. The laboratory probes were much smaller than the field probes. Also, the specimen of soil used in the laboratory was obviously a smaller medium for testing than in situ testing. Remolding the soil changed the natural soil structure that existed in the field which could significantly affect the thermal resistivity. The probe needed to be in uniform contact with the surrounding soil to give accurate measurements of thermal resistivity. The probe used in the field was larger and was placed in a larger medium than the laboratory probe. This may have led to a more uniform contact between the soil and the field probe.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

In Chapter VI, the engineering and thermal properties were discussed for each soil layer at each site. The soils tested in the laboratory followed the basic trends discussed in the literature review. The composition, density, moisture content and suction of the soil layers all influenced the thermal resistivity found in the testing program. Table 4 contains specimen test conditions, description, critical water content, and base thermal resistivity for each layer of each site. For the most part, an increase in coarse-grained material shifted the thermal resistivity versus water content curve to the left. In other words, an increase in the amount of coarse-grained material meant a decrease in the critical moisture content value.

An example of this was observed when comparing Layers 2 and 3 to Layer 1 for Stillwater. The critical moisture content for Layer 1 was approximately 17.2 %. Layers 2 and 3 both contained more coarse-grained material and both had reduced critical moisture content values. The critical moisture content for Layer 2 at Stillwater was not apparent from the data given in Figure 31, but it was obviously below 17.2 %. The critical moisture content for Layer 3 at Stillwater was approximately 13.5%. This shift to the left on the thermal resistivity versus water content curve due to an increase in coarse-grained material was also observed for the curves at the Chickasha, Fairview, and McAlester sites. The thermal resistivity versus water content curves for the two layers at the Ada site were completely in the stable region, above the critical moisture content. More data points at lower moisture content values were needed to draw the complete curve showing the critical moisture content.

TABLE 4

SUMMARY OF SPECIMEN TEST CONDITIONS AND THERMAL PROPERTY TEST RESULTS

Site	Layer No.	Average Water Content (%)	Average Dry Density (pcf)	Average Plasticity Index (%)	Average % Minus No. 200 Sieve	Description ASTM D2488	Critical Water Content (%)	Base Thermal Resistivity °C–cm/W
Stillwater	1	21.6	98.1	12	85	Sandy, silty clay	17.2	175
	2	18.0	102.2	18	74	Silty clay	--	300
	3	15.2	108.1	13	57	Sandy clay	13.5	150
Chickasha	1	19.3	97.9	14	77	Silty clay	18.1	200
	2	21.2	98.5	22	93	Clay to silty clay	20.1	140
	3	25.0	91.9	9	81	Silty and clayey fine sand	19.9	160
Ada	1	16.2	110.1	NP	47	Clayey sand	--	160
	2	18.3	105.7	13	54	Sandy clay	--	140
Fairview	1	16.4	102.8	7	88	Clayey silt	--	200 to 400
	2	14.6	108.2	14	78	Silty clay	13.6	140
	3	20.1	100.6	7	61	Silty sand	9.1	550
McAlester	1	18.1	99.2	21	58	Sandy clay	11.6	300
	2	15.0	103.0	NP	29	Clayey sand	11.0	300

The plasticity index influenced the thermal resistivity in the laboratory testing program. Layer 2 at Stillwater had a higher plasticity index than Layer 3 which has a higher plasticity index than Layer 1. Figures 30 through 32 show that Layer 2 had a higher resistivity than Layer 3, but Layer 3 had a lower resistivity than Layer 1. However, Layer 3 contained 43% coarse-grained material and Layer 1 contained only 15% coarse-grained material. Therefore, when comparing Layers 1 and 3 for Stillwater, the soil composition had more of an effect on the thermal resistivity than the plasticity index.

The critical moisture content was determined for each layer at each site except for Layer 2 at Stillwater, Layers 1 and 2 at Ada, and Layer 1 at Fairview. From Table 4, it can be shown that the critical moisture content was consistently lower than the average in situ moisture content for each layer. In other words, the soil is thermally stable in its natural state for each layer of each site.

The values of thermal resistivity determined in the field using field thermal probes were very consistent over the time period measured. These values also followed the basic trends discussed in the literature review. The soil composition, density and moisture content all seem to influence the value of resistivity measured in the field. For instance, the Ada and McAlester sites had resistivities lower than the other three sites. This is consistent with the fact that these two sites contained more coarse-grained material than the other sites.

The values of thermal resistivity found in the field were lower than the values found for the same soil in the laboratory testing program. The differences in resistivity values were caused by a number of factors. Some of the possible factors include: (1) scale effects, (2) remolded versus undisturbed testing, and (3) installation procedure for the probes. The size of the thermal probe used in the laboratory testing program was much smaller than the field probe which could have an influence on the measured resistivity value. Remolding a soil can change the structure of the soil which causes a difference in measured thermal resistivity values. From the results of the laboratory and field testing programs, soil seems to have a lower thermal resistivity value in its natural state as opposed to a recompacted sample. Another reason for the difference in the field and laboratory values was the installation procedure for the probes. In the field, the probe likely had more uniform contact with the surrounding soil than in the laboratory due to both probe size and soil type. This could also be linked to the fact that the soil structure was totally changed when the soil was remolded.

The problems with scale effects and remolded soil are the basis for suggestions for future research. Soil structure obviously has an effect on the measured value of thermal resistivity. The effect that disturbing the soil's natural structure has on its thermal properties, for coarse-grained soil as compared to fine-grained soil, is an opportunity for further research. Also, the effect that sample size versus probe size has on the thermal resistivity of a soil is an opportunity for further research.

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APPENDIX A

SOIL DESCRIPTIONS FOR FIVE EPRI/OSU SITES

TABLE 5

DESCRIPTION OF SAMPLES WITH DEPTH AT STILLWATER SITE

Depth (cm)		Description	Type of Sample
From	To		*
0	5	Grass cover and roots–discarded	
5	10	Dark brown, moist, medium, sandy clay	A
10	20	Dark brown, moist, medium, sandy silty clay	P
20	30	Dark brown, moist, medium, sandy silty clay	A
30	40	Dark reddish brown, moist, medium, sandy silty clay	P
40	50	Dark reddish brown, moist, medium, sandy silty clay	A
50	60	Dark reddish brown, moist, medium, sandy silty clay	P
60	70	Reddish brown, moist, stiff, silty clay	A
70	80	Reddish brown, moist, very stiff, silty clay	P
80	90	Light reddish brown, moist, very stiff, silty clay	A
90	100	Light reddish brown, moist, very stiff, silty clay	P
100	110	Light reddish brown with tan mottles, damp, very stiff, silty clay	A
110	120	Light reddish brown with tan mottles, damp, very stiff, silty clay	P
120	130	Reddish brown with black mottles, damp, very stiff, silty clay	A
130	140	Reddish brown with black mottles, damp, very stiff silty clay	P
140	150	Reddish brown with black and yellow mottles, damp, very stiff, sandy clay	A
150	160	Reddish brown with yellow mottles, damp, hard, clayey sand to sandstone	P
160	170	Dark reddish brown, moist, very stiff, sandy clay	A
170	180	Dark reddish brown, moist, very stiff, sandy clay	P
180	190	Light reddish brown, moist, very stiff, sandy clay	A
190	200	Light reddish brown, moist, very stiff, sandy clay	P

* P = push tube samples; A = auger samples.

TABLE 6

DESCRIPTION OF SAMPLES WITH DEPTH AT CHICKASHA SITE

Depth (cm)		Description	Type of Sample
From	To		*
0	10	Reddish brown, moist, medium, silty clayey gravel–gravel discarded	A
10	20	Dark grey crusher run gravel	P
20	30	Dark brown-black, damp, medium, silty clay with few gravel pieces	A
30	40	Dark brown with reddish mottles, damp, medium, silty clay	P
40	50	Dark brown and reddish brown, damp, stiff, clay	A
50	60	Dark brown and reddish brown, damp, stiff clay	P
60	70	Reddish brown, damp, stiff, silty clay	A
70	80	Reddish brown, damp, stiff, silty clay	P
80	90	Reddish brown, damp, stiff, silty clay	A
90	100	Light reddish brown, damp, medium stiff, clayey silt	P
100	110	Light reddish brown, moist, medium, clayey fine sand	A
110	120	Light reddish brown, wet, silty fine sand	P
120	130	Light reddish brown, wet, silty fine sand	A
130	140	Light reddish brown, wet, silty fine sand	P
140	150	Light reddish brown, wet, soft, clayey fine sand	A
150	170	Light reddish brown, saturated, soft, clayey fine sand	P
170	190	Light reddish brown, saturated, soft, fine sandy clay	A
190	200	Light reddish brown, saturated, soft, fine sandy silt with some clay	P

* P = push tube samples; A = auger samples.

TABLE 7

DESCRIPTION OF SAMPLES WITH DEPTH AT ADA SITE

Depth (cm)		Description	Type of Sample
From	To		*
0	10	Grey, moist, firm, clayey sand	A
10	20	Grey, moist, firm, clayey sand	P
20	30	Grey, moist, firm, clayey sand	A
30	40	Grey, moist, firm, clayey sand	P
40	50	Grey, moist, firm, clayey sand	A
50	60	Grey, moist, firm, clayey sand	P
60	70	Grey, moist, firm, clayey sand	A
70	80	Grey, moist, firm, clayey sand	P
80	90	Grey, moist, firm, sandy clay	A
90	100	Grey, moist, firm, sandy clay	P
100	110	Grey, moist, firm, sandy clay	A
110	120	Grey, moist, firm, sandy clay	P
120	130	Grey, moist, soft, sandy clay	A
130	140	Grey, moist, soft, sandy clay	P
140	150	Grey, moist, soft, sandy clay	A
150	160	Grey, moist, firm, sandy clay	P
160	170	Grey, moist, firm, sandy clay	A
170	180	Grey, moist, firm, sandy clay	P
180	190	Grey, moist, soft, sandy clay	A
190	200	Grey, moist, soft, sandy clay	P

* P = push tube samples; A = auger samples.

TABLE 8

DESCRIPTION OF SAMPLES WITH DEPTH AT FAIRVIEW SITE

Depth (cm)		Description	Type of Sample
From	To		*
0	10	Dark brown, moist, medium, clayey silt with roots	A
10	20	Dark brown, moist, medium, clayey silt	P
20	30	Dark brown, moist, medium, clayey silt	A
30	40	Dark brown, moist, medium, clayey silt	P
40	50	Dark brown with some brown , moist, medium, clayey silt	A
50	60	Dark brown with some brown, moist, medium, silty clay	P
60	70	Dark brown with some brown, damp, medium to stiff, silty clay	A
70	80	Reddish brown, damp, stiff, silty clay with some fine sand	P
80	90	Reddish brown, damp, stiff, silty clay	A
90	100	Reddish brown, damp, stiff to very stiff, silty clay	P
100	110	Reddish brown, damp, stiff to very stiff, silty clay	A
110	120	Dark reddish brown, damp, stiff, sandy silty clay	P
120	140	Reddish brown, moist, soft to medium, silty sand	A
140	160	Reddish brown, wet, soft to medium, silty sand	P
160	170	Reddish brown, wet to saturated, soft, silty sand	A
170	180	Reddish brown, wet to saturated, soft, silty sand	P
180	190	Reddish brown, wet to saturated, soft, clayey silty sand	A
190	200	Reddish brown, wet to saturated, soft, clayey silty sand	P

* P = push tube samples; A = auger samples.

TABLE 9

DESCRIPTION OF SAMPLES WITH DEPTH AT MCALESTER SITE

Depth (cm)		Description	Type Of Sample
From	To		*
0	10	Brown, fine, poorly graded, damp, sand with roots	A
10	20	Brown, fine, poorly graded, damp, sand with roots	P
20	30	Brown, fine, poorly graded, damp, sand with fewer roots	A
30	40	Red and tan, damp, medium, clay	P
40	50	Red and tan, damp, stiff, clay with some black mottles	A
50	60	Red and tan, damp, stiff, sandy clay with black mottles	P
60	70	Red with some tan, damp, stiff, sandy clay	A
70	80	Red with some tan, damp, stiff, sandy clay	P
80	90	Red with tan mottles, damp, stiff, clayey sand	A
90	100	Red with tan mottles, damp, soft, sandstone	P
100	110	Red with tan mottles and some grey, damp, soft, sandstone with silt	A
110	120	Red with tan mottles and some grey, damp, soft, sandstone with clay balls	P
120	130	Red with tan mottles, damp, fine, poorly graded, soft, sandstone with some clay	A
130	140	Red with tan mottles, damp, fine, poorly graded, soft, sandstone with some clay	P
140	150	Red with tan mottles, damp, fine , poorly graded, soft, sandstone with some clay	A
150	160	Red with tan mottles, damp, fine, poorly graded, soft, sandstone with some clay	P
160	170	Red with some grey, fine, poorly graded, damp, clayey sand	A
170	180	Red with some grey, fine, poorly graded, damp, clayey sand	P
180	190	Red with some grey, fine, poorly graded, damp to wet, clayey sand	A
190	200	Red with some grey, fine, poorly graded, damp to wet, clayey sand	P

* P = push tube samples; A = auger samples.

APPENDIX B

PERCENT PASSING THE U.S. NO. 200 SEIVE TEST RESULTS

TABLE 10

PERCENT PASSING U.S. NO. 200 SEIVE, STILLWATER SITE

Depth (cm) From	To	Percent Passing No. 200 Seive
5	10	94
20	30	80
40	50	78
60	70	79
80	90	76
100	110	75
120	130	67
140	150	58
160	170	60
180	190	52

TABLE 11

PERCENT PASSING U.S. NO. 200 SEIVE, CHICKASHA SITE

Depth (cm) From	To	Percent Passing No. 200 Seive
0	10	Data Not Available
20	30	77
40	50	95
60	70	92
80	90	91
100	110	82
120	130	70
140	150	94
170	190	76

TABLE 12

PERCENT PASSING U.S NO. 200 SEIVE, ADA SITE

Depth (cm) From	To	Percent Passing No. 200 Seive
0	10	44*
20	30	48*
40	50	48*
60	70	47*
80	90	52
100	110	52
120	130	53
140	150	54
160	170	53
180	190	62

*Atterberg limits test was not run on these samples because, according to the USCS, soil with less than 50% passing the No. 200 seive is considered coarse-grained. Also, a mehanical seive analysis was run on these samples to determine grain size distribution.

TABLE 13

PERCENT PASSING U.S. NO. 200 SEIVE, FAIRVIEW SITE

Depth (cm) From	To	Percent Passing No. 200 Seive
0	10	88
20	30	89
40	50	88
60	70	88
80	90	81
100	110	64
120	140	54
160	170	46*
180	190	82

*Atterberg limits test was not run on this sample because, according to the USCS, soil with less than 50% passing the No. 200 seive is considered coarse-grained. Also, a mechanical seive analysis was run on this sample to determine grain size distribution.

TABLE 14

PERCENT PASSING U.S. NO. 200 SEIVE, McALESTER SITE

Depth (cm) From	To	Percent Passing No. 200 Seive
0	10	Data Not Available
20	30	Data Not Available
40	50	64
60	70	51
80	90	39*
100	110	31*
120	130	32*
140	150	27*
160	170	25*
180	190	21*

*Atterberg limits test was not run on these samples because, according to the USCS, soil with less than 50% passing the No. 200 seive is considered coarse-grained. Also, a mechanical seive analysis was run on these samples to determine grain size distribution.

APPENDIX C

GRAIN SIZE ANALYSIS RESULTS

TABLE 15

GRAIN SIZE ANALYSIS, ADA SITE
(DEPTH = 0 TO 10 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	99
100	47.5
200	24.6

TABLE 16

GRAIN SIZE ANALYSIS, ADA SITE
(DEPTH = 20 TO 30 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	98.8
100	50.8
200	28.8

TABLE 17

GRAIN SIZE ANALYSIS, ADA SITE
(DEPTH = 40 TO 50 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	99
100	85.3
200	30.1

TABLE 18

GRAIN SIZE ANALYSIS, ADA SITE
(DEPTH = 60 TO 70 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	98.6
100	49.5
200	28.4

TABLE 19

GRAIN SIZE ANALYSIS, MCALESTER SITE
(DEPTH = 0 TO 30 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	100
100	49.2
200	21.4

TABLE 20

GRAIN SIZE ANALYSIS, MCALESTER SITE
(DEPTH = 80 TO 90 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	100
100	39
200	14

TABLE 18

GRAIN SIZE ANALYSIS, ADA SITE
(DEPTH = 60 TO 70 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	98.6
100	49.5
200	28.4

TABLE 19

GRAIN SIZE ANALYSIS, MCALESTER SITE
(DEPTH = 0 TO 30 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	100
100	49.2
200	21.4

TABLE 20

GRAIN SIZE ANALYSIS, MCALESTER SITE
(DEPTH = 80 TO 90 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	100
100	39
200	14

TABLE 21

GRAIN SIZE ANALYSIS, MCALESTER SITE
(DEPTH = 100 TO 110 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	100
100	30.7
200	10.4

TABLE 22

GRAIN SIZE ANALYSIS, MCALESTER SITE
(DEPTH = 120 TO 130 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	100
100	48.5
200	11.3

TABLE 23

GRAIN SIZE ANALYSIS, MCALESTER SITE
(DEPTH = 140 TO 150 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	100
100	40
200	12

TABLE 24

GRAIN SIZE ANALYSIS, MCALESTER SITE
(DEPTH = 160 TO 170 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	100
100	35
200	10

TABLE 25

GRAIN SIZE ANALYSIS, MCALESTER SITE
(DEPTH = 180 TO 190 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	100
100	22
200	7

TABLE 26

GRAIN SIZE ANALYSIS, FAIRVIEW SITE
(DEPTH = 160 TO 170 CM)

U.S. Seive Number	Percent Passing Seive
4	100
10	100
40	100
100	55
200	30

APPENDIX D

IN SITU MOISTURE CONTENT AND DENSITY CONDITIONS FROM UNDISTURBED SAMPLES

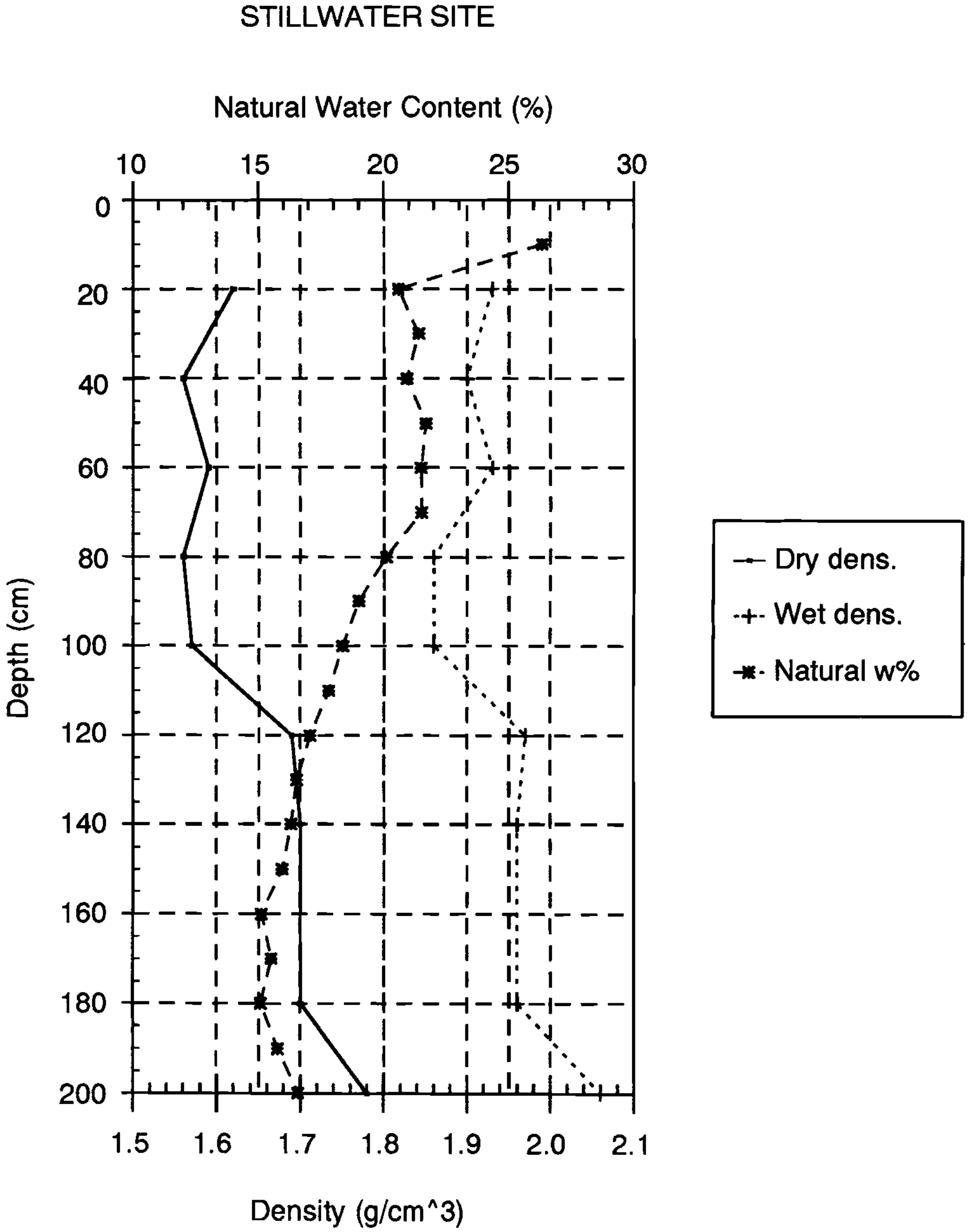


Figure 15. Plot of Wet Density, Dry Density, and Natural Water Content for Stillwater Test Site

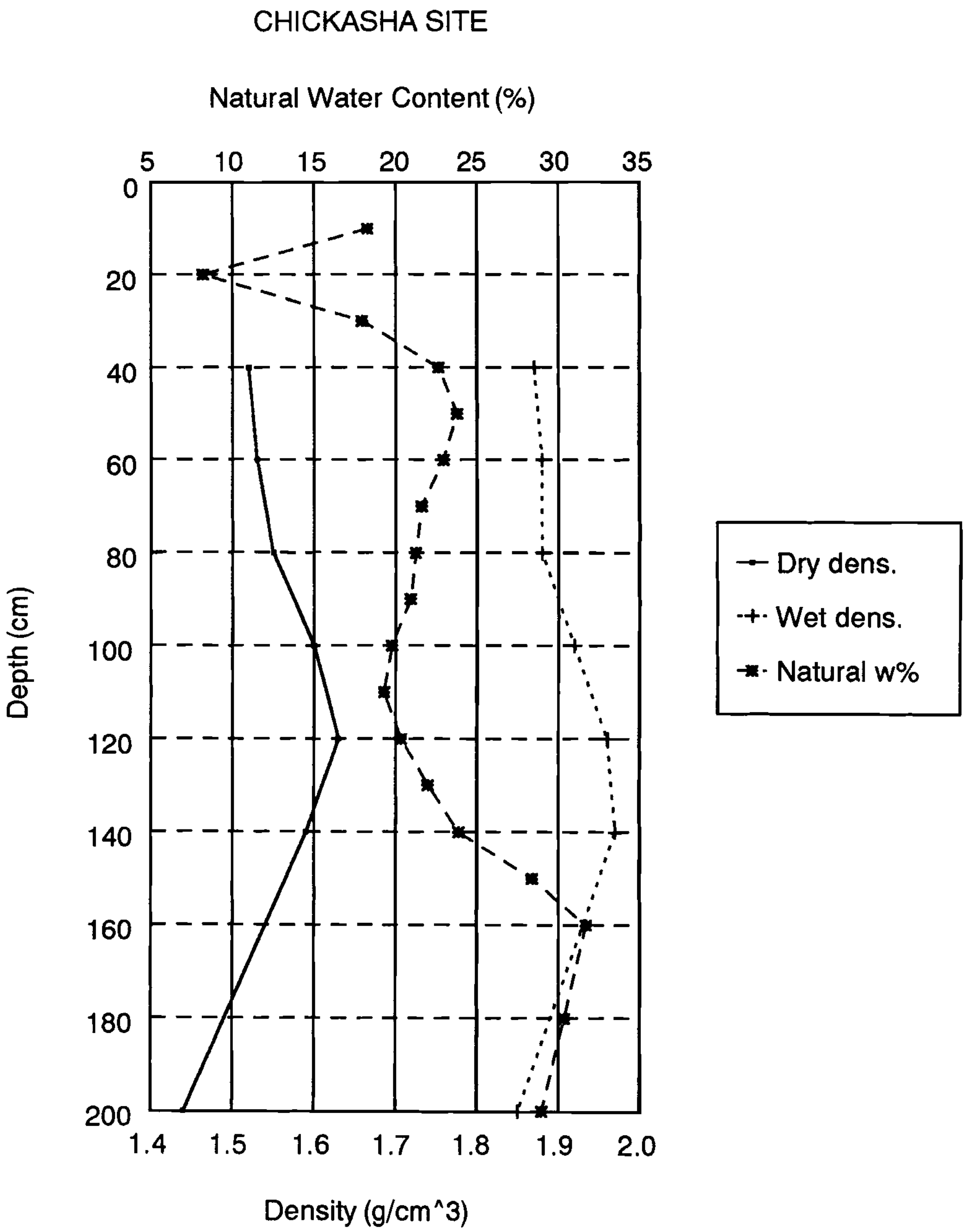


Figure 16. Plot of Wet Density, Dry Density, and Natural Water Content for Chickasha Test Site

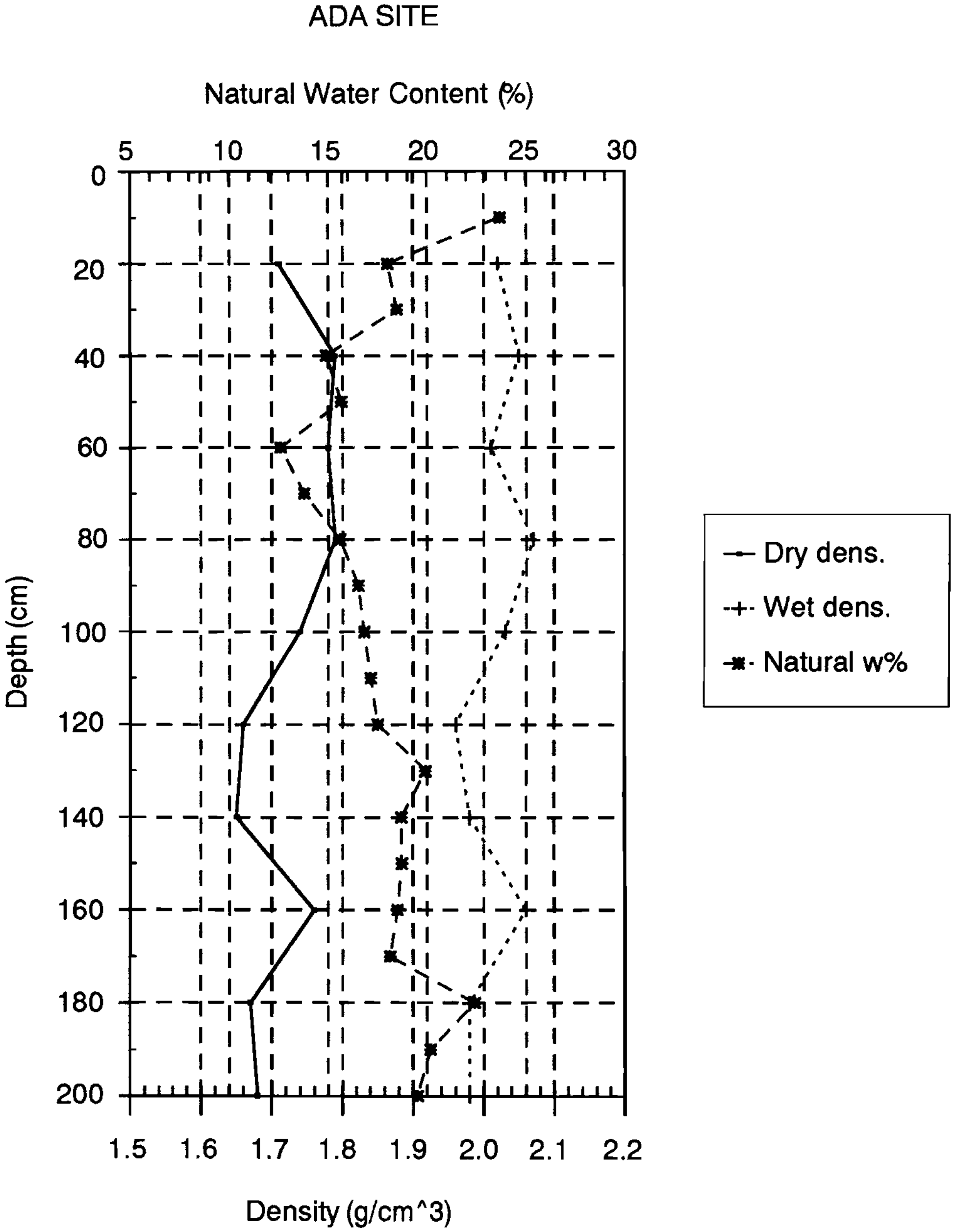


Figure 17. Plot of Wet Density, Dry Density, and Natural Water Content for Ada Test Site

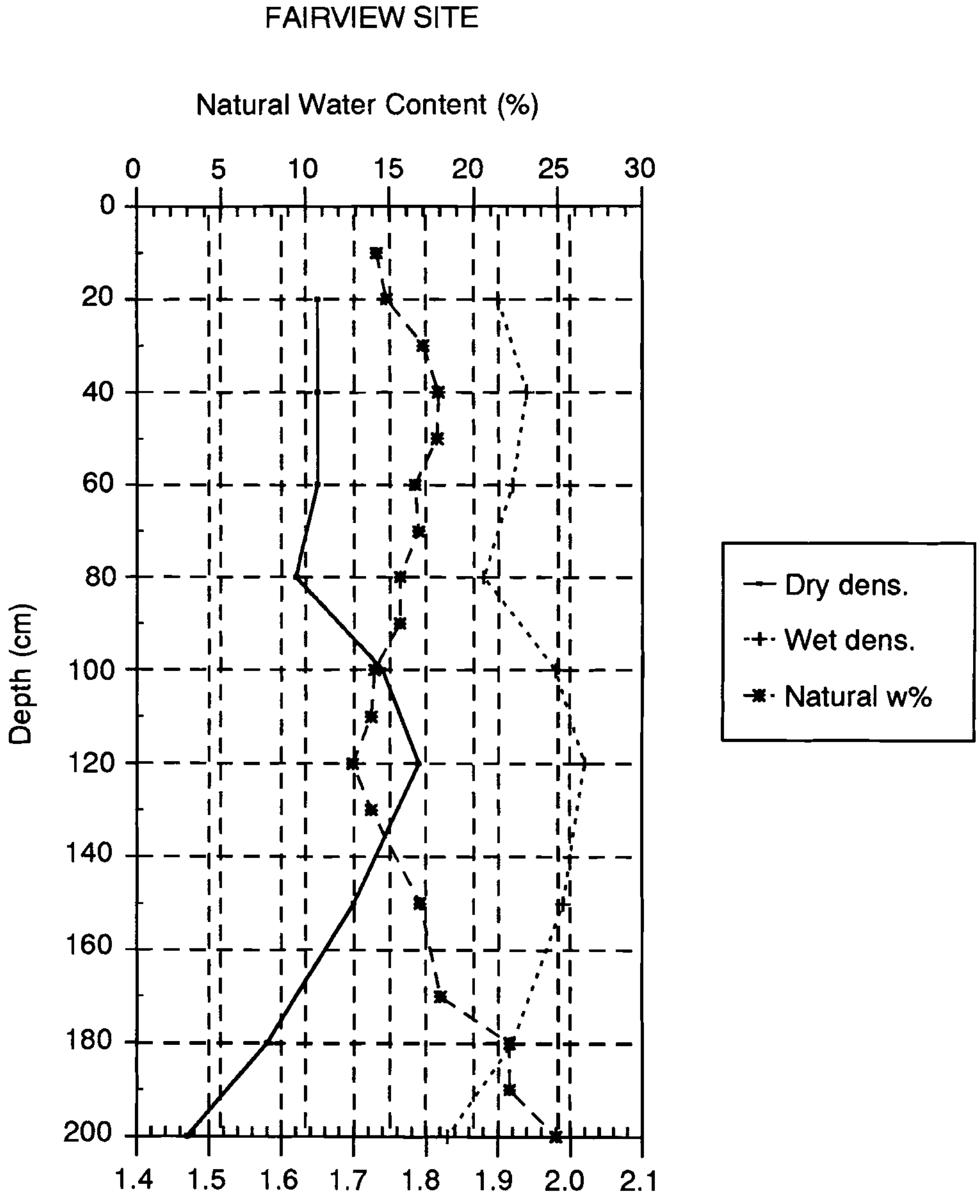


Figure 18. Plot of Wet Density, Dry Density, and Natural Water Content for Fairview Test Site

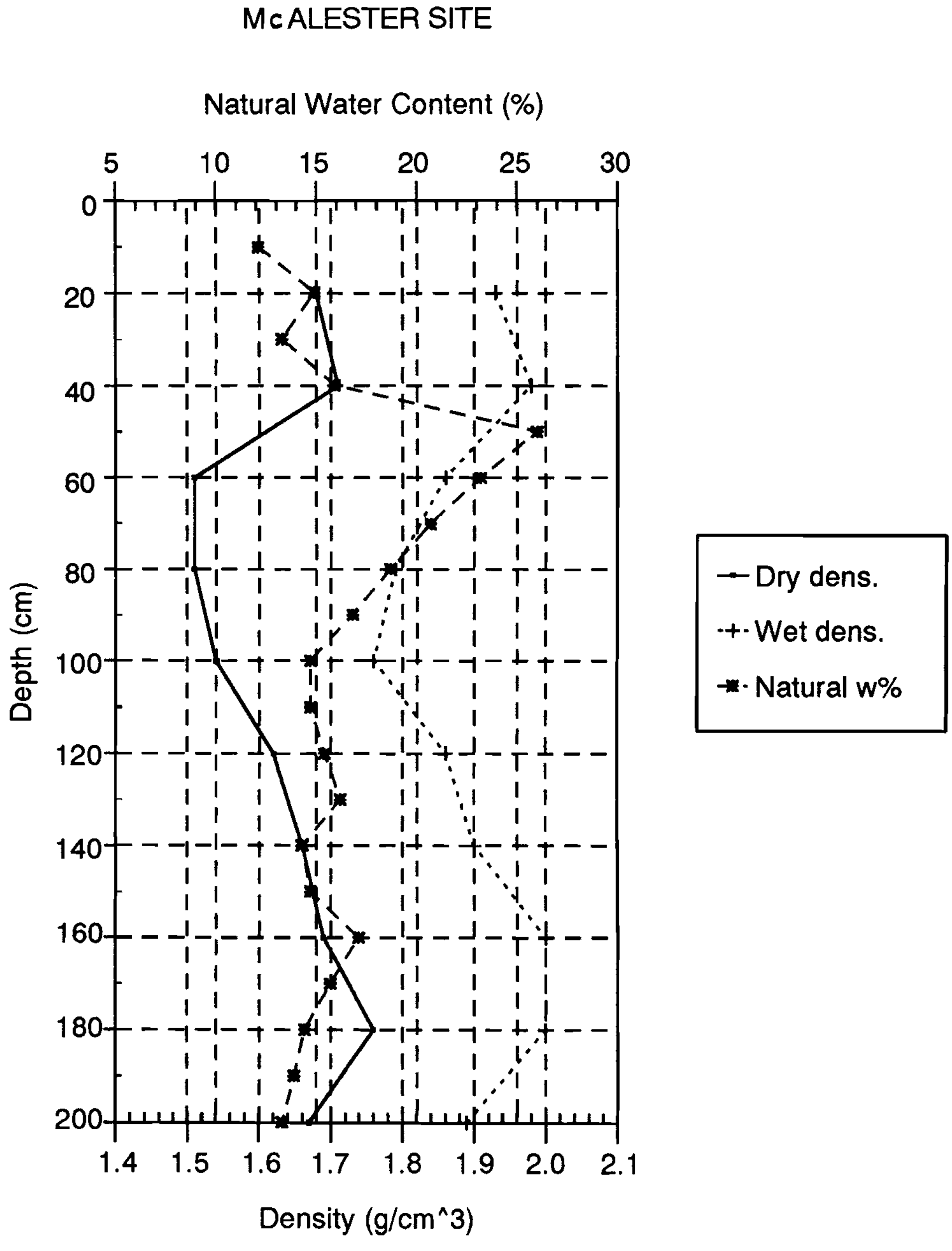


Figure 19. Plot of Wet Density, Dry Density, and Natural Water Content for McAlester Test Site

APPENDIX E

NATURAL SOIL SUCTION AND MOISTURE CONTENT FROM UNDISTURBED SAMPLES

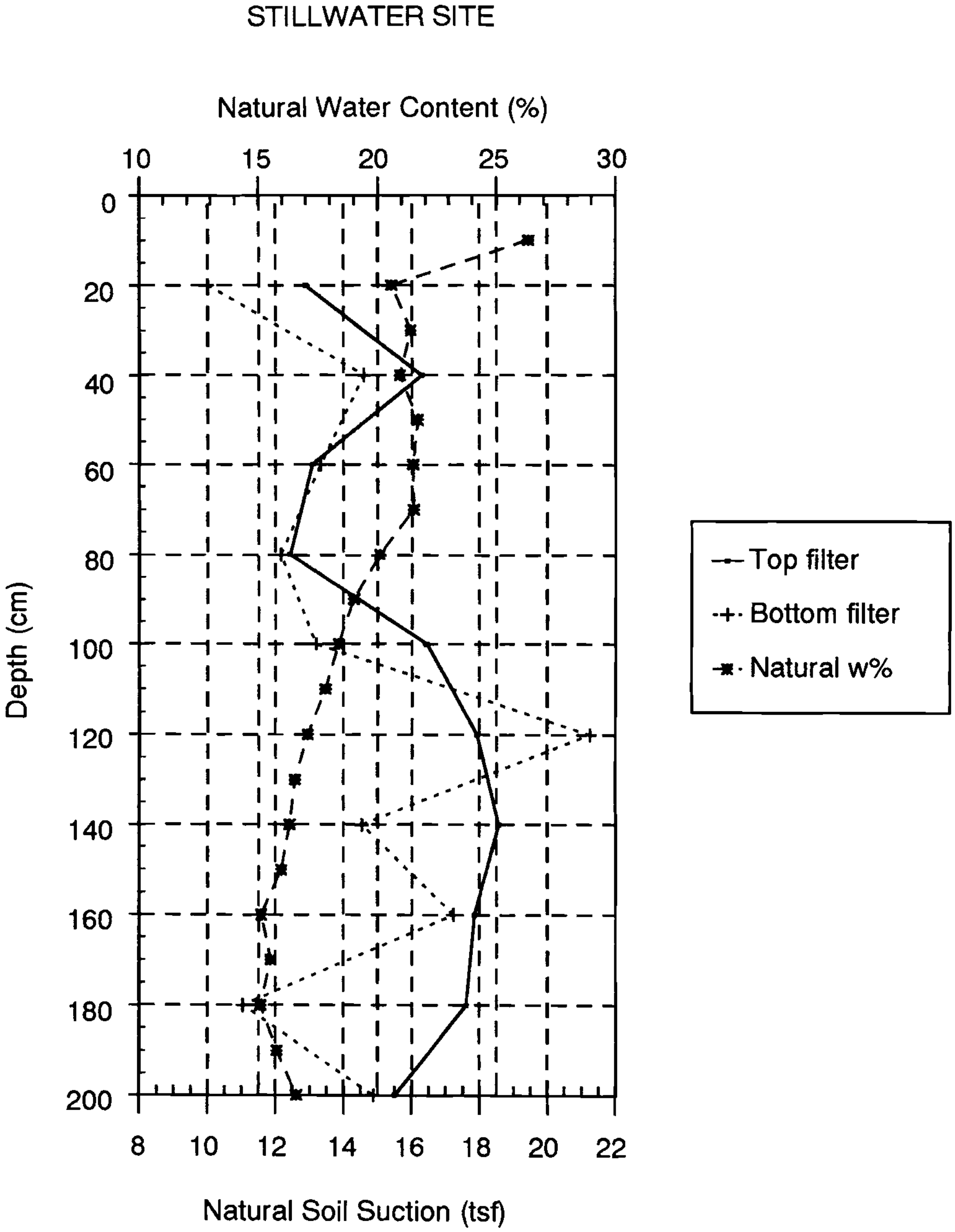


Figure 20. Plot of Natural Soil Suction and Water Content for Stillwater Test Site

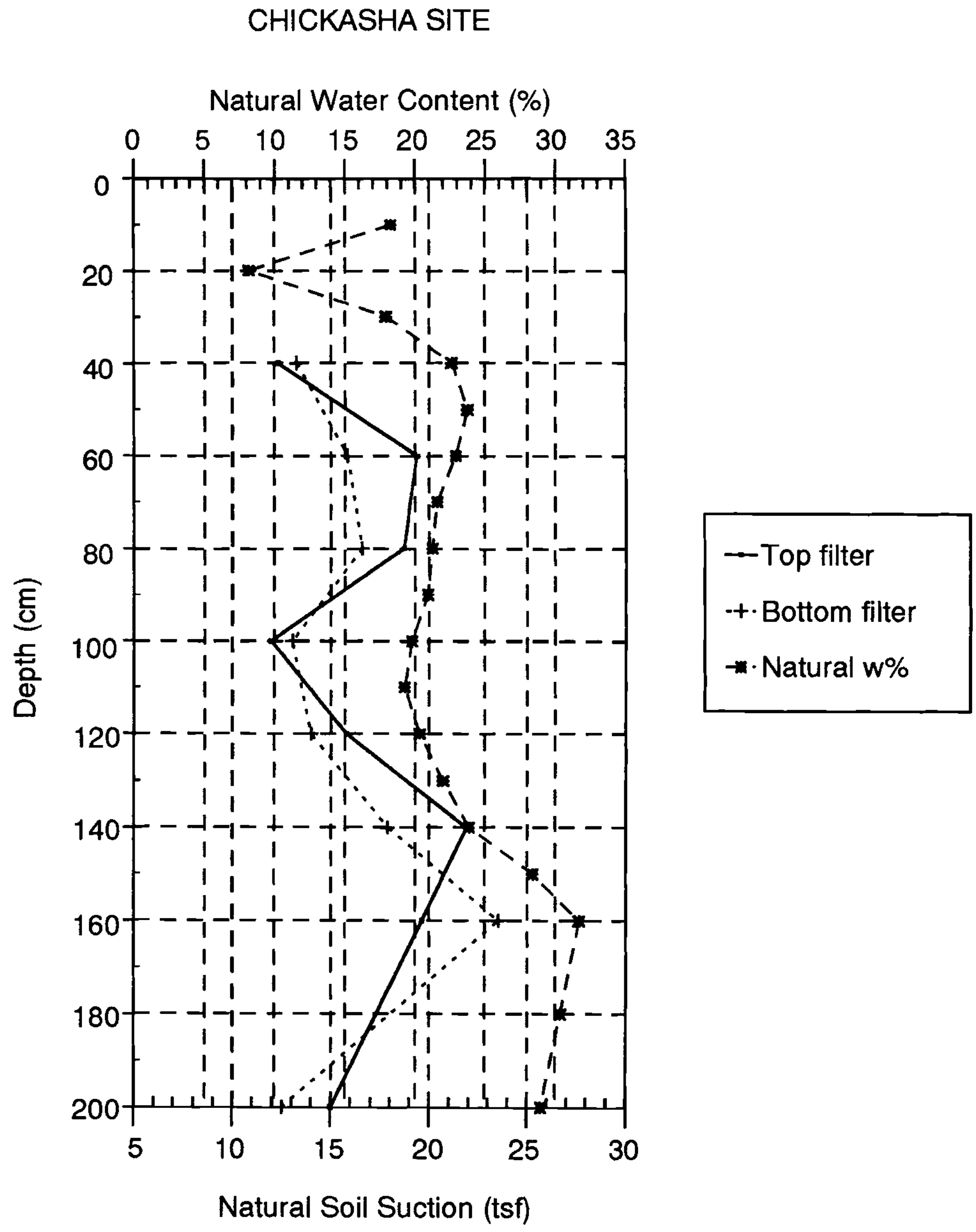


Figure 21. Plot of Natural Soil Suction and Water Content for Chickasha Test Site

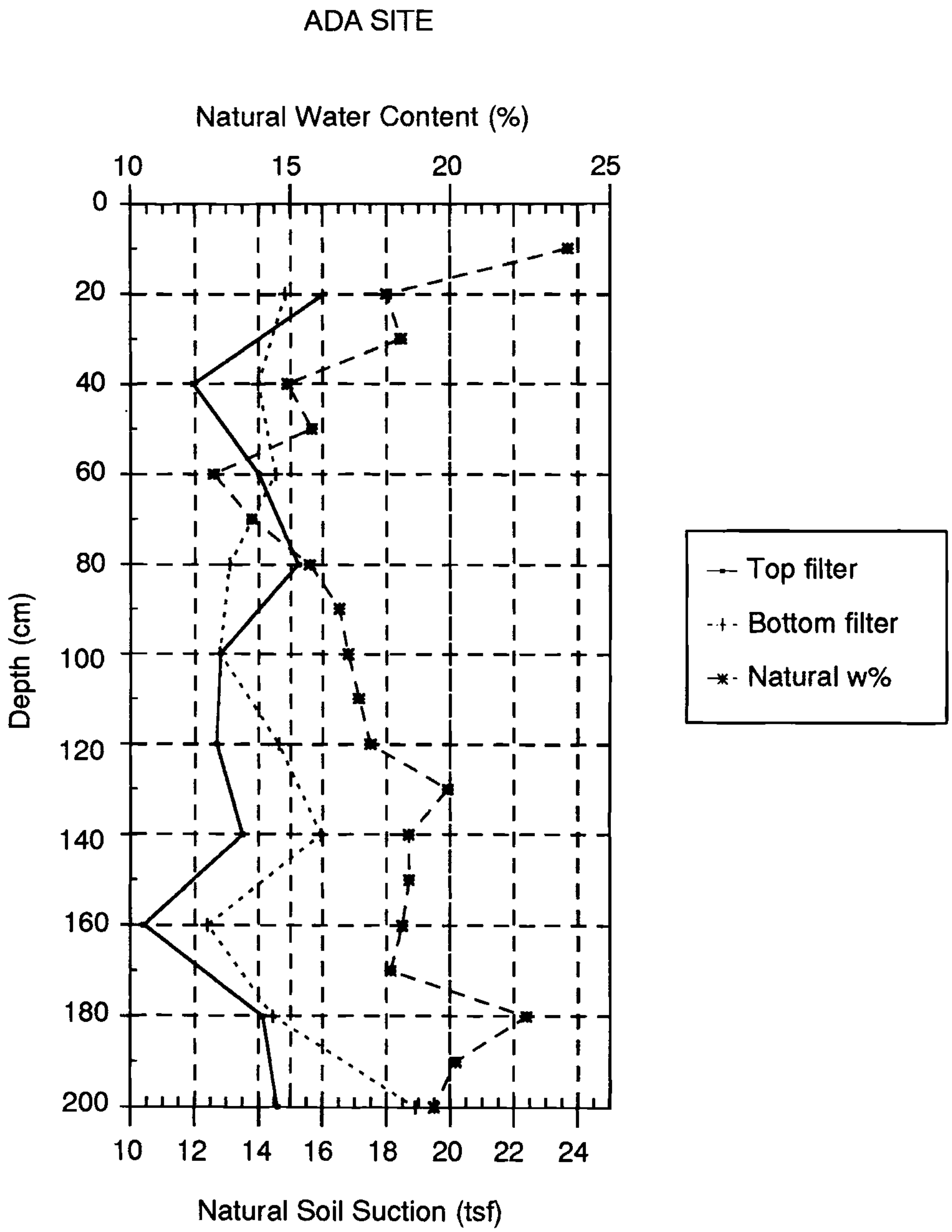


Figure 22. Plotof Natural Soil Suction and Water Content for Ada Test Site

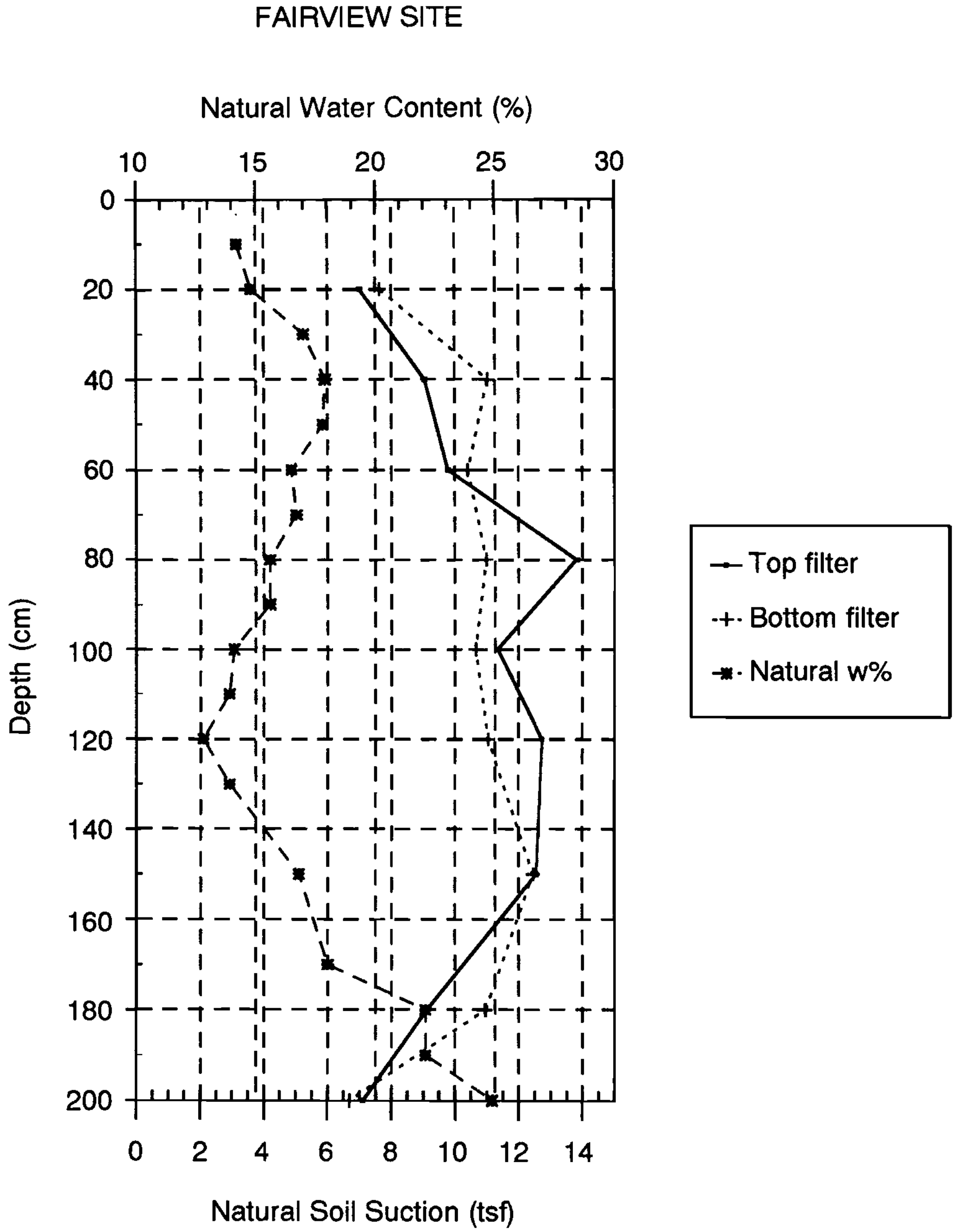


Figure 23. Plot Of Natural Soil Suctionand Water Content for Fairview Test Site

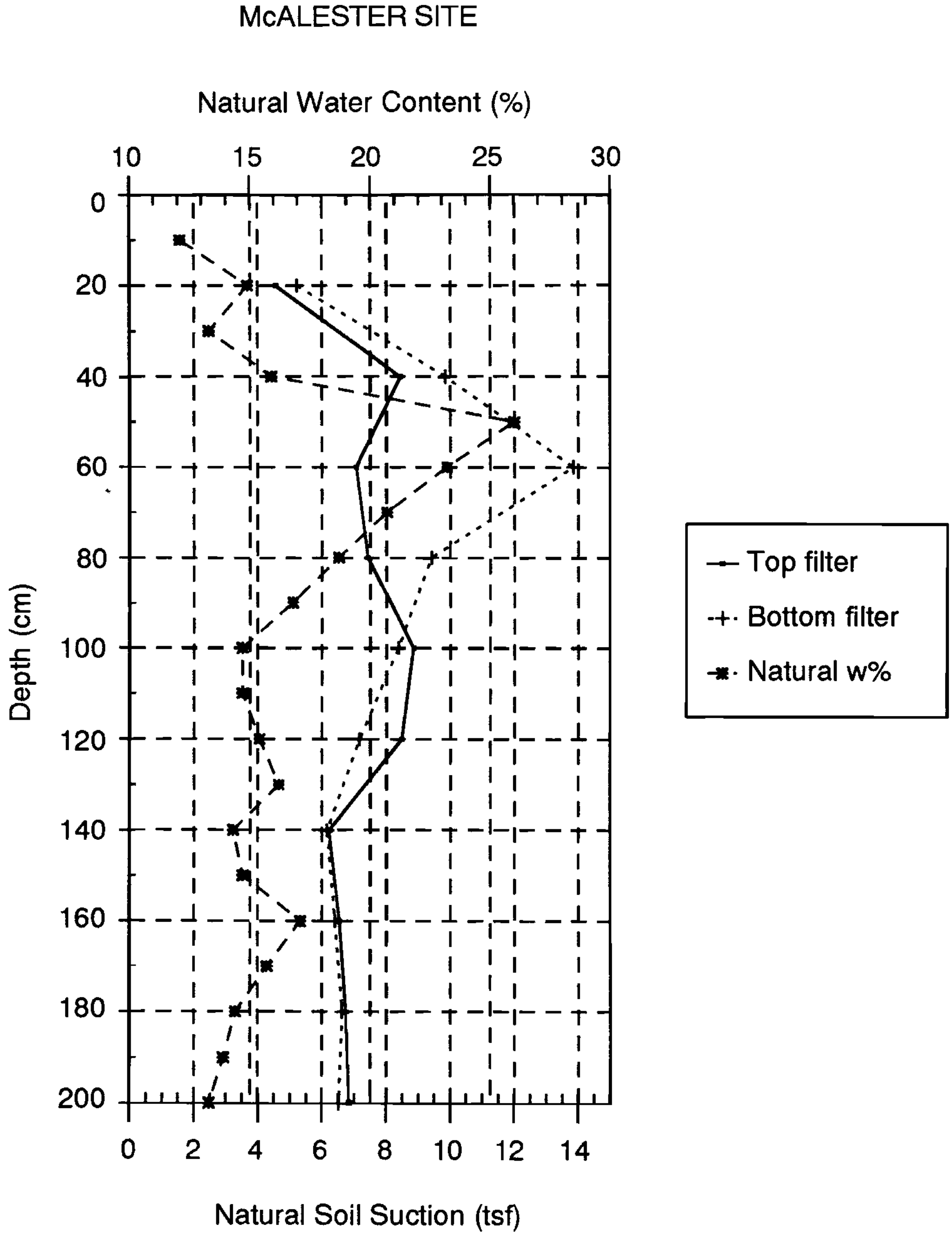


Figure 24. Plotof Natural Soil Suction and Water Content for McAlester Test Site

APPENDIX F

ATTERBERG LIMITS AND NATURAL MOISTURE CONTENT FROM DISTURBED SAMPLES

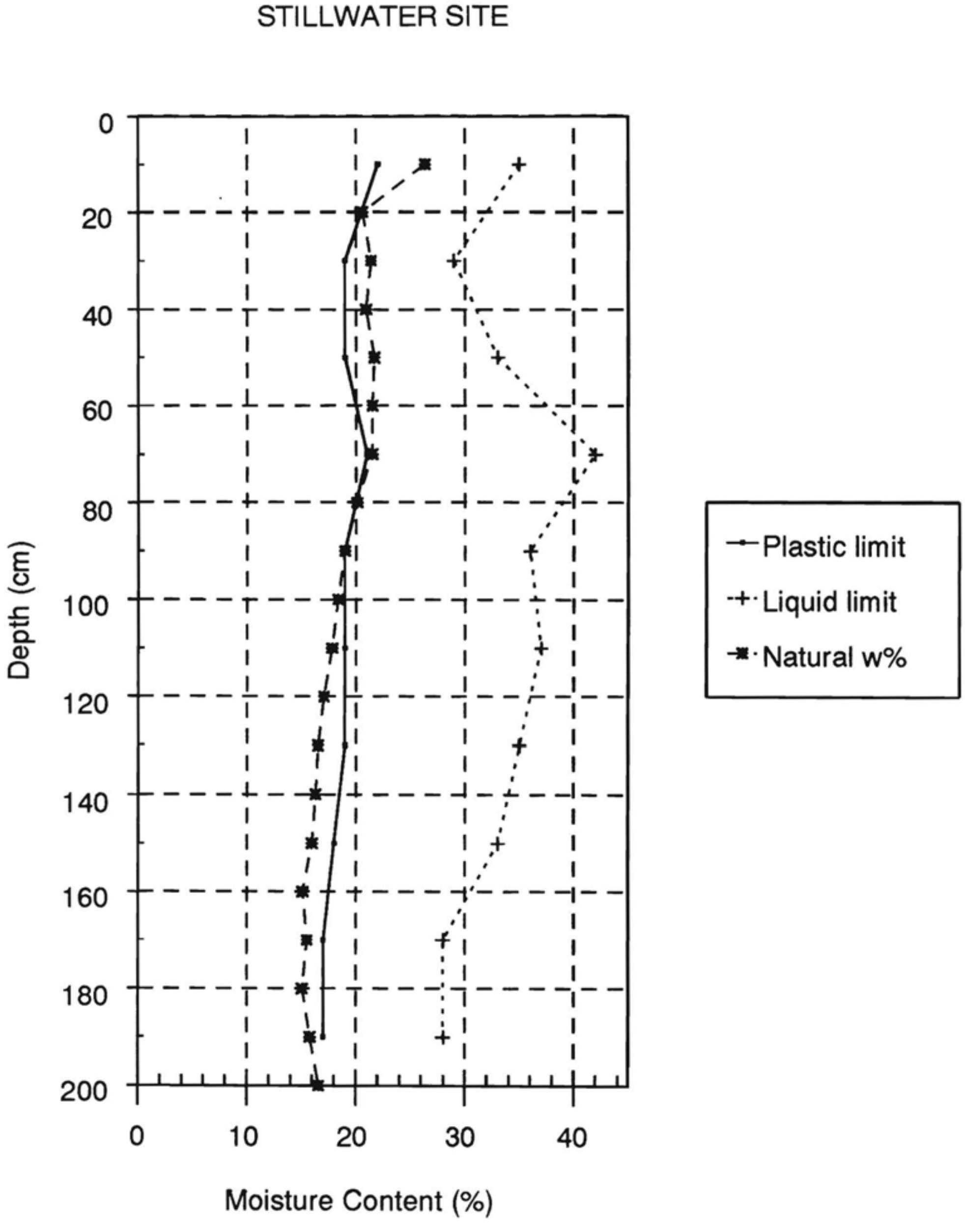


Figure 25. Plot of Atterberg Limits and Natural Moisture Content for Stillwater Test Site

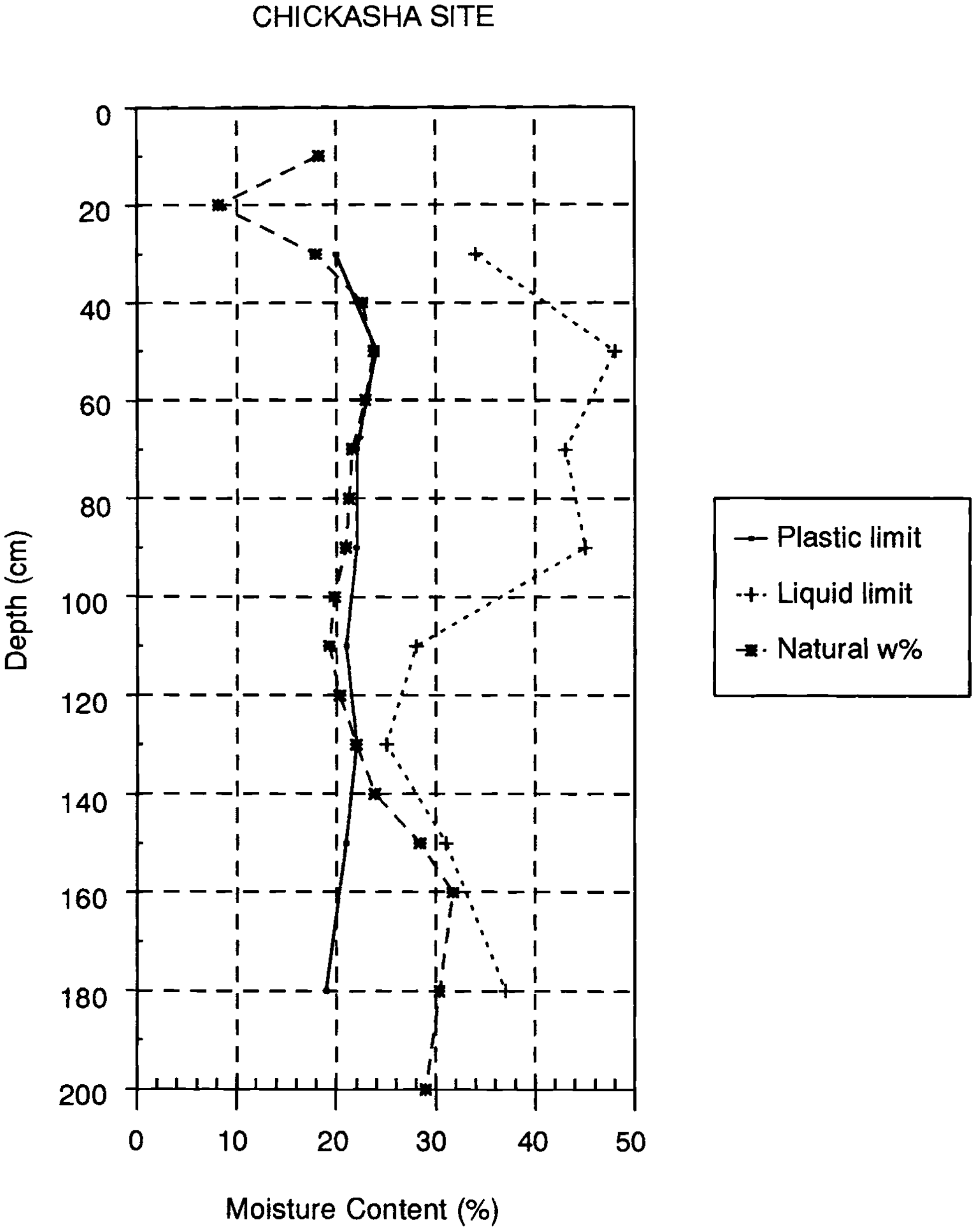


Figure 26. Plot of Atterberg Limits and Natural Moisture Content for Chickasha Test Site

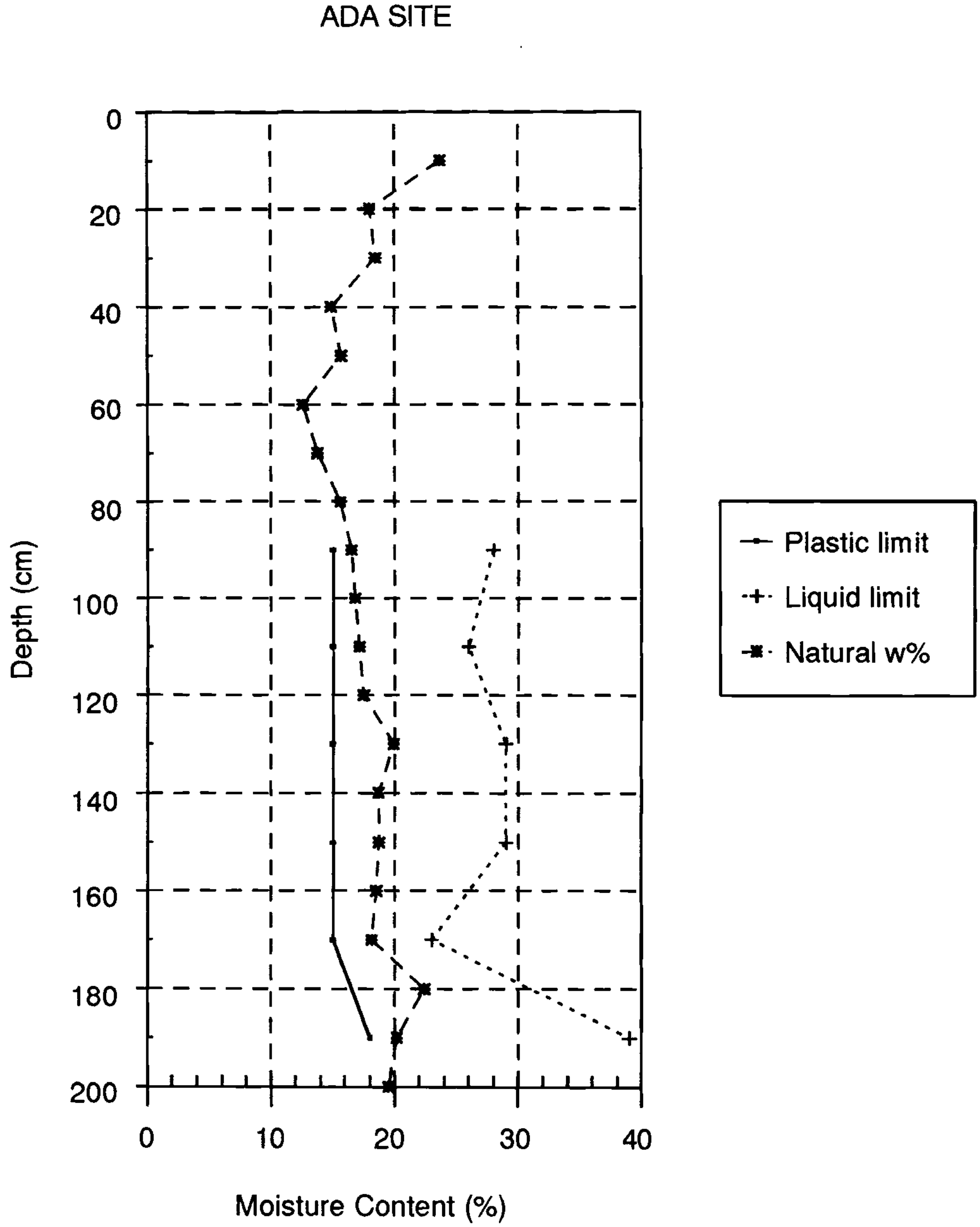


Figure 27. Plot of Atterberg Limits and Natural Moisture Content for Ada Test Site

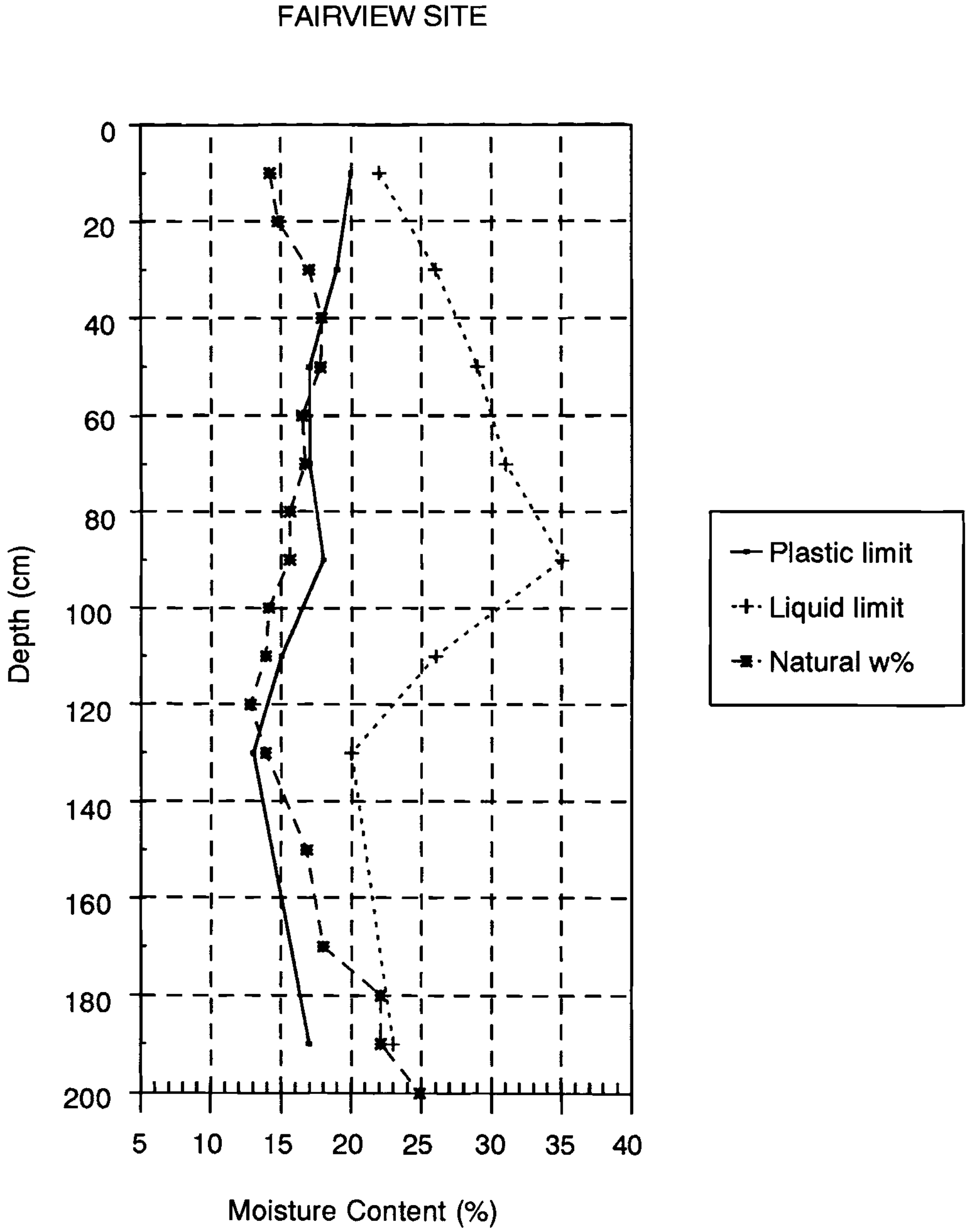


Figure 28. Plot of Atterberg Limits and Natural Moisture Content for Fairview Test Site

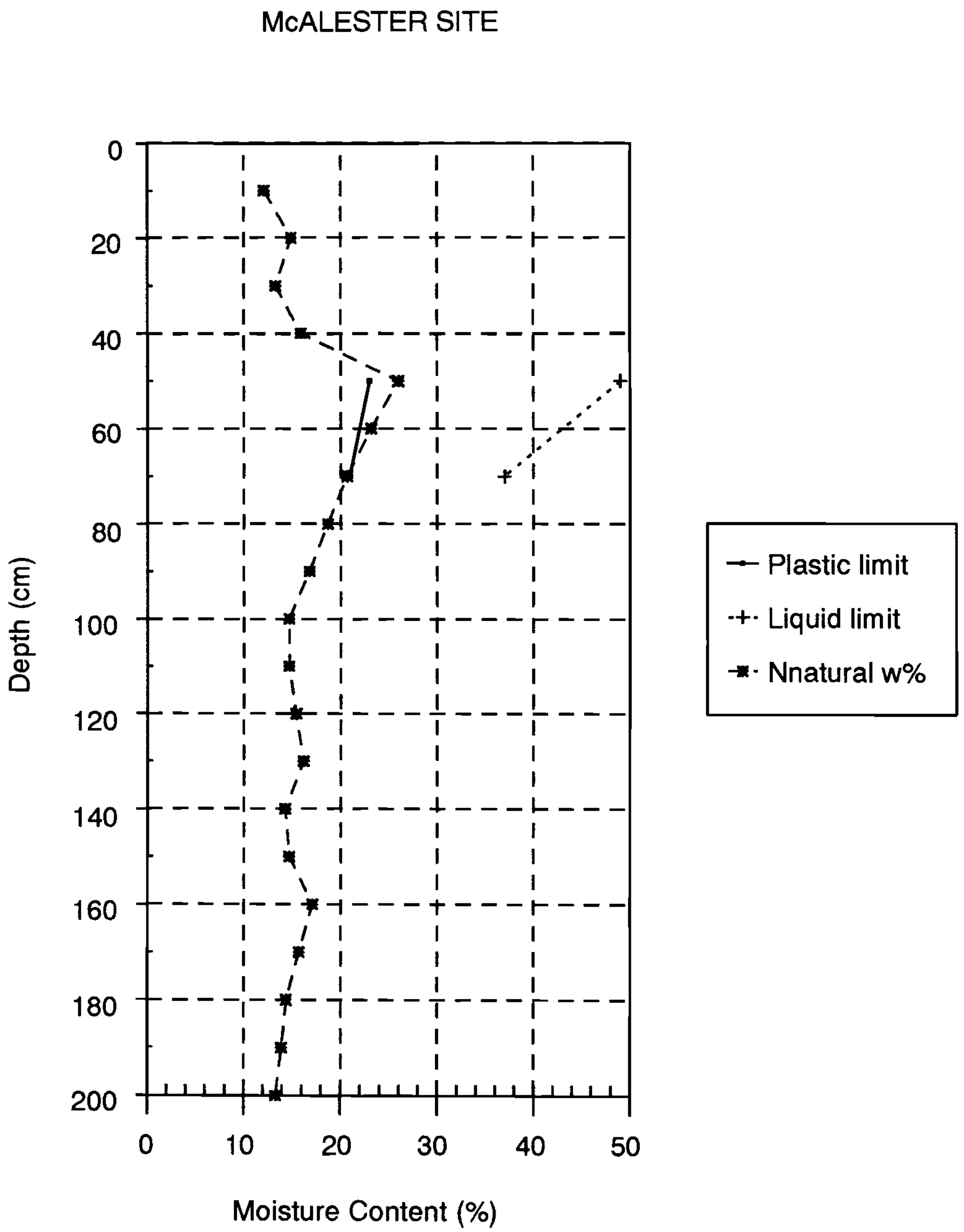


Figure 29. Plot of Atterberg Limits and Natural Moisture Content for McAlester Test Site

APPENDIX G

MOLDING CONDITIONS FOR LABORATORY TESTING PROGRAM

TABLE 27

MOLDING CONDITIONS FOR LABORATORY TESTING PROGRAM, STILLWATER SITE

	Water Content (%)	Dry Density (pcf)	Wet Density (pcf)
Layer 1 (5 to 60 cm)			
	18.6	98.1	116.3
	19.6	98.1	117.3
	20.6	98.1	118.3
	21.6	98.1	119.3
	22.6	98.1	120.3
Layer 2 (60 to 140 cm)			
	16.0	102.2	118.6
	17.0	102.2	119.6
	18.0	102.2	120.6
	19.0	102.2	121.6
	20.0	102.2	122.6
Layer 3 (140 to 200 cm)			
	13.2	108.1	122.4
	14.2	108.1	123.5
	15.2	108.1	124.5
	16.2	108.1	125.6
	17.2	108.1	126.7

TABLE 28

MOLDING CONDITIONS FOR LABORATORY TESTING PROGRAM, CHICKASHA SITE

	Water Content (%)	Dry Density (pcf)	Wet Density (pcf)
Layer 1 (0 to 40 cm)			
	17.3	97.9	114.8
	18.3	97.9	115.8
	19.3	97.9	116.8
	20.3	97.9	117.8
	21.3	97.9	118.8
Layer 2 (40 to 100 cm)			
	19.2	98.5	117.4
	20.2	98.5	118.4
	21.2	98.5	119.4
	22.2	98.5	120.4
	23.2	98.5	121.4
Layer 3 (100 to 200 cm)			
	20.0	91.9	110.3
	21.0	91.9	111.2
	22.0	91.9	112.1
	23.0	91.9	113.0
	24.0	91.9	114.0

TABLE 29

MOLDING CONDITIONS FOR LABORATORY TESTING PROGRAM, ADA SITE

	Water Content (%)	Dry Density (pcf)	Wet Density (pcf)
Layer 1 (0 to 80 cm)			
	14.2	110.1	125.7
	15.2	110.1	126.8
	16.2	110.1	127.9
	17.2	110.1	129.0
	18.2	110.1	130.1
Layer 2 (80 to 200 cm)			
	16.3	105.7	122.9
	17.3	105.7	124.0
	18.3	105.7	125.0
	19.3	105.7	126.1
	20.3	105.7	127.2

TABLE 30

MOLDING CONDITIONS FOR LABORATORY TESTING PROGRAM, FAIRVIEW SITE

	Water Content (%)	Dry Density (pcf)	Wet Density (pcf)
Layer 1 (0 to 60 cm)			
	14.4	102.8	117.6
	15.4	102.8	118.6
	16.4	102.8	119.7
	17.4	102.8	120.7
	18.4	102.8	121.7
Layer 2 (60 to 120 cm)			
	12.6	108.2	121.8
	13.6	108.2	122.9
	14.6	108.2	124.0
	15.6	108.2	125.1
	16.6	108.2	126.2
Layer 3 (120 to 200 cm)			
	9.0	100.6	109.7
	10.0	100.6	110.7
	11.0	100.6	111.7
	12.0	100.6	112.7
	13.0	100.6	113.7

TABLE 31

MOLDING CONDITIONS FOR LABORATORY TESTING PROGRAM, MCALESTER SITE

	Water Content (%)	Dry Density (pcf)	Wet Density (pcf)
Layer 1 (0 to 80 cm)			
	13.1	99.2	112.2
	14.1	99.2	113.2
	15.1	99.2	114.2
	16.1	99.2	115.2
	17.1	99.2	116.2
Layer 2 (80 to 200 cm)			
	11.0	103.0	114.3
	12.0	103.0	115.4
	13.0	103.0	116.4
	14.0	103.0	117.4
	15.0	103.0	118.5

APPENDIX H

THERMAL RESISTIVITY VERSUS WATER CONTENT PLOTS

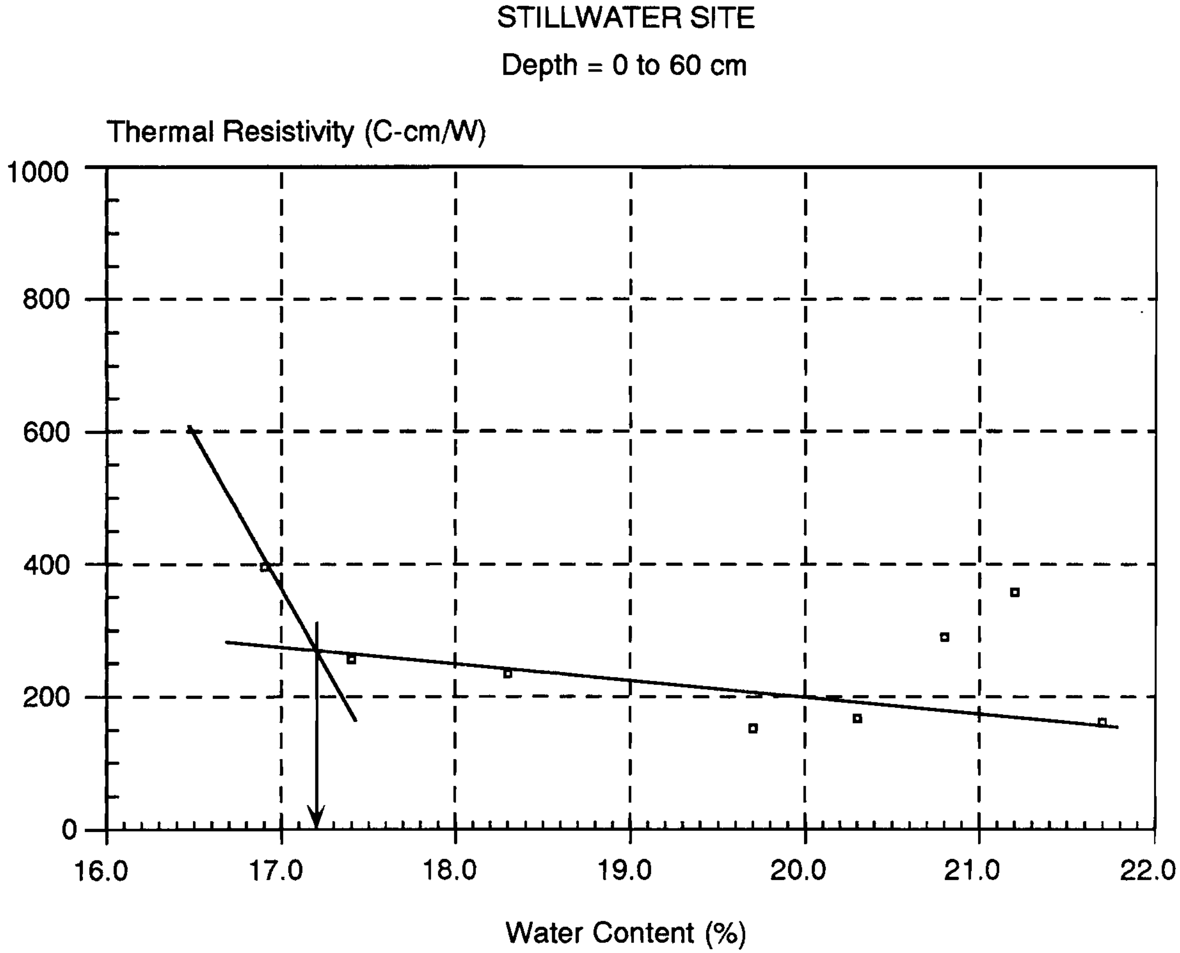


Figure 30. Lab Thermal Property Testing Results for Layer 1 at Stillwater Site

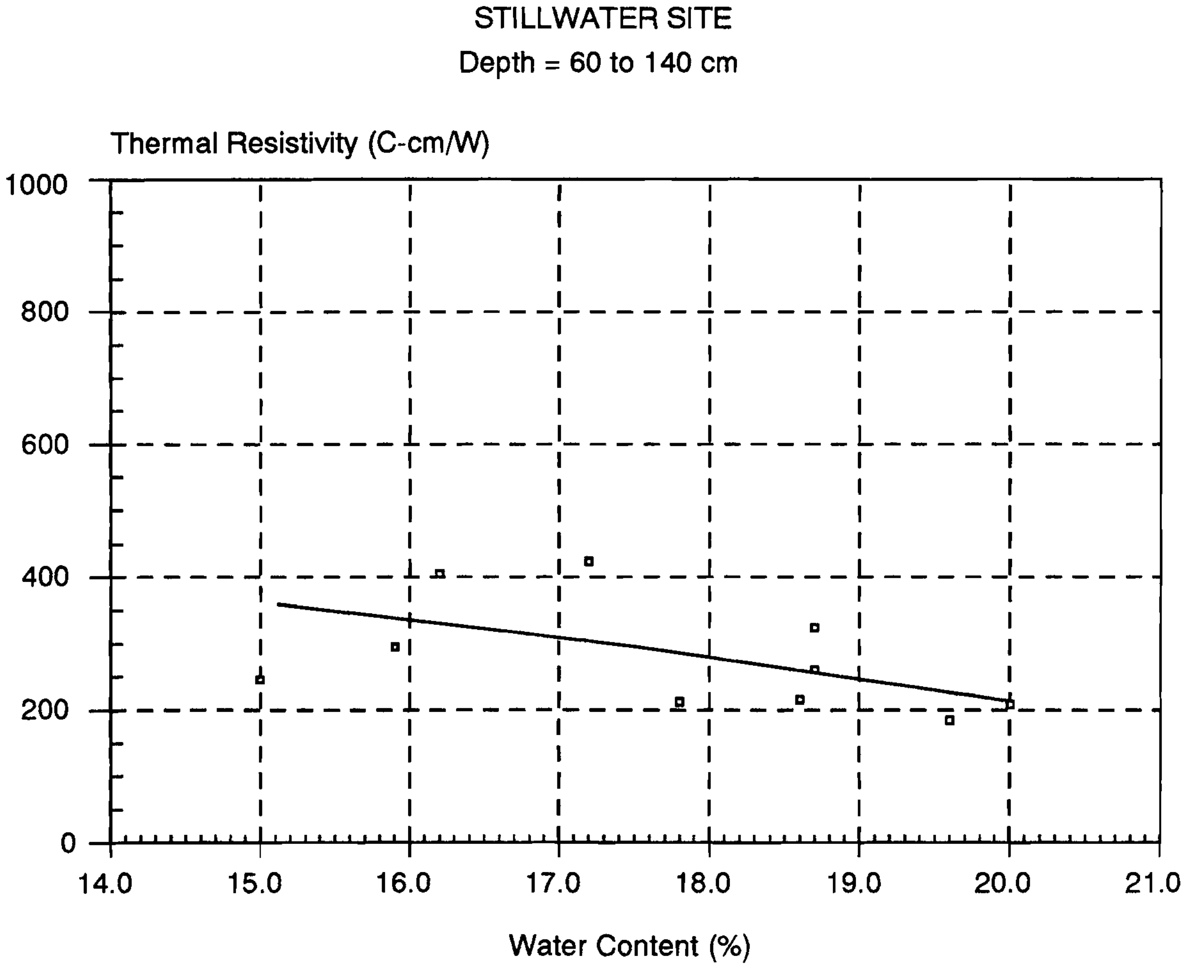


Figure 31. Lab Thermal Property Testing Results for Layer 2 at Stillwater Site

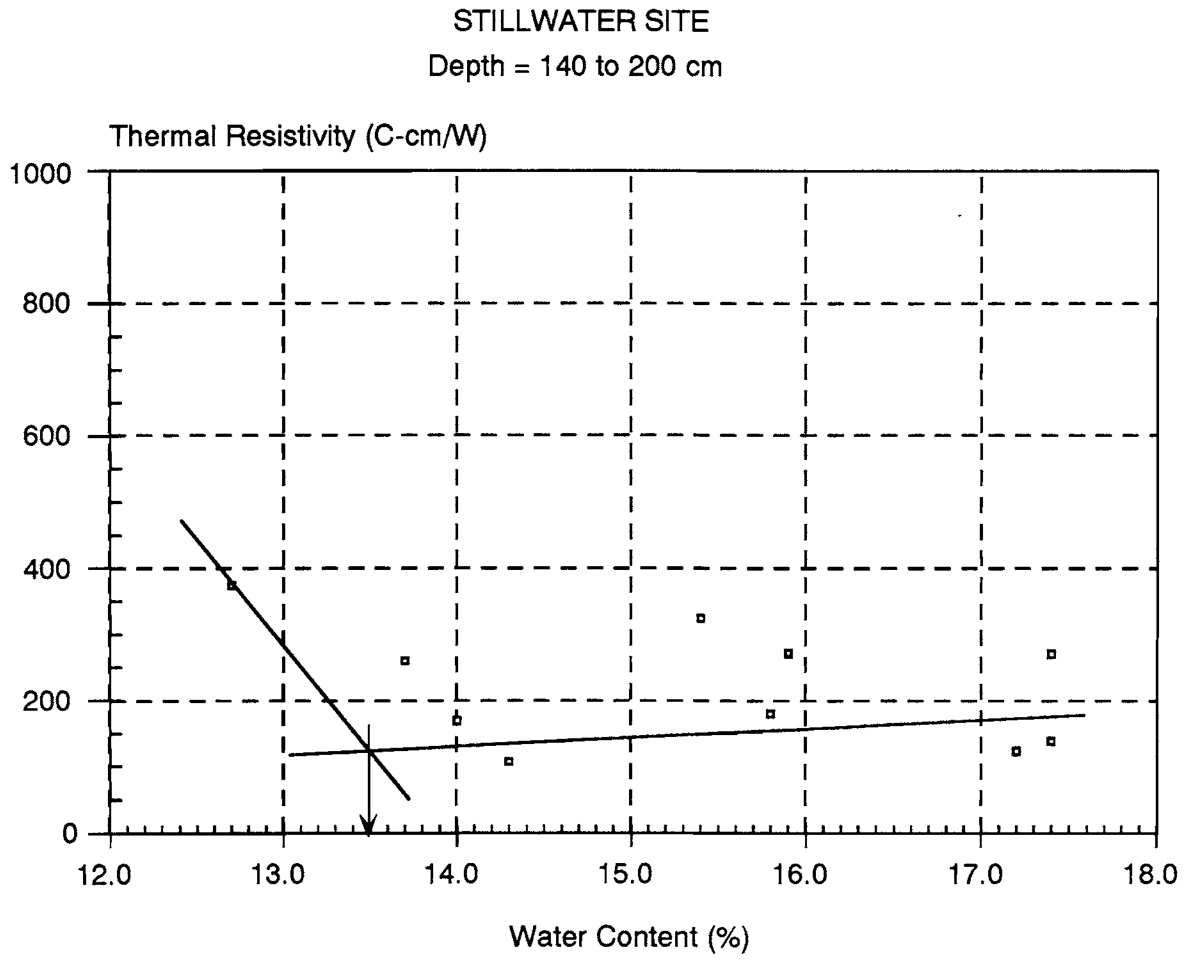


Figure 32. Lab Thermal Property Testing Results for Layer 3 at Stillwater Site

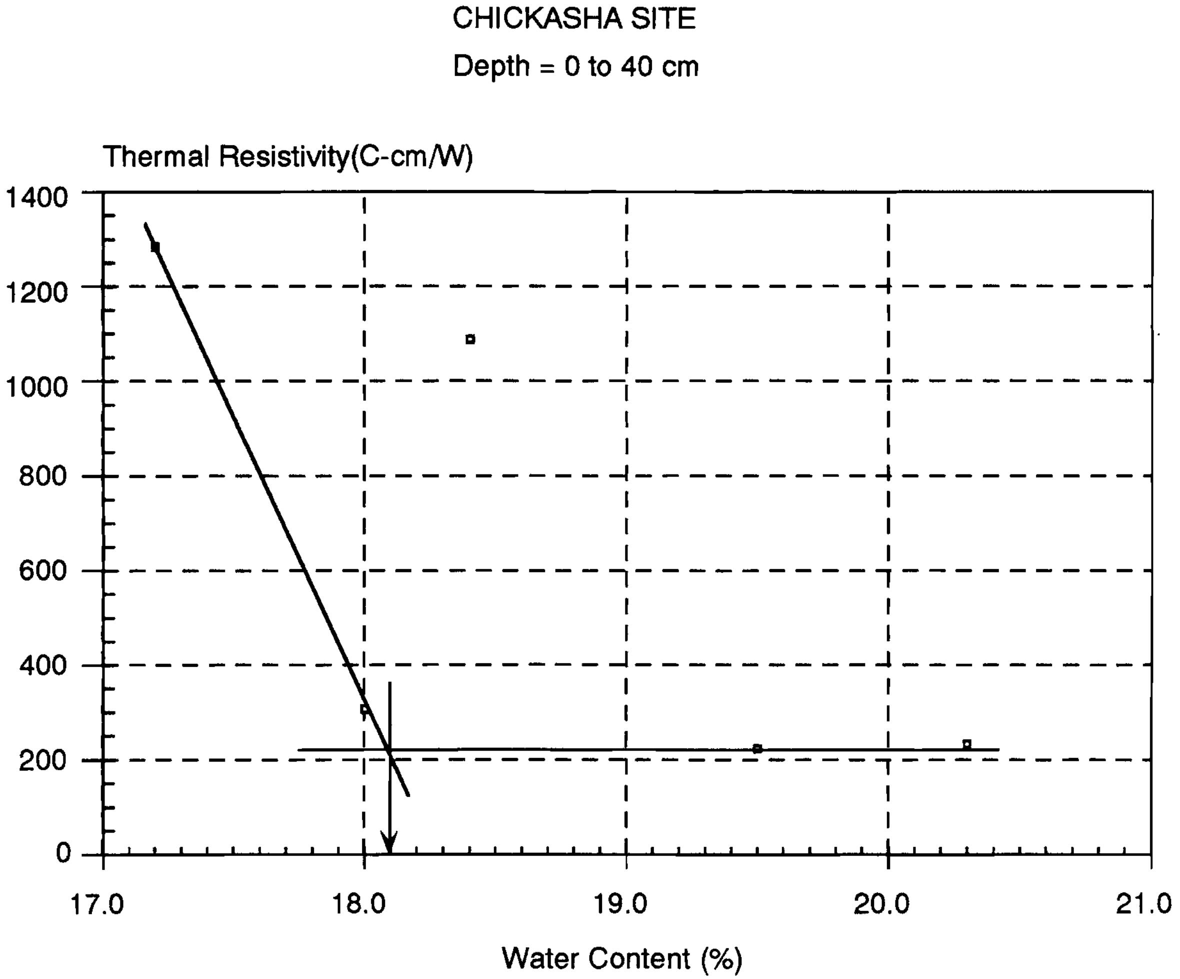


Figure 33. Lab Thermal Property Testing Results for Layer 1 at Chickasha Site

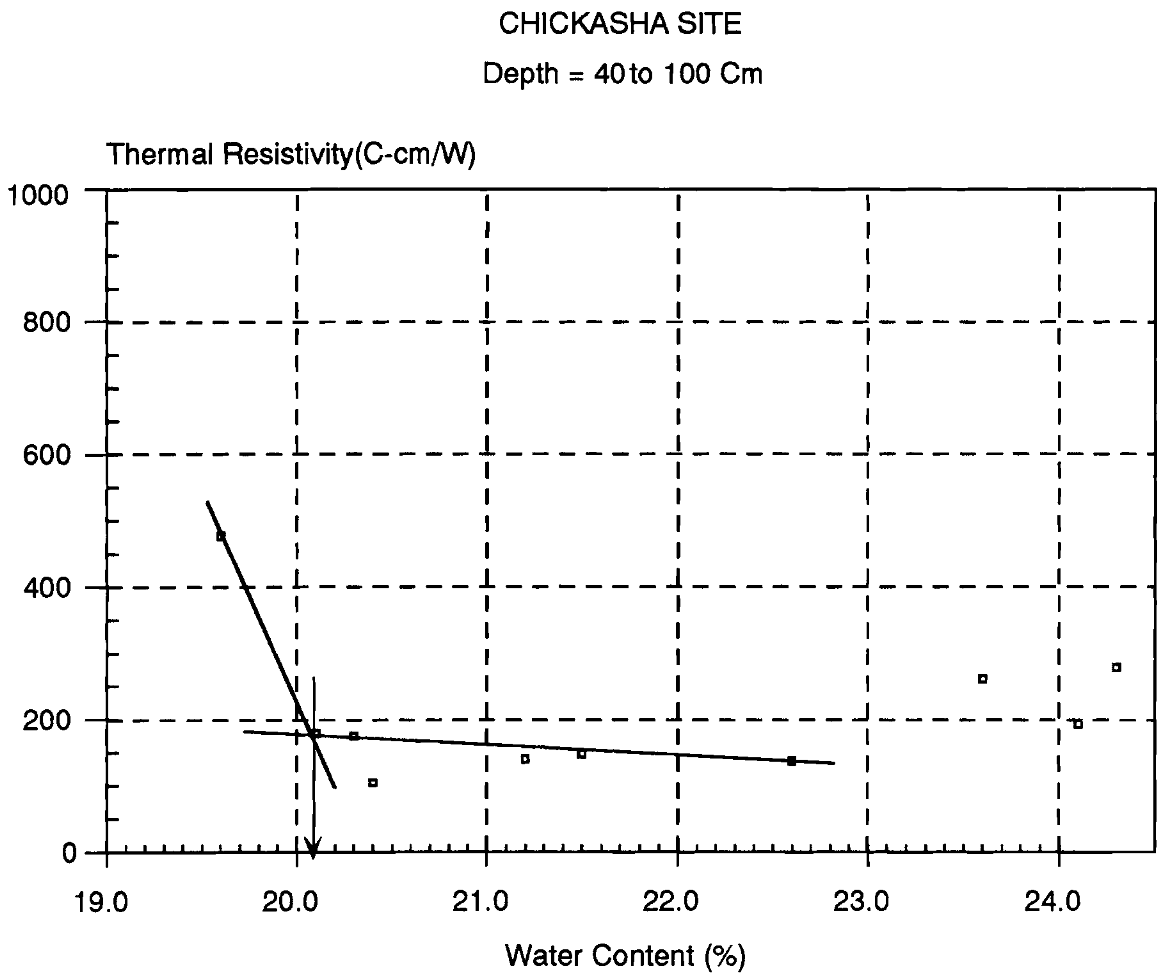
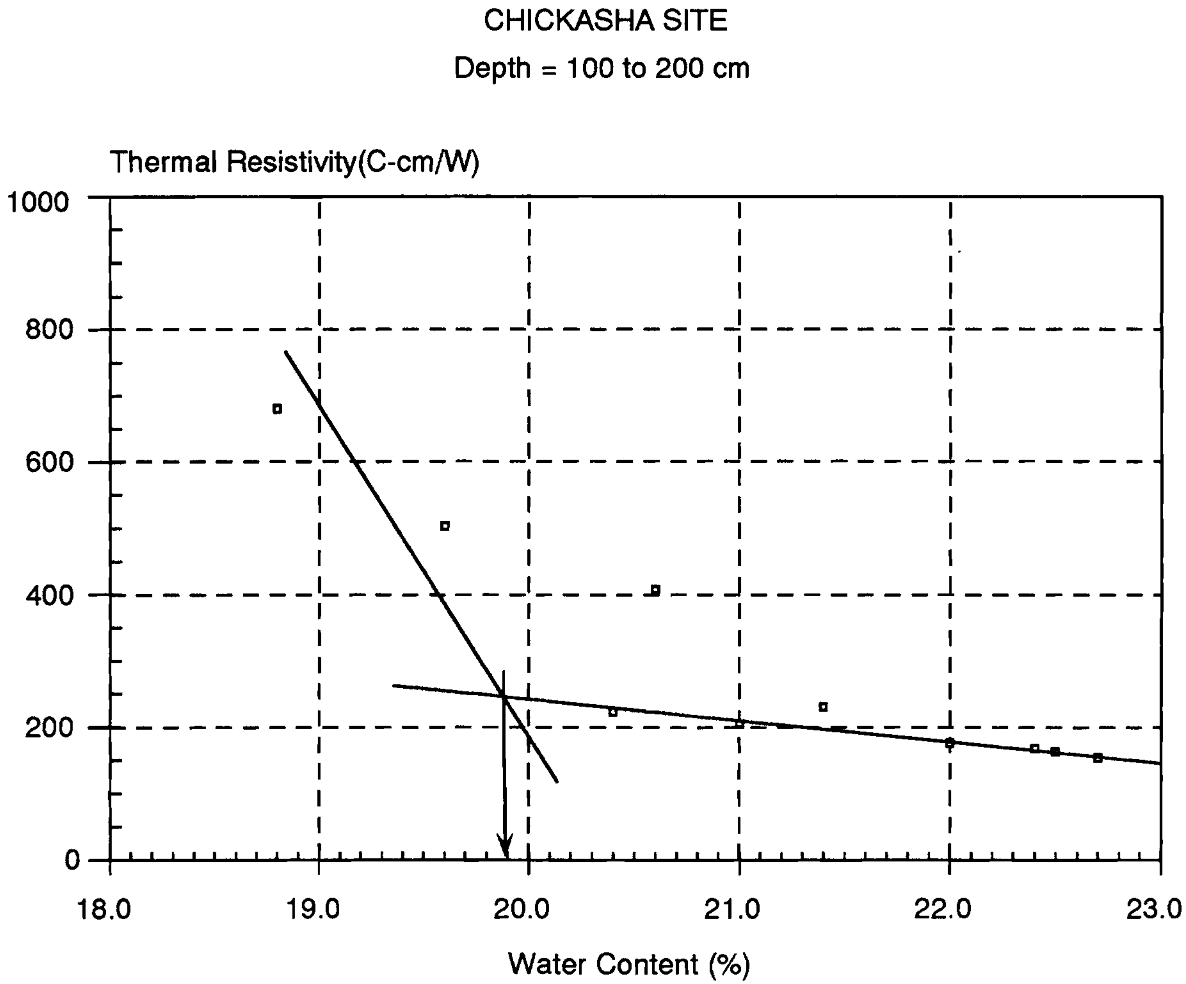


Figure 34. Lab Thermal Property Testing Results for Layer 3 at Chickasha Site



CHICKASHA SITE

Depth = 100 to 200 cm

Figure 35. Lab Thermal Property Testing Results for Layer 3 at Chickasha Site

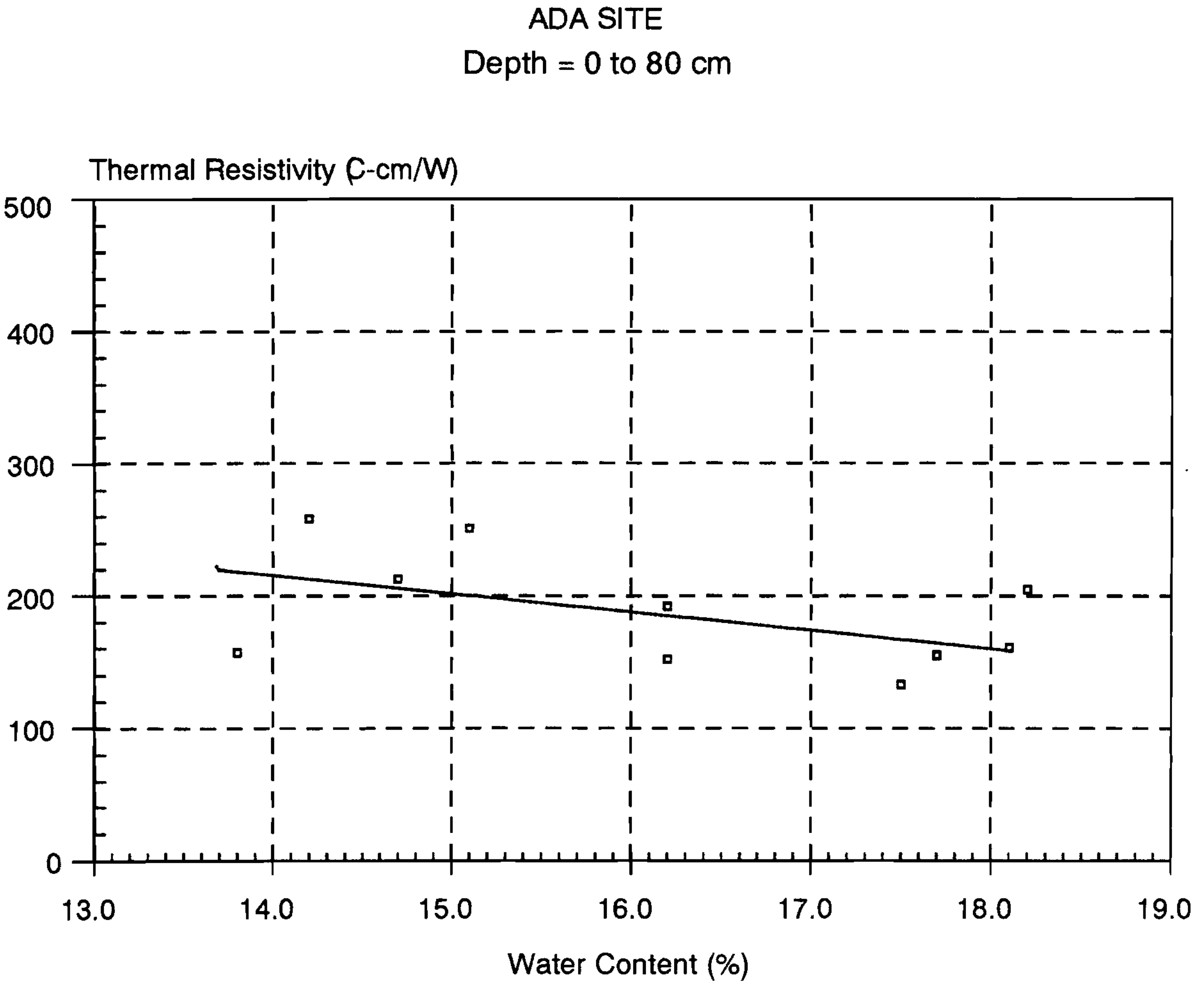


Figure 36. Lab Thermal Property Testing Results for Layer 1 at Ada Site

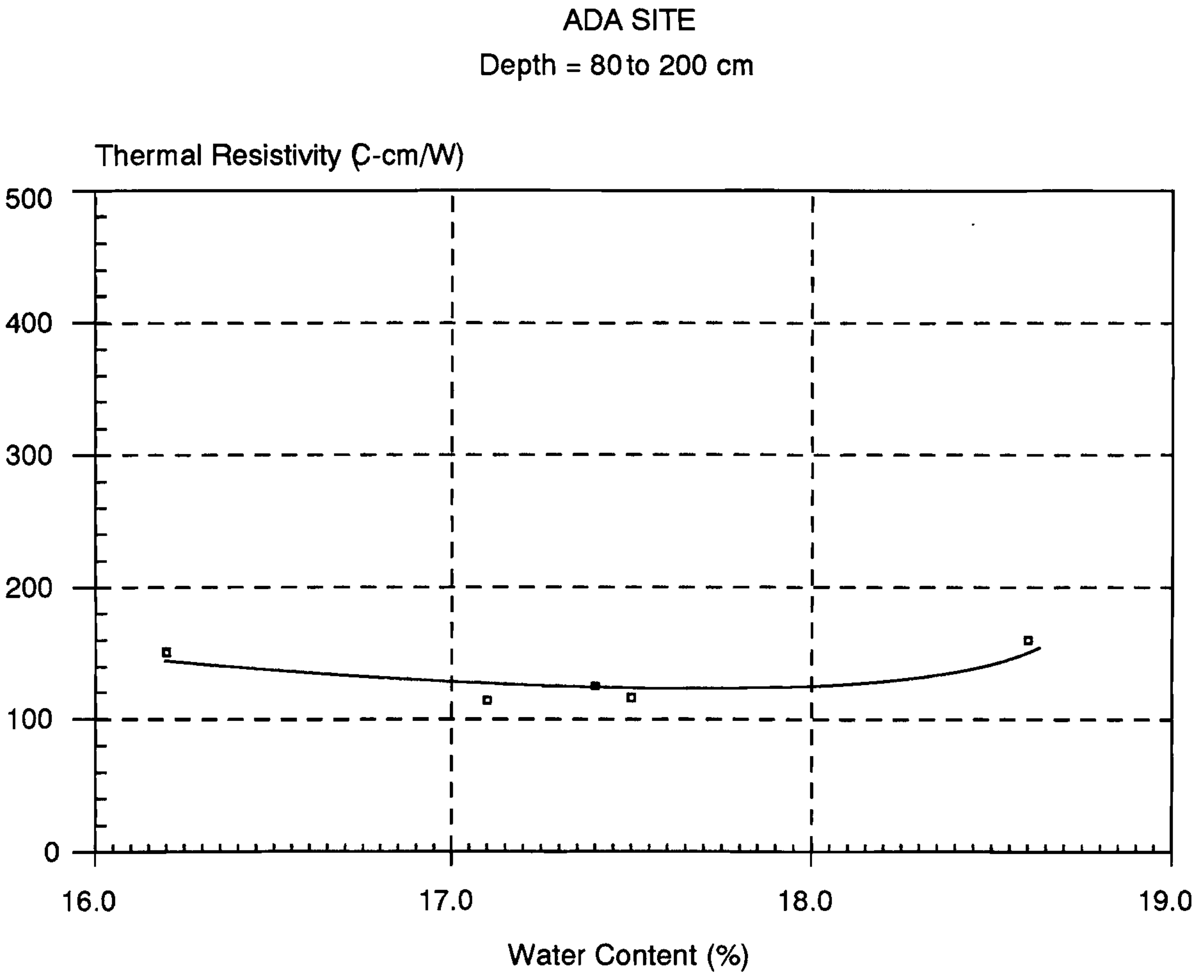


Figure 37. Lab Thermal Property Testing Results for Layer 2 at Ada Site

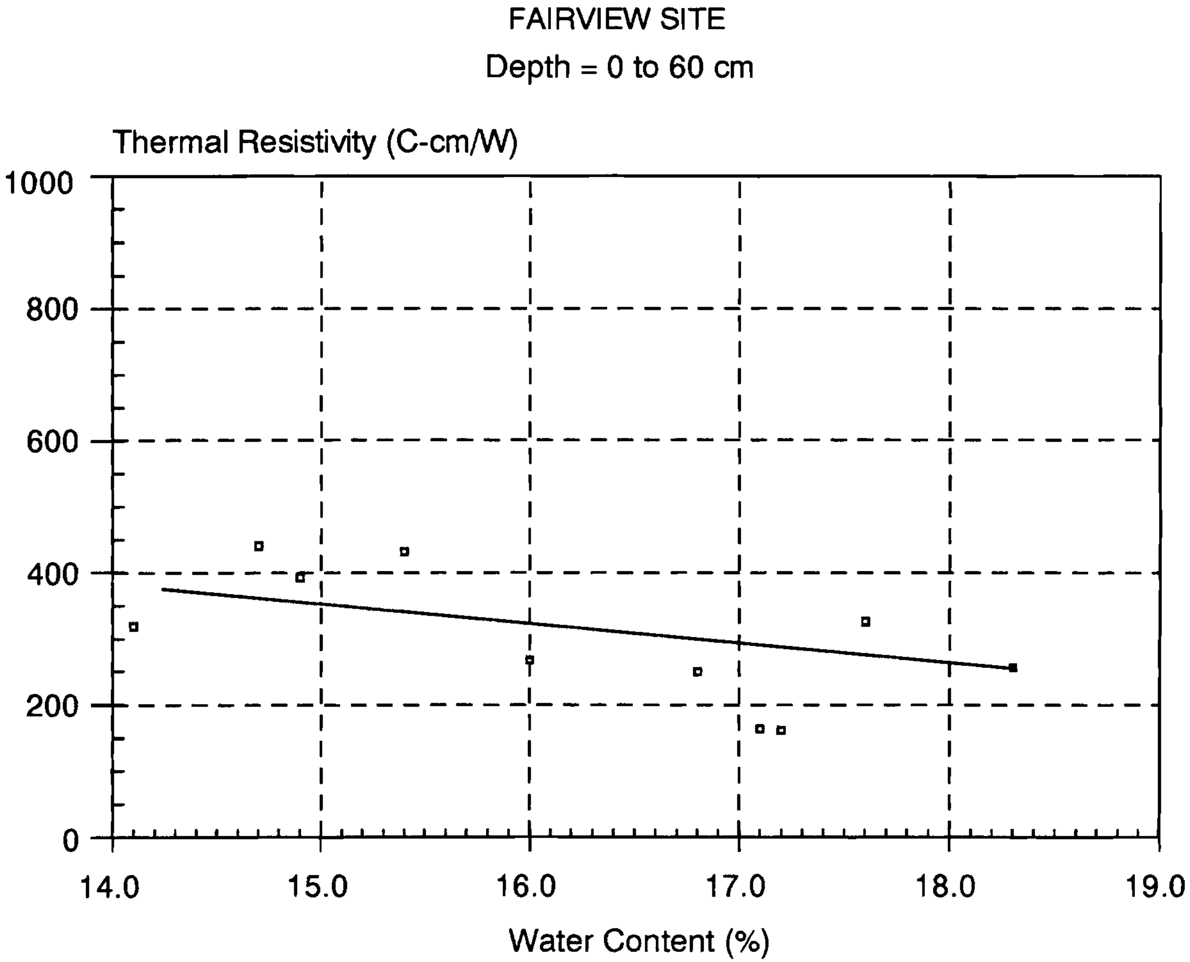


Figure 38. Lab Thermal Property Testing Results for Layer 1 at Fairview Site

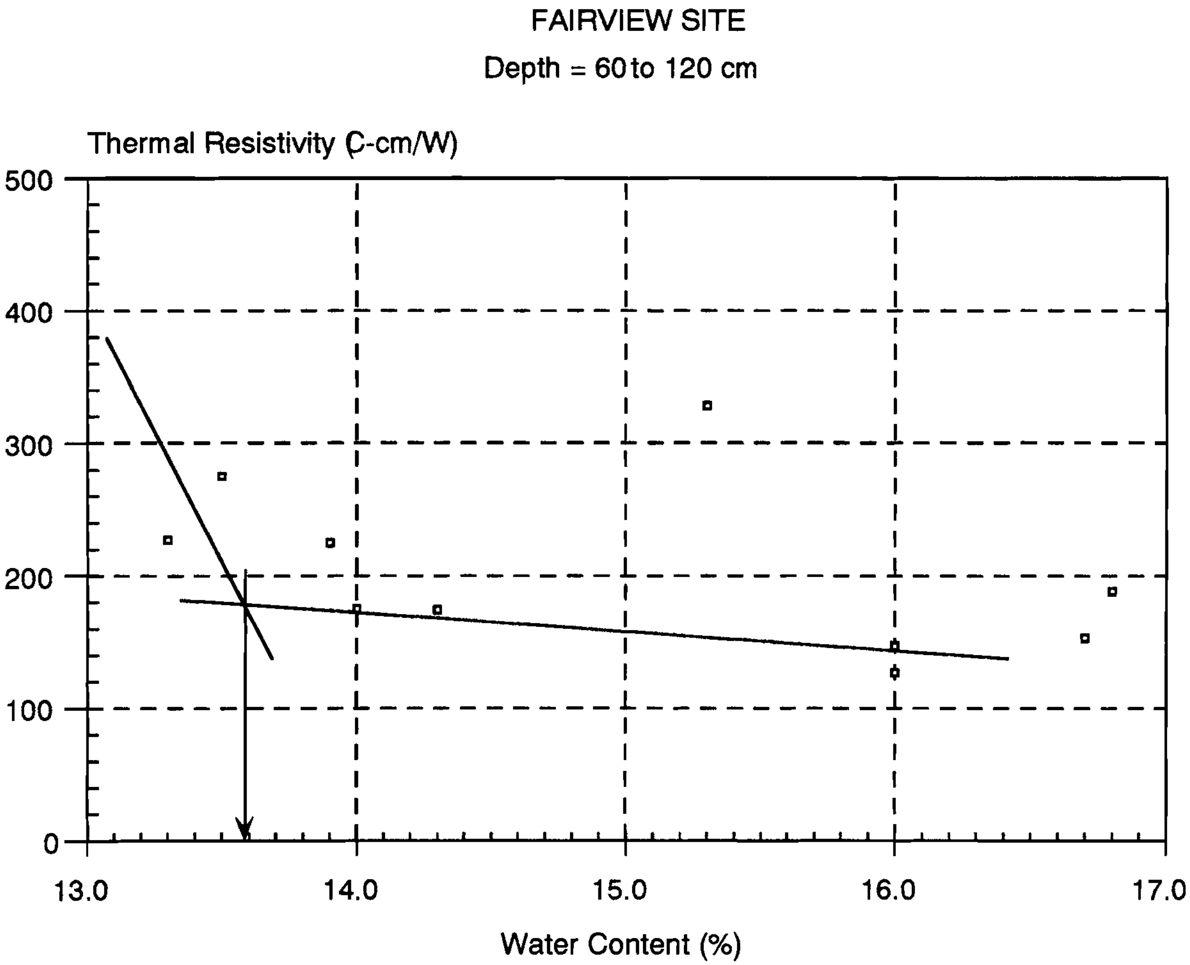


Figure 39. Lab Thermal Property Testing Results for Layer 2 at Fairview Site

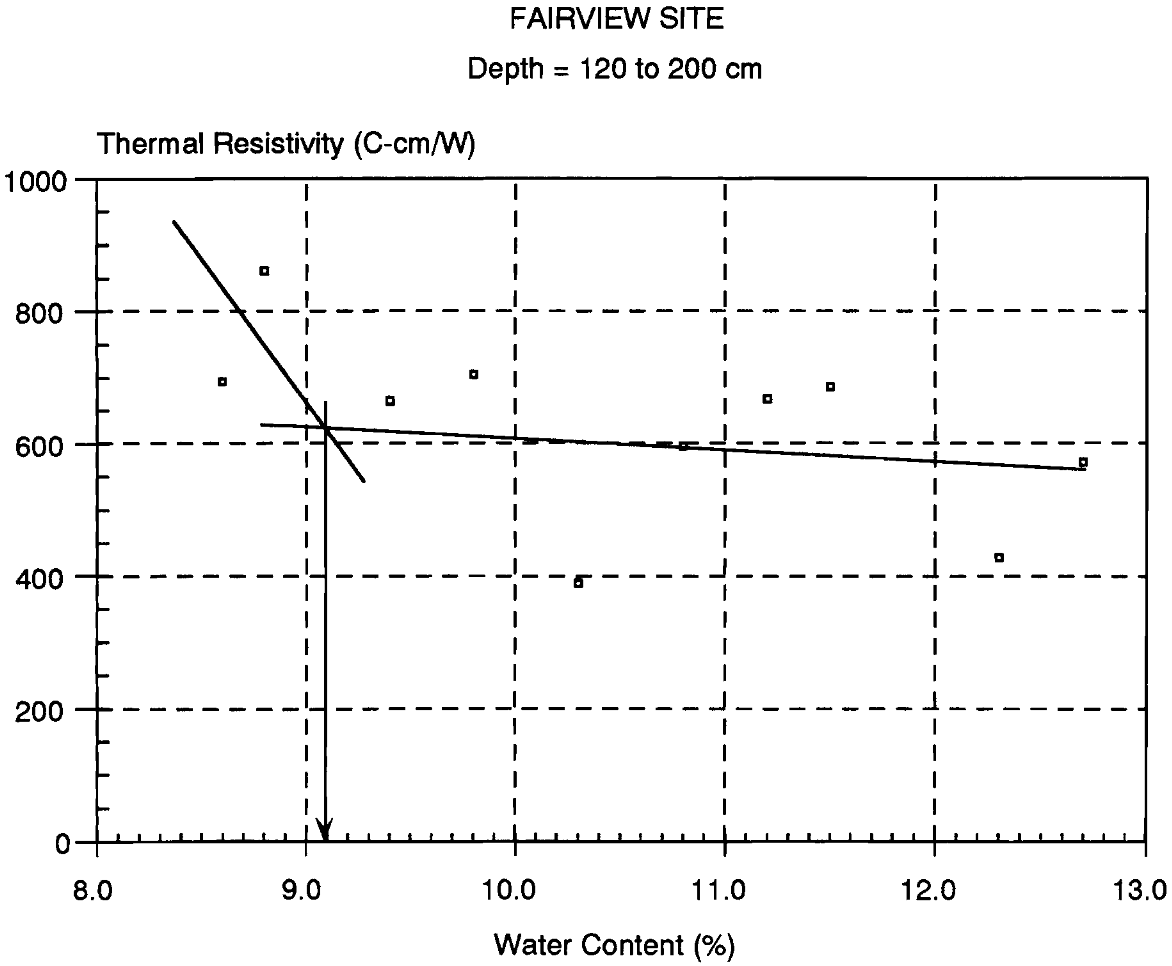
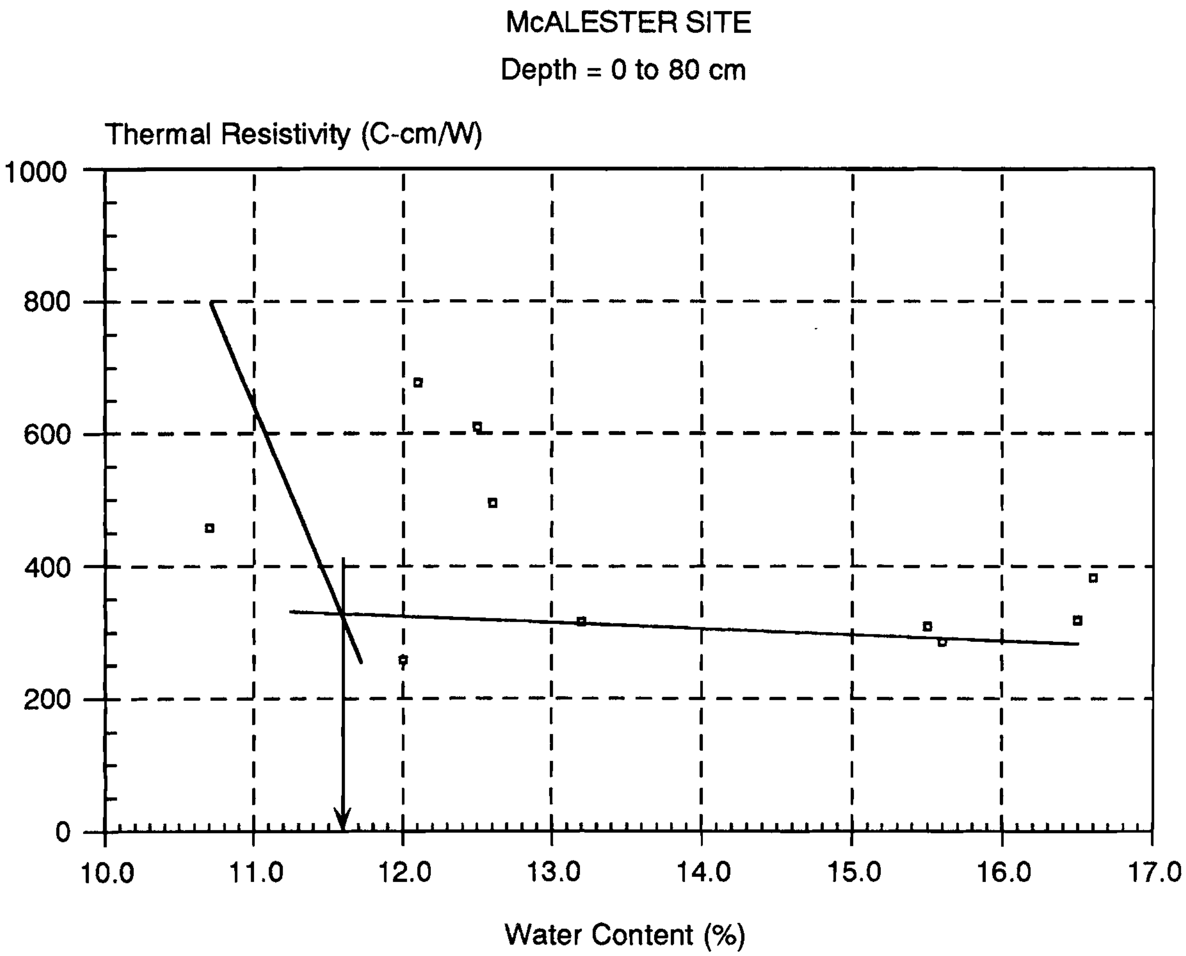


Figure 40. Lab Thermal Property Testing Results for Layer 3 at Fairview Site



McALESTER SITE

Depth = 0 to 80 cm

Figure 41. Lab Thermal Property Testing Results for Layer 1 at McAlester Site

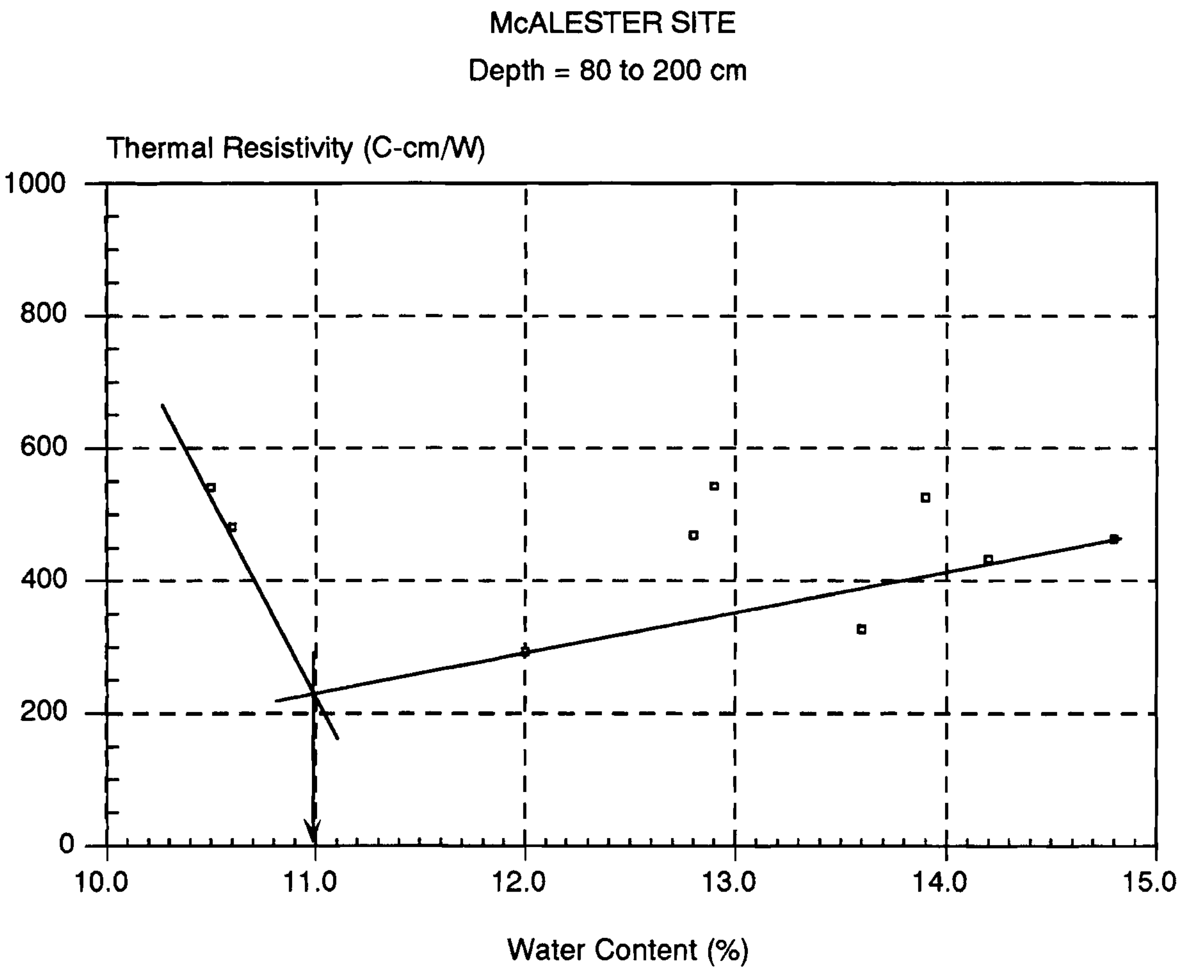


Figure 42. Lab Thermal Property Testing Results for Layer 2 at McAlester Site

APPENDIX I

SOIL SUCTION VERSUS WATER CONTENT PLOTS

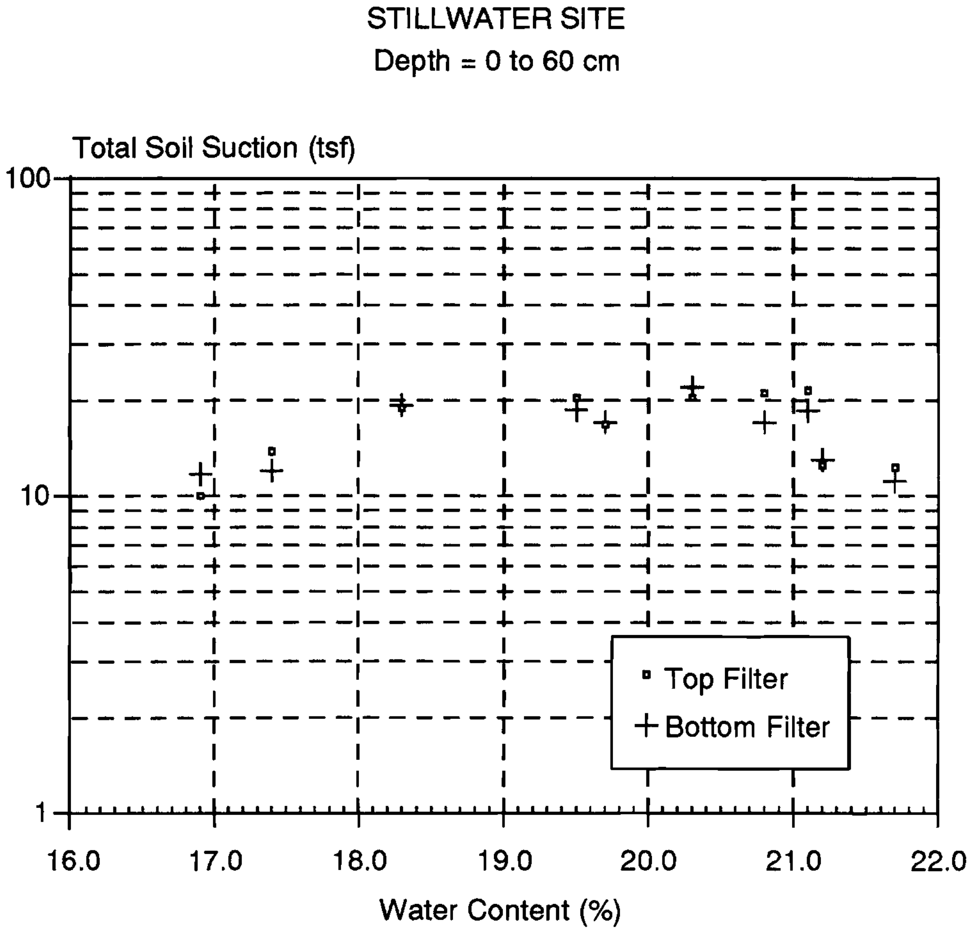


Figure 43. Soil Suction Versus Water Content for Layer 1
at Stillwater Site

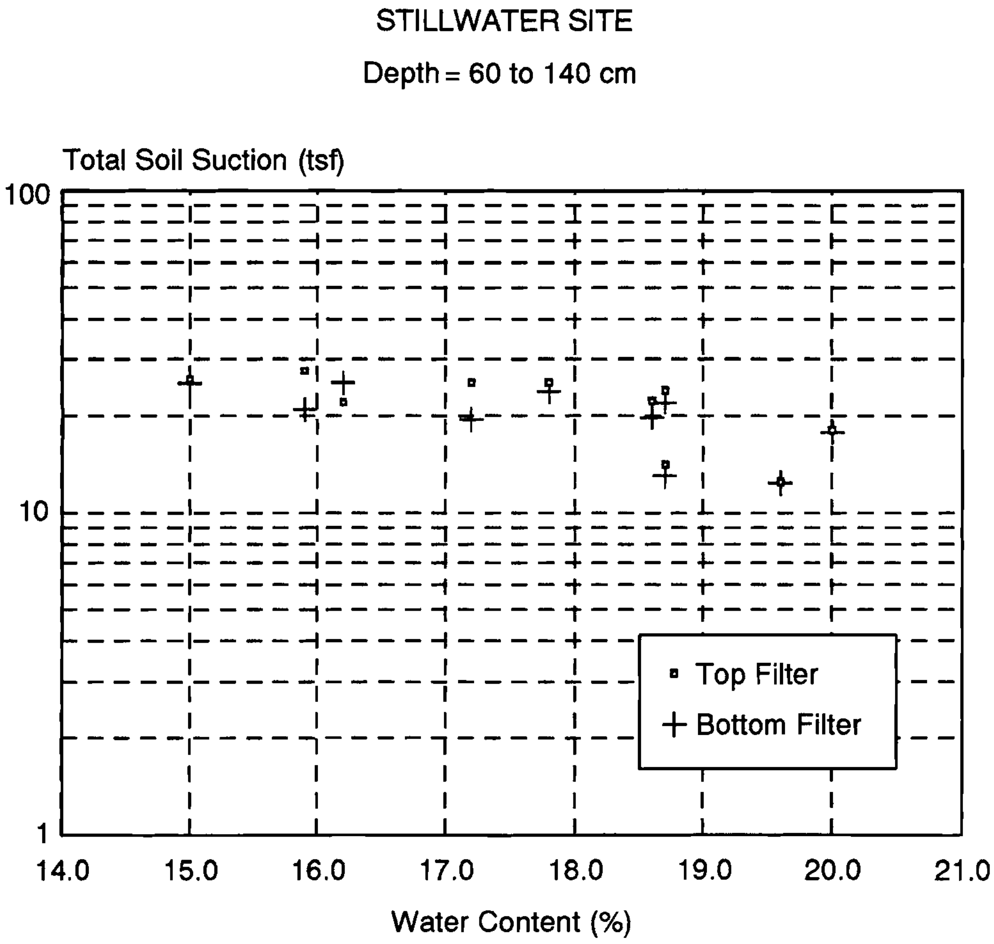


Figure 44. Soil Suction Versus Water Content for Layer 2 at Stillwater Site

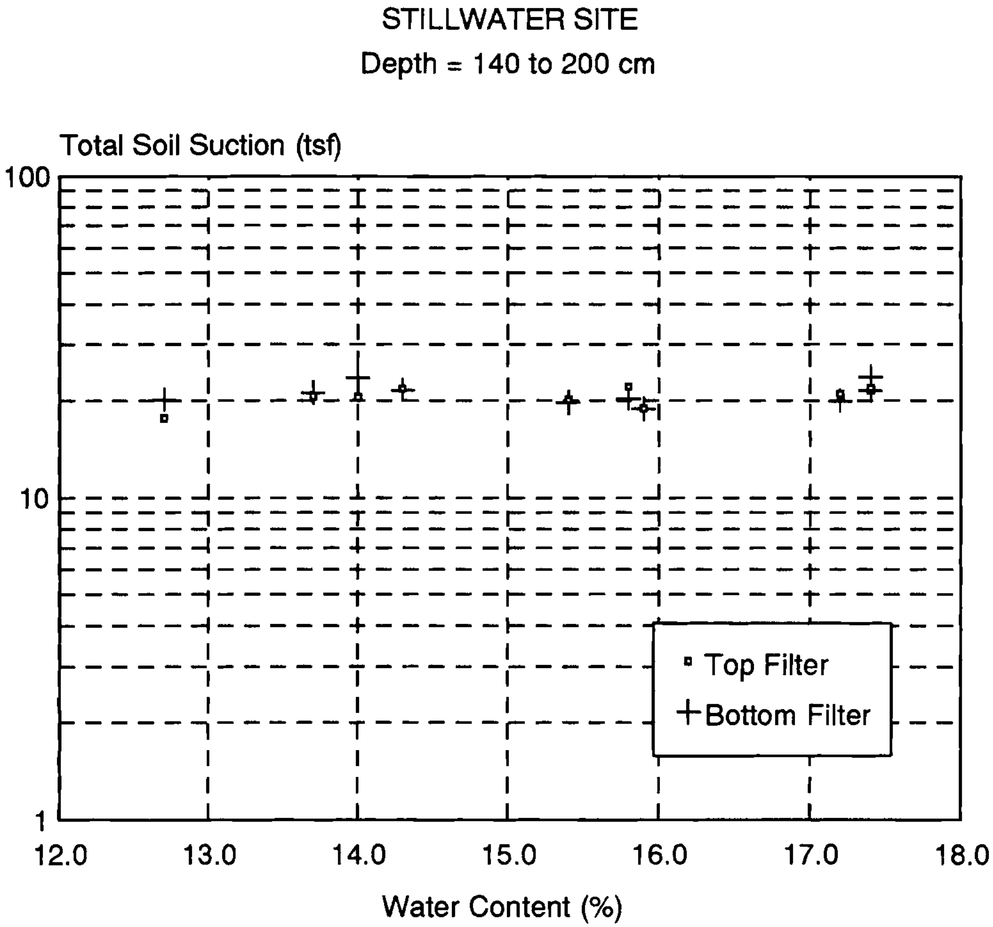


Figure 45. Soil Suction Versus Water Content for Layer 3 at Stillwater Site

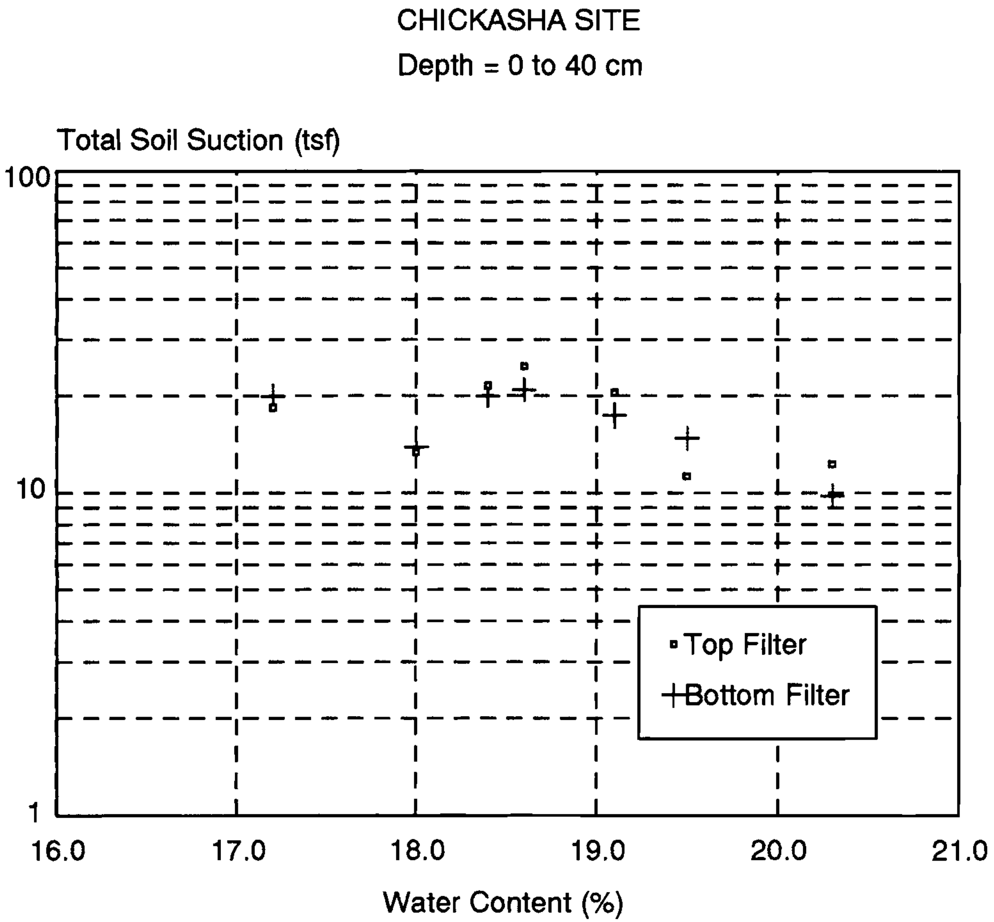


Figure 46. Soil Suction Versus Water Content for Layer 1
at Chickasha Site

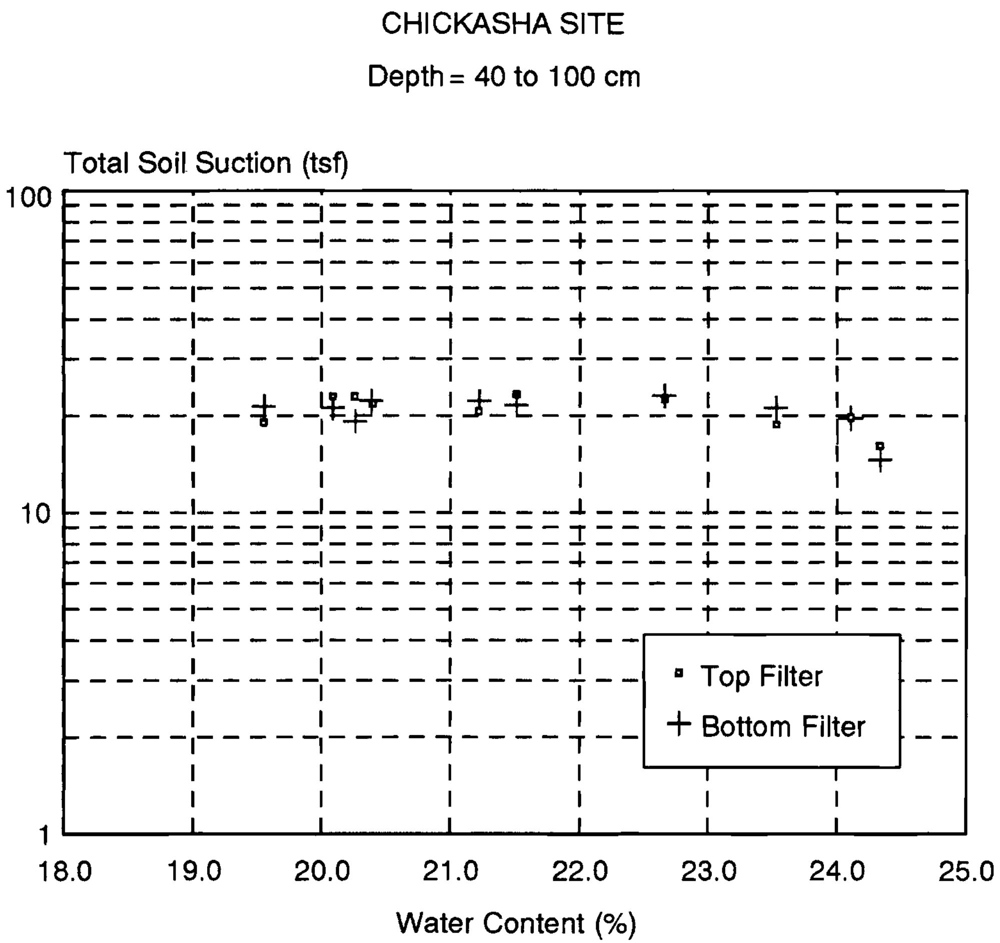


Figure 47. Soil Suction at Varied Water Content Values for Layer 2 at Chickasha Site

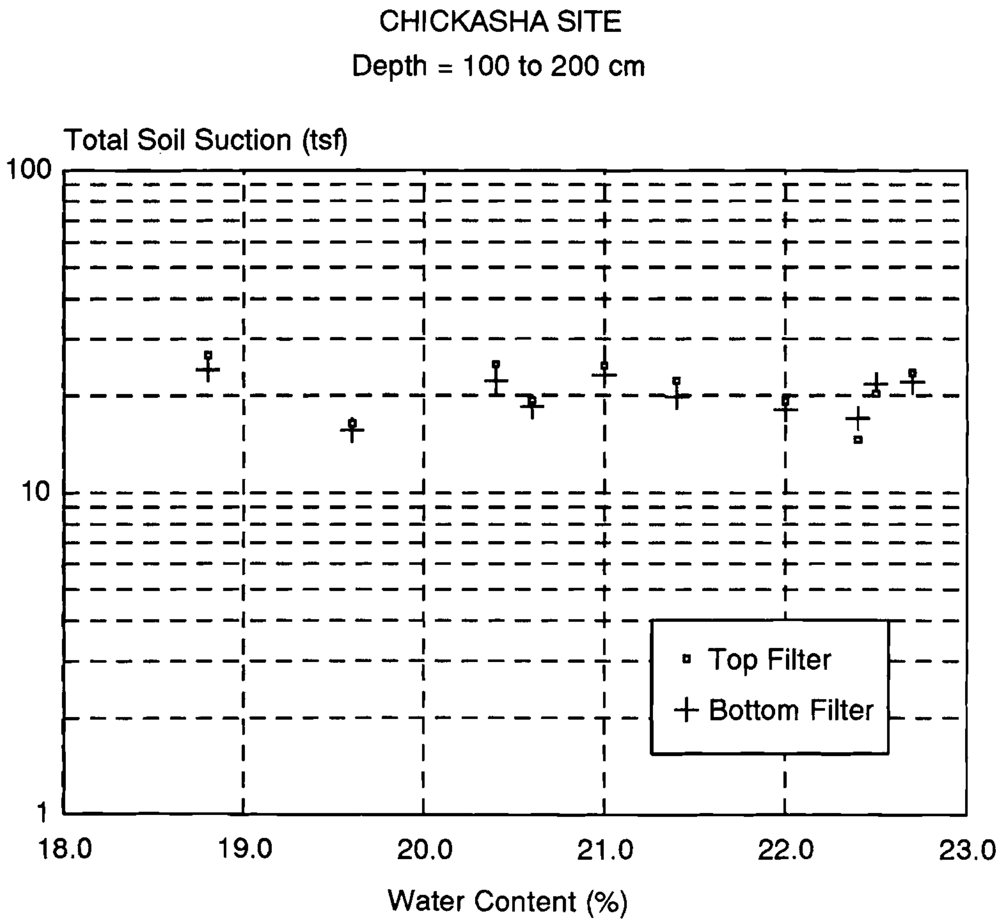


Figure 48. Soil Suction Versus Water Content for Layer 3 at Chickasha Site

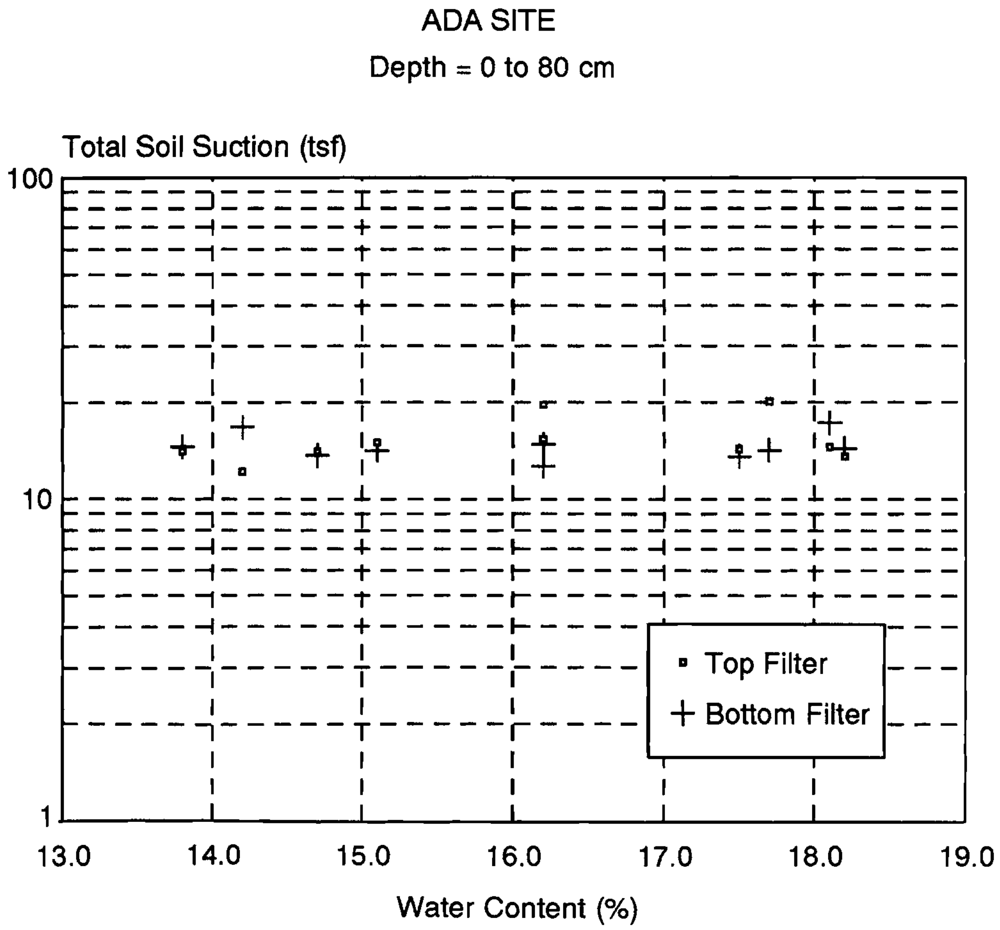


Figure 49. Soil Suction Versus Water Content for Layer 1 at Ada Site

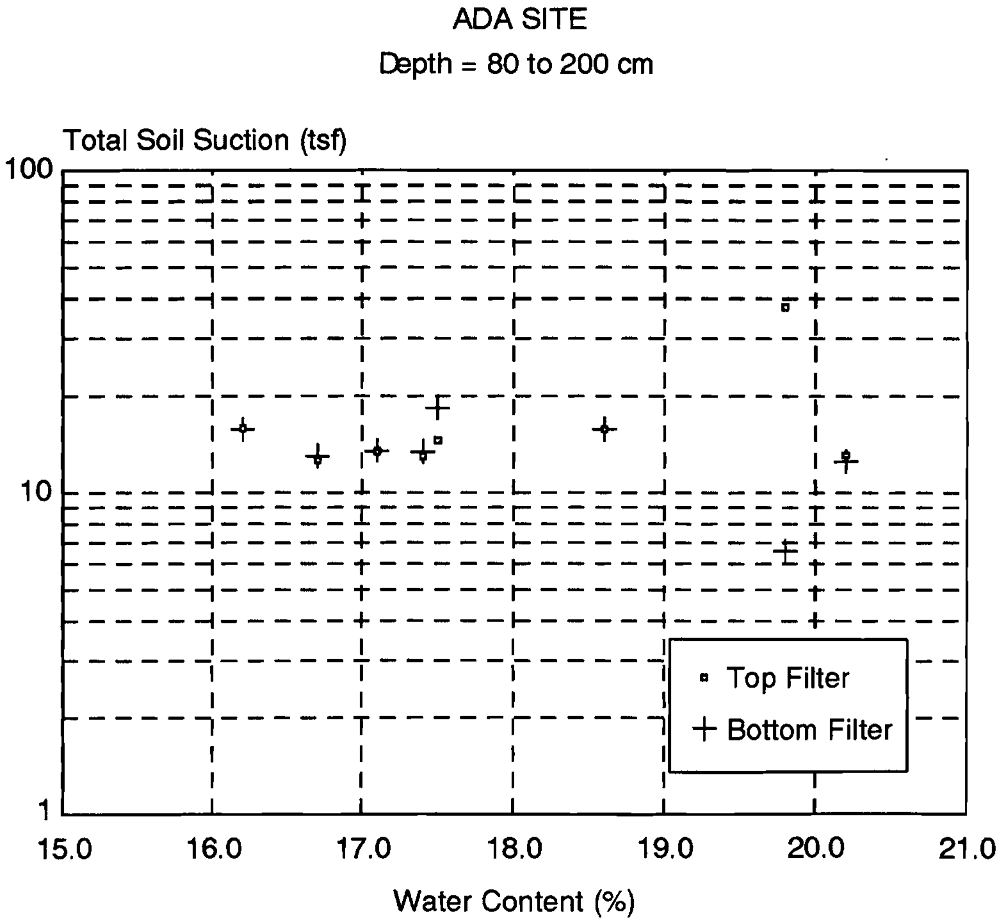
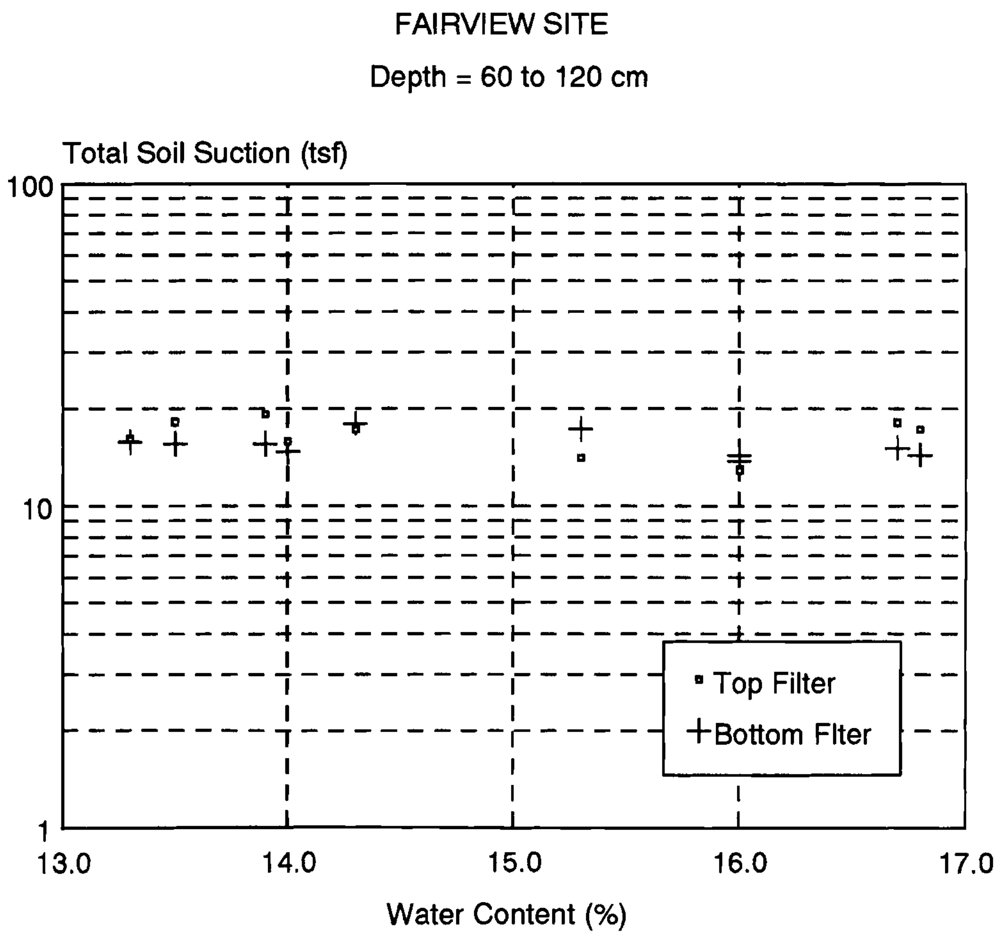


Figure 50. Soil Suction Versus Water Contentfor Layer 2 at Ada Site


FAIRVIEW SITE

Depth = 60 to 120 cm

Figure 52. Soil Suction Versus Water Content for Layer 2 at Fairview Site

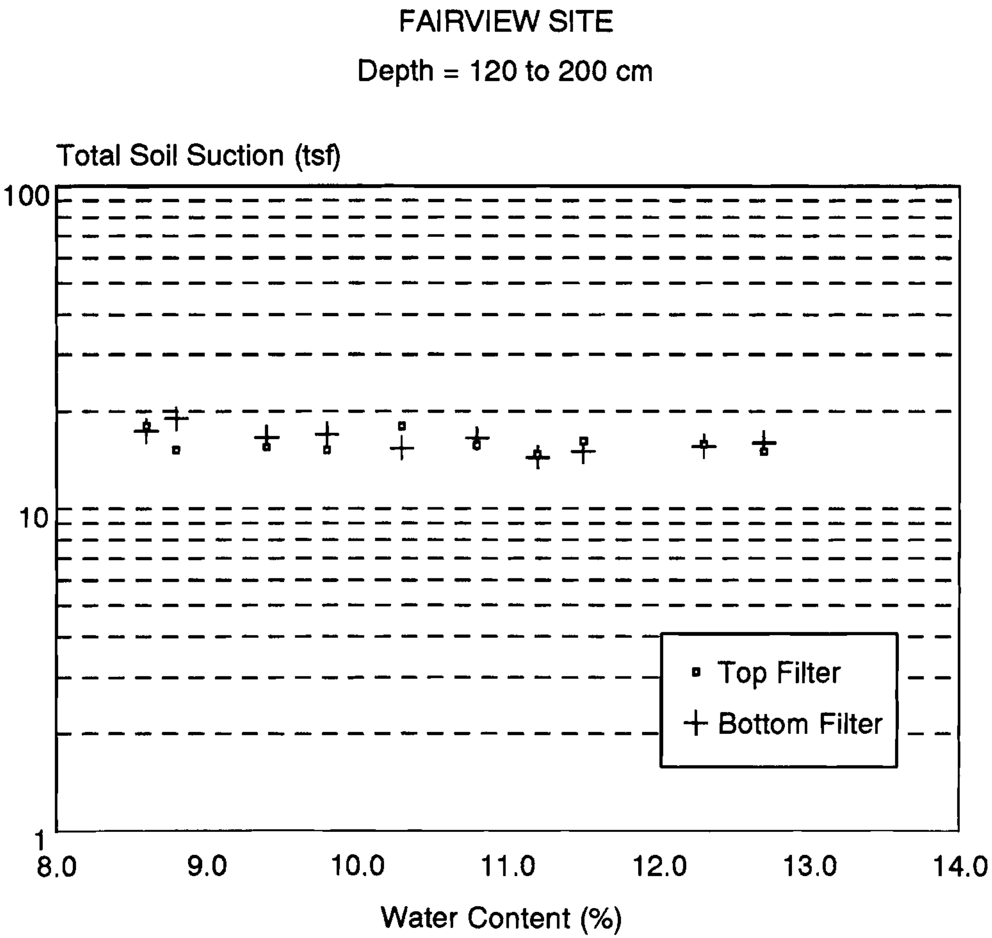


Figure 53. Soil Suction Versus Water Content for Layer 3 at Fairview Site

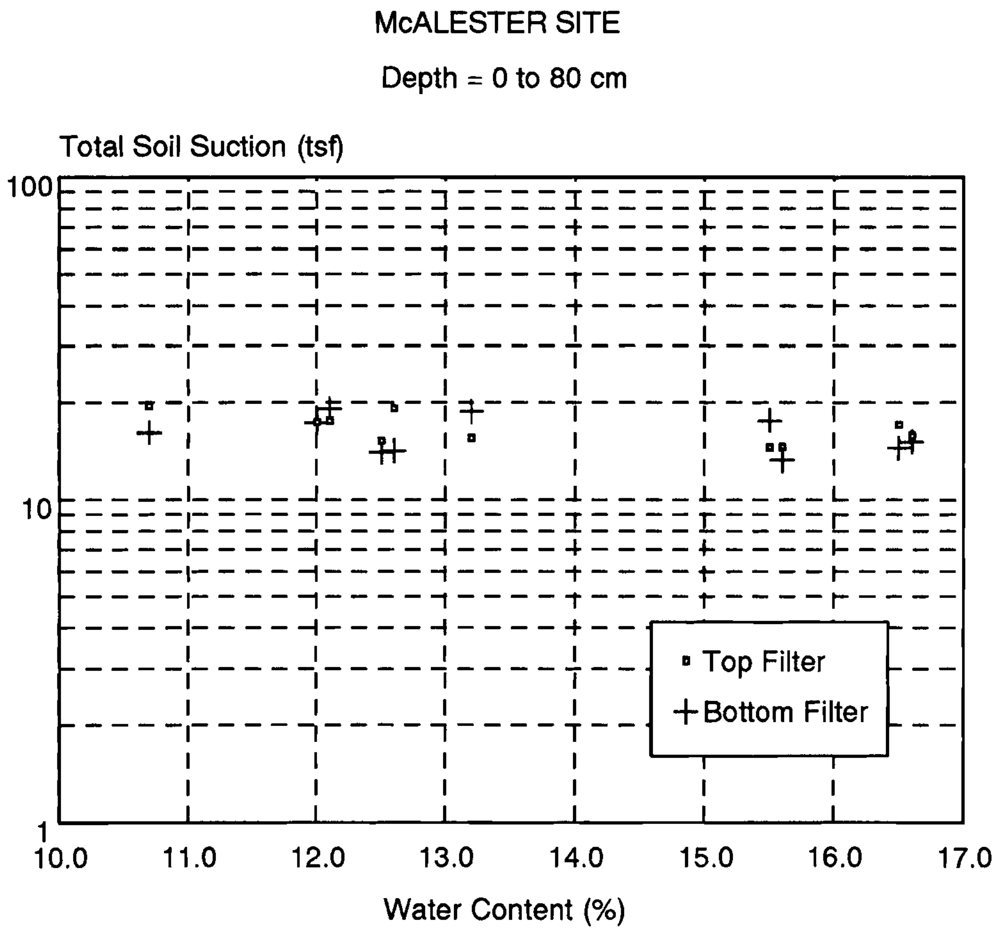


Figure 54. Soil Suction Versus Water Content for Layer 1 at McAlester Site

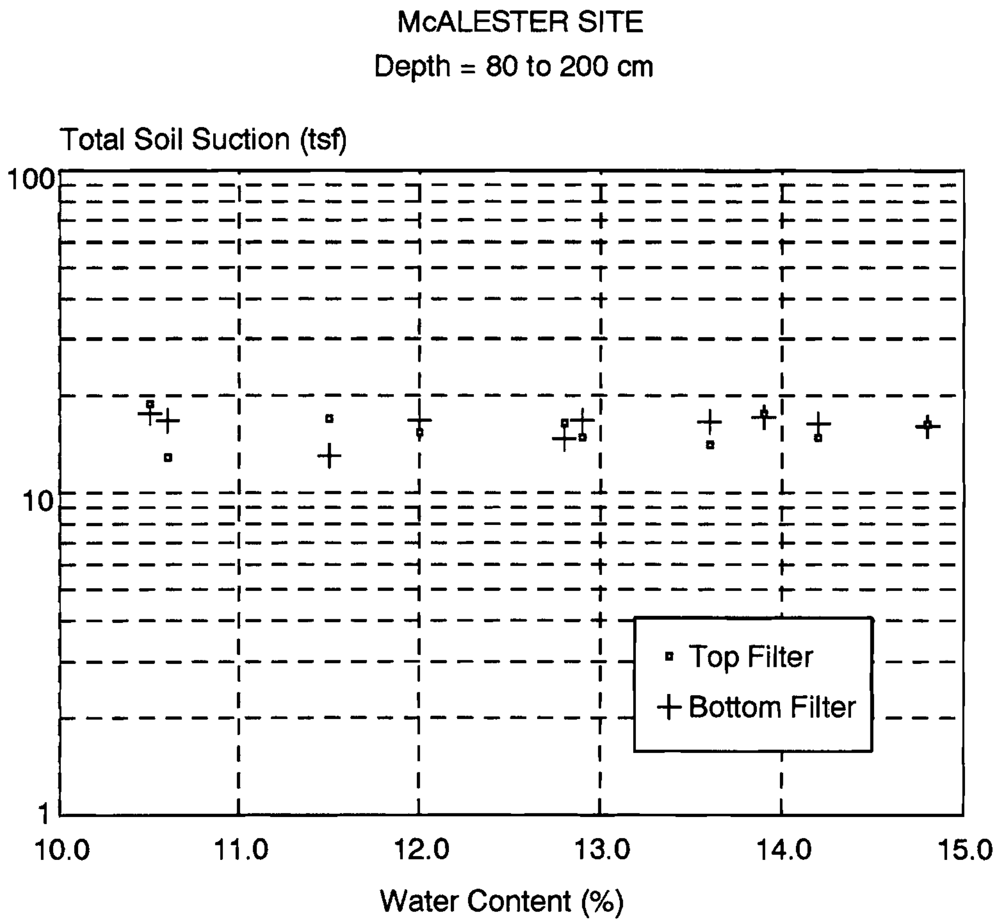


Figure 55. Soil Suction Versus Water Content for Layer 2 at McAlester Site

APPENDIX J

THERMAL RESISTIVITY DATA SHOWN FOR EACH SAMPLE

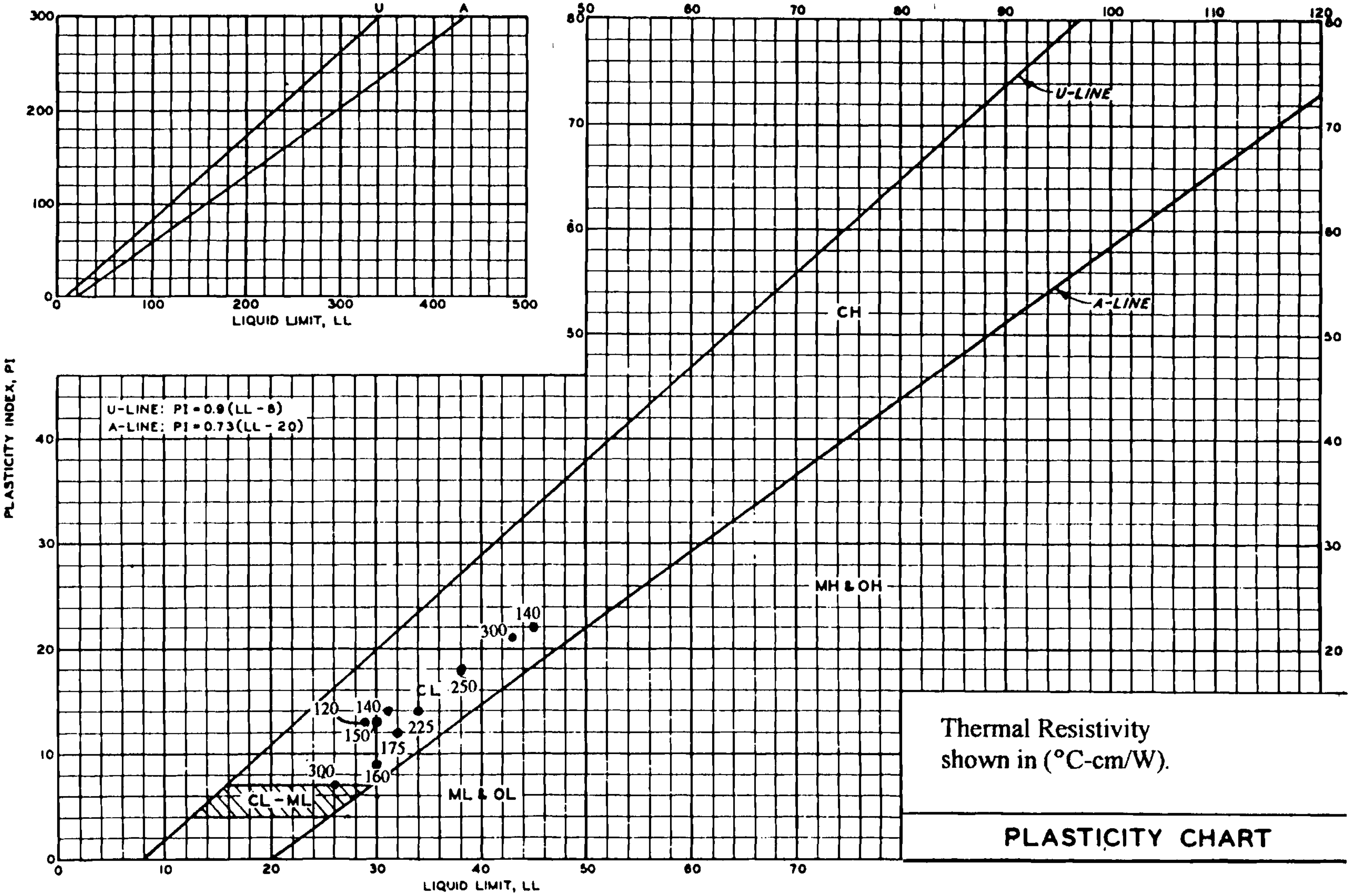


Figure 56. Plot of Thermal Resistivity Data Shown for Each Sample

VITA

Michael W. Southern

Candidate for the Degree of

Master of Science

Thesis: EVALUATION OF SOIL PROPERTIES AND THEIR CORRELATION WITH SOIL THERMAL PROPERTIES FOR FIVE OKLAHOMA MESONETWORK SITES

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