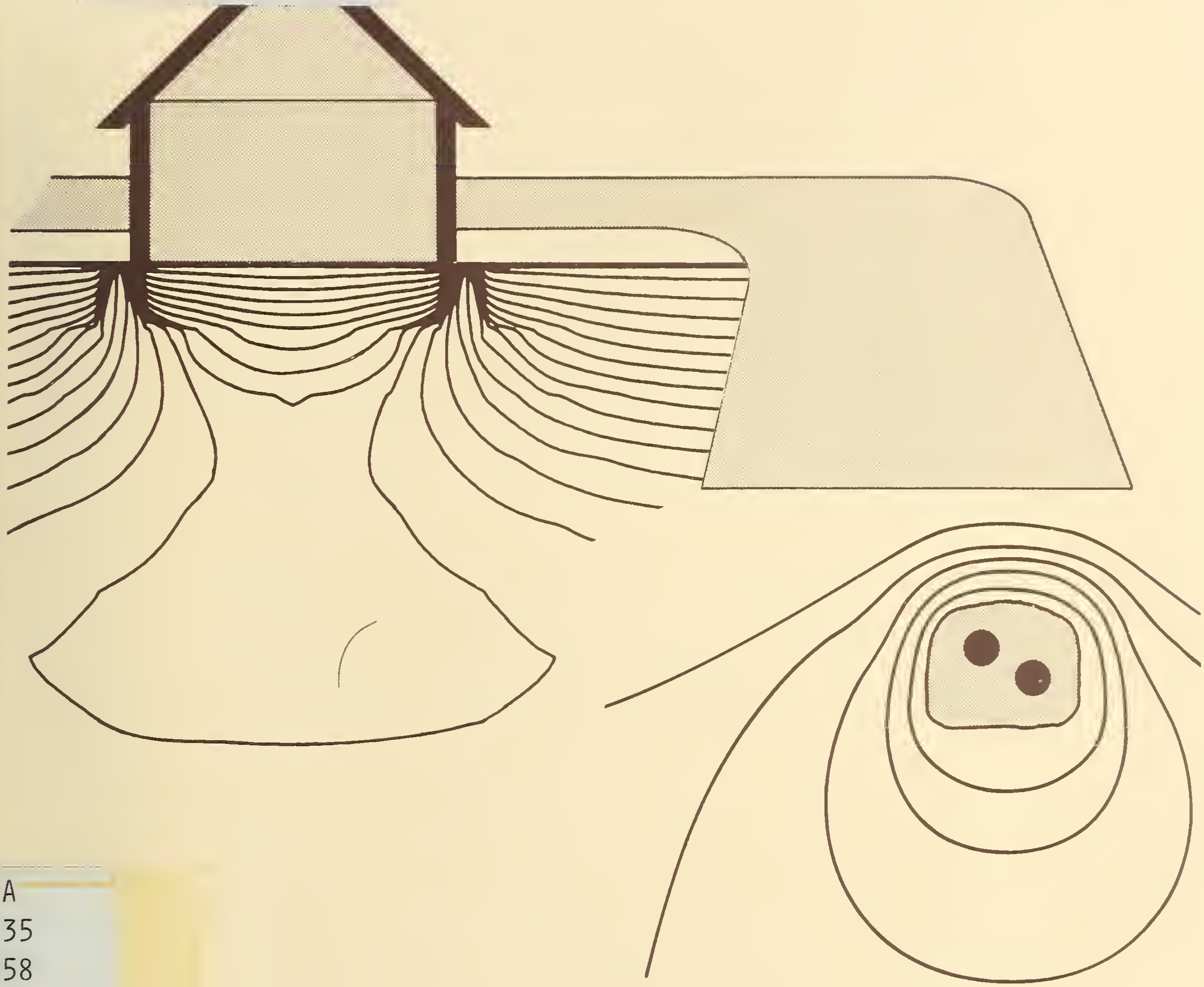

NBS BUILDING SCIENCE SERIES BSS 149

Thermal Behavior of Fine-Grained Soils

U.S. DEPARTMENT OF COMMERCE • NATIONAL BUREAU OF STANDARDS

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NBS BUILDING SCIENCE SERIES BSS 149

Thermal Behavior of Fine-Grained Soils

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ABSTRACT

Laboratory thermal probe tests performed on an AASHTO standard reference material (a silty clay) showed that thermal resistivity (°C•cm/watt) varies with soil moisture content and dry density. The tests were performed to correlate soil thermal behavior with the limit states of fine-grained soils. Over 80 thermal resistivity measurements were made on specimens compacted to various densities and moisture contents.

Results are presented which indicate that the optimum moisture content of soils and the Atterberg Limits can be correlated with the thermal behavior of fine-grained soils. It was found that the minimum thermal resistivity (i.e. the critical moisture content) occurred at the optimum moisture content when the soils were compacted using various compactive efforts. The critical moisture content defines the knee of the thermal resistivity versus moisture content curve. When the soils were compacted using a compactive effort of 1.42×10^5 J/m^3 (2970 ft-lbs per cubic foot), the minimum thermal resistivity occurred at the plastic limit of the AASHTO standard reference material. Also, indices are defined which allow comparison of the thermal behavior of fine-grained soils.

Keywords: Atterberg limit tests; compaction; compaction tests; heat flow; laboratory tests; soil moisture; soil tests; tests; thermal conductivity; thermal resistivity.

COVER: Temperature contours beneath a house and around underground electric transmission lines.

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NOTATION

A,B = soil constants in eq. 9

A_1 = the slope of the line, equation 10

B_1 = the value of the intercept of the curve at 1 percent moisture

Ei = designation for exponential integral (eq. 2)

k = thermal conductivity of the medium, W/°C•cm

LL = liquid limit as defined by ASTM D423-72 procedures, percent

pF = logarithm to the base 10 of the negative pressure (tension, or suction) of the soil moisture in centimeters of water

PL = plastic limit as defined by ASTM D424-71 procedures, percent

q = power per unit length

r = distance from line heat source

T = temperature rise above initial temperature

t = time elapsed since initiation of heating

TPI = thermal performance index

TSI = thermal stability index

w = inner core moisture content, percent

w_D = minimum moisture content expected under design conditions, percent

w_{nat} = natural moisture content, percent

w_{opt} = optimum moisture content using modified energy (ASTM D1557-78 procedures), percent

W = moisture content, percent

W_s = dry mass of soil, g

w_{sc} = supercritical moisture content: i.e., the moisture content at which the thermal resistivity increases with increasing moisture content, percent

W_t = wet mass of soil, g

α = thermal diffusivity of the medium

γ = Euler's constant = 0.5772

ρ_d = dry density, Mg/m^3

ρ_M = thermal resistivity of a sample prepared using modified energy (ASTM D 1557-78 procedures) and a moisture content equal to the modified optimum moisture content, °C•cm/W

ρ_S = thermal resistivity of a sample prepared using standard energy (ASTM D 698-78 procedures) and a moisture content equal to the liquid limit, °C•cm/W

FACING PAGE: Sample compacted using the 102-mm (4-in) mold and the 5.5-lbf (2.49-kg) hammer according to ASTM D698-78 procedures.

1. INTRODUCTION

1.1 GENERAL

Evaluation of the thermal properties of soils is a problem facing many geotechnical engineers. Selection of suitable backfill soils for nuclear waste disposal sites requires a thorough knowledge of the thermal properties of the material that surrounds the containment areas and of the factors which affect these properties. Likewise, knowledge of the thermal properties of soils is necessary to predict the heat loss in buried structures and in residential housing with slab-on-grade construction. Through an understanding of thermal soil properties, energy savings are being obtained by using soils to moderate the temperature to which a structure is subjected. The importance of evaluating thermal properties of soils surrounding buried electric power cables is evident when one considers that temperatures greater than 50°C to 60°C may lead to breakdown of buried cable insulation if the soil surrounding the cable is unable to conduct the heat away as it is generated. It is this need to use soil as an insulating material or as a conductor to dissipate heat that requires an understanding of the soil characteristics that affect thermal soil behavior.

In simple terms, soils with a high thermal resistance will not dissipate heat from a heat source as rapidly as low resistivity soils. The thermal resistivity of soil is a measure of the thermal performance of soil. It is the reciprocal of thermal conductivity. The thermal resistivity of the soil is primarily influenced by: soil composition, moisture content and dry density. When it is considered that the resistivity (in thermal ohms*) of quartz is 11, water 165 and air 4000, the need for examining each of the three phases (solid material, water, and air) and their interrelationship is evident. The laboratory testing program described herein was designed for the purpose of finding low cost, simple, index property tests and defining soil indices that establish the thermal behavior of fine-grained soils.

1.2 LIMITATIONS OF PRESENT PROCEDURES USED TO EVALUATE THERMAL SOIL PROPERTIES

Progress in the prediction of thermal soil properties is limited by the fact that relevant information is scattered in a variety of technical fields. Also, authors have not used a common language to describe the results of field and laboratory measurements of these properties.

Geotechnical investigations consisting of in situ and laboratory thermal probe tests, soil sampling and determinations of moisture and density are frequently performed to evaluate the thermal resistivity of soils. These investigations often are conducted using routine procedures adopted over the years, based on research done in the late fifties and early sixties [1],[1] but not necessarily reflecting all the information and techniques now available. Furthermore, much of the valuable work performed by or under the direction of the Power industry in the above periods and on which these procedures are based, is reported in language more familiar to agronomists and electrical engineers [1]. On the other hand, more recent contributions to the state-of-the-art by geotechnical engineers are not documented using similar terminology nor correlated with the findings of the earlier work [2]. This communication barrier limits present progress in the prediction of thermal soil properties because of possible duplication of efforts with earlier researchers and the inability of researchers and engineers to exchange information easily and to compile their accumulated experience using common terminology.

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* The thermal ohm is the unit of resistivity. It is defined as the number of degrees centigrade of temperature drop that occurs when heat flows through a 1 centimeter cube at the rate of 1 watt. The unit of thermal resistivity is °C•cm/W. Note: 100°C•cm/W = 1°K•m/W and .01731°C•cm/W = 1 hr•ft•°F/Btu.

[1] Numbers in brackets indicate the literature references at the end of the paper.

The key to improving our predictive capability in the field of thermal soil mechanics is to have a thorough understanding of the soil characteristics that affect soil thermal behavior and to use this knowledge to develop a common language which will eliminate the communication barrier.

1.3 PURPOSE

The purpose of this study is to provide an approach for determining the thermal behavior of fine-grained soils using index property tests.

1.4 SCOPE

The index properties of soils (e.g., particle-size distribution and Atterberg Limits) have been found to correlate well with engineering properties (strength, stiffness, and compressibility) of soils [3]. By knowing the index properties of soils, the engineer is able to obtain an indication of the performance of various types of soils under various engineering situations. At the present time index property tests are not used in the field of thermal soil mechanics to provide an indication of the thermal performance of various types of soils. This is true even though tests, which measure the changes in the state of soil relative to changes in moisture content, could provide an indication of thermal soil behavior as a result of the influence of moisture content on the thermal resistivity of soil. Identification of index property tests to achieve this purpose was accomplished in this study by:

1. Examining those soil moisture concepts from the fields of agronomy and geotechnical engineering, that were considered applicable to understanding better the Atterberg Limits (i.e. the limit states of soil behavior).

2. Measuring the thermal resistivity of a fine-grained soil whose index properties were known from the AASHTO Materials Reference Laboratory (AMRL) using laboratory thermal probe tests and establishing the relationships of thermal resistivity to moisture content at various densities for this soil. Over 80 thermal resistivity measurements were made on specimens compacted to various moisture contents and densities.

3. Obtaining index property and thermal resistivity test data for fine-grained soils from the literature.

4. Correlating the thermal resistivity test data obtained from items 2 and 3 above with the agronomy and geotechnical limit states shown in figure 1-1.*

   An example of how this can be done is shown in figure 1-2 from Salomone [4] which presents Atterberg Limits and thermal resistivity test data showing the correlation between the Atterberg Limits and soil thermal resistivity for fine-grained soils.

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* Figures are provided at the end of the section in which they are first cited.

SOIL MOISTURE CONDITION	DRY	MOIST	WET	SATURATED
Classification of Soil Moisture	Hygroscopic Water	Capillary Water	Gravitational Water	Groundwater
Approximate Soil Moisture Tension in pF*	7.0	4.5 4.2	2.8 2.5	0.5
STATES OF FINE-GRAINED SOIL	BRITTLE SOLID	SEMI-SOLID	PLASTIC SOLID	LIQUID
Approximate Agronomy Limit States		Friable Hygroscopic Coefficient Wilting Coefficient	Field Capacity	Settling Volume Sticky Limit
Approximate Geotechnical Limit States (Atterberg Limits)		Shrinkage Limit	Plastic Limit	Liquid Limit

* pF is the logarithm to the base 10 of the negative pressure (tension, or suction) of the soil moisture in centimeters of water.

Figure 1-1. A qualitative comparison of the differences in terminology used by agronomists and geotechnical engineers (modified from [4]).

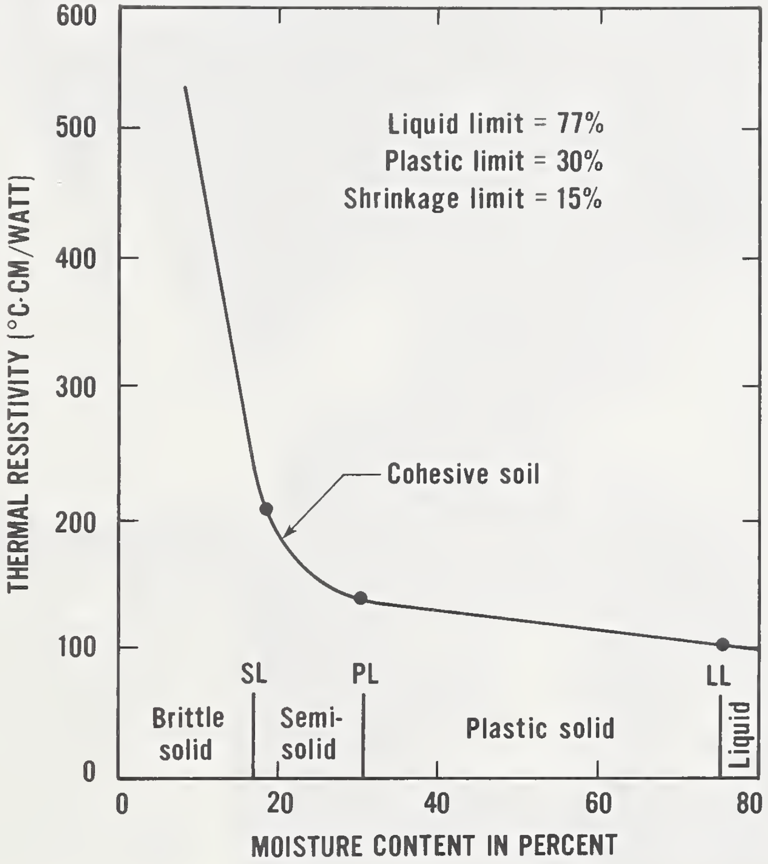


Figure 1-2. Correlation of thermal resistivity with the Atterberg Limits (from [4]).

FACING PAGE: Using drill press to push laboratory thermal probe into compacted sample.

2. LABORATORY TESTING

2.1 TEST INSTRUMENTATION

2.1.1 General

The equipment used to determine the thermal conductivity (or thermal resistivity) of the laboratory soil samples tested included:

1. Six laboratory thermal probes, and
2. Electric Power Research Institute (EPRI) Thermal Property Analyzer.*

2.1.2 Thermal Probes

Figure 2-1 shows a sectional view of a laboratory thermal probe similar to those used in this study. Because the interpretation of probe readings depends on the validity of line heat source theory, exact specifications of the probe with respect to: uniformity of cross-section along the probe length, thermocouple placement, heater resistance and length, proper insulation against electrical short circuits and mechanical durability must be followed when constructing a thermal probe to comply with the major assumptions of line heat source theory. The theory is based on the assumptions that the heating element is a straight line of infinite length and infinitely small diameter. The heating element is homogeneous and isotropic and is embedded in a homogeneous and isotropic medium of infinite extent. Also, the heating element possesses the same thermal properties as the surrounding medium.

Wechsler [5] has made recommendations about the construction of thermal probes. He also presented an abridged version of the line heat source theory upon which the interpretation of the probe reading is based. For convenience to the reader, Wechsler's [5] presentation of line heat source theory is provided in the next section. This derivation is based on information found in Ref. [6].

2.1.2.1 Line Heat Source Theory

Consider an infinite line source of heat placed in an infinite homogeneous medium initially at uniform temperature. Beginning at time t = 0, heat is released by this source at a rate q per unit source length. The temperature rise T (above the initial temperature) at a distance r from the line source of heat is given [6] as a function of time t by:

$$T = \frac{-q}{4\pi k} \mathrm{Ei} \left(\frac{-r^2}{4\alpha t}\right) \tag{1}$$

where k is the thermal conductivity and α the thermal diffusivity of the medium and Ei indicates the exponential integral evaluated by eq. 2 [6] and tabulated in the literature [7]:

$$-\mathrm{Ei} \left(\frac{-r^2}{4\alpha t}\right) = \int_{\frac{r^2}{4\alpha t}}^{\infty} \frac{e^{-u}}{u} \, du. \tag{2}$$

---

* Trade names are identified to specify adequately the experimental procedures. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material identified is necessarily the best available for the purpose.

For large values of time, the exponential integral may be approximated by a series expansion as follows:

$$-Ei(\frac{-r^2}{4\alpha t}) \cong \ln(\frac{4\alpha t}{r^2}) - (\frac{r^2}{4\alpha t}) + \frac{1}{4}(\frac{r^2}{4\alpha t})^2 + \ldots - \gamma \qquad (3)$$

where γ = Euler's constant = 0.5772. By neglecting the term $\frac{1}{t}$ of first order and higher in equation 3, and substituting in equation 1, we obtain:

$$T = \frac{q}{4\pi k}\left[\ln(\frac{4\alpha t}{r^2}) - \gamma\right] \qquad (4)$$

or

$$T = \frac{q}{4\pi k}\left[\ln t + \ln\frac{4\alpha}{r^2} - \gamma\right] \qquad (5)$$

For fixed values of r and α, the temperature rise increases logarithmically with time. A plot of temperature rise versus logarithm of time should give a straight line of slope $\frac{q}{4\pi k}$. This technique is customarily used with the line heat source method to evaluate the thermal conductivity. At any point in the medium, the temperature rise T_1, at time t_1, is related to the temperature rise T_2, at time t_2, by the following equation:

$$T_2 - T_1 = \frac{q}{4\pi k}\ln(\frac{t_2}{t_1}) \qquad (6)$$

Thus, in theory, it is possible to obtain a conductivity value if the temperature rises at only two experimental times are known. To apply eqs. 4, 5, and 6, sufficient times must be allowed so that the exponential integral is approximately equal to the simple logarithmic expression.

2.1.3 EPRI Thermal Property Analyzer

The EPRI Thermal Property Analyzer was developed by Ontario Hydro Research Laboratory under an EPRI contract. A manual for the operation and use of the Thermal Property Analyzer (TPA) was prepared by Ontario Hydro Research Laboratory [8]. This report describes the TPA as follows.

"The TPA consists of an electric current source and a six-input thermocouple reader under microprocessor control, housed in a rugged type of attache case. The front-panel layout is shown in figure 2-2. The probe current is determined on the basis of the resistance/unit length and on the anticipated thermal resistivity to give one of three probe powers per unit length appropriate for soils of high, medium, and low thermal resistivity. The thermal resistivity is calculated by the microprocessor from a least squares fit to time-temperature data collected between 300 and 1000 seconds. A special function keyboard is available so that all parameters such as probe powers, times, etc., can be varied from the pre-set (default) values stored in the microprocessor memory (ROM). An RS 232 interface which is capable of supporting a printer or other digital accessories, along with an appropriate printer to produce hard copy of time-temperature data and thermal properties, is provided. During a "run", the elapsed time is continuously displayed along with any one of the thermocouple temperatures, probe power per unit length, or thermal resistivity for any thermocouple input, based on data accumulated to that time in the run. When the reset button is depressed, all six thermocouple inputs are scanned and those without thermocouples attached are ignored in future measurements. If the temperature of any thermocouple goes over 100°C, the thermal resistivity for input is "frozen" and future data from that input are ignored. If the temperture goes over 140°C, the probe power is removed to protect the stability of the heater. The entire system is designed to operate on 90-140 V rms sine wave, or 100-160 V rms square wave; 47-65 Hz.

Numerous error-reducing features are incorporated into the software. For example, probe power cannot be initiated until the probe has come to thermal equilibrium with the soil. Also, a coefficient of determination is calculated for the least squares fit, and an error message is sent if the coefficient of determination is less than a predetermined value (0.92). Automation of all aspects of thermal property measurement greatly reduces the likelihood of error in data acquisition and reduction."

2.2 DESCRIPTION OF AMRL REFERENCE SOIL

Participants in the AASHTO Soil Reference Sample Program were provided two boxes of Soil Reference Samples. Each box was a separate sample of soil marked with a card stamped either #61 or #62. Soil from boxes marked #61 were used for this study. Each individual test performed by the participating laboratories was conducted by the same operator. However, it was not required that the different tests be conducted by the same person. Participating laboratories performing these tests were asked to report the results of a single determination only, not the average of two or more. All tests were conducted according to the AASHTO Standards Methods and Instructions [9]. The results are summarized in table 2-1 [10].

In general, the soil can be described as a silty clay. The Unified Soil Classification [11] is CL.

2.3 TEST PROCEDURE

2.3.1 General

The laboratory testing program included:

1. Selection of Molding Moisture Content,
2. Soil Preparation,
3. Thermal Probe Sample Preparation,
4. Thermal Probe Tests, and
5. Moisture and Density Determinations.

The procedures used during each of these steps are described below.

Table 2-1. Summary of Index Property Test Data
AMRL Soil Reference Sample No. 61 (from [10])

TEST TITLE		NO. OF LABS.	SAMPLE NO. 61		
			AVERAGE	STAND. DEV.	C.V. (PERCENT)
PASS NO. 10	PRCNT	146	9.8398+01	1.4415+00	1.465
PASS NO. 40	PRCNT	140	9.6014+01	1.1897+00	1.239
PASS NO. 200	PRCNT	140	8.9855+01	1.8107+00	2.015
PASS .02MM	PRCNT	116	8.0406+01	5.0292+00	6.255
PASS .002MM	PRCNT	116	4.5463+01	4.6154+00	10.152
PASS .001MM	PRCNT	116	3.6035+01	4.4790+00	12.430
LIQUID LIMIT	PRCNT	157	4.5121+01	3.6110+00	8.003
PLASTIC LIMIT	PRCNT	157	2.3513+01	1.9520+00	8.302
OPT MOISTURE	PRCNT	150	1.8396+01	1.3899+00	7.555
MAX DENSITY	LB/CF	152	1.0800+02	1.7500+00	1.620
SP GR - NO. 10		125	2.7669+00	4.4041-02	1.592
R-VALUE 300 PSI		17	1.1618+01	6.0396+00	51.986

2.3.2 Selection of Molding Moisture Content

The moisture contents for the thermal probe tests were selected initially based on those moisture contents required to establish the moisture-density relationship at compactive efforts of standard (5.92×10^5 J/m^3) intermediate (16.16×10^5 J/m^3) and modified (26.93×10^5 J/m^3) energies. Moisture contents from 17.5 to 32.5 percent at three percent increments were used for each of these compactive efforts until the relationship among moisture-density and compactive efforts were known. With these relationships determined it became apparent that additional compactive efforts were required to obtain samples at a wide range of moisture content and density. The compactive efforts used are summarized in table 2-2 in section 2.3.4. Moisture contents required to determine the relationship of moisture and density for these additional compactive efforts were then selected. With the compaction curves known for the various compactive efforts, the various molding moisture contents (and densities) at which thermal probe tests were to be made were selected by a study of the compaction curves to obtain thermal resistivity test data for a wide range of moisture content and density.

2.3.3 Soil Preparation

The soil to be tested was air-dried and a sample was taken to determine the initial moisture content of the air-dried soil. This was used to establish the quantity of water required to produce the molding moisture content.

After the desired moisture content (and density) for a test had been selected, a quantity of air-dried soil equivalent to 2500 g oven-dry weight (or 2000 g for 5 of the S6 samples tested at the end of the program) was thoroughly mixed with the necessary amount of water to achieve the molding moisture content. The soil was then stored in an airtight pan for a minimum curing time of 16 hours to absorb the moisture. To provide a controlled environment for the airtight pan during the curing period, the pan was stored in a plastic bag in which a minimum of 20 g of water was placed.

2.3.4 Sample Preparation

When the soil test sample had completed curing, a compactive effort was selected from those listed in table 2-2, after reviewing the moisture-density data, to achieve the desired density. The equipment used for sample preparation is described in detail in ASTM D 698-78 [Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 5.5-lbf (2.49-kg) Rammer and 12-in (305-mm) Drop] and ASTM D 1557-78 [Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 10-lbf (4.54 kg) Rammer and 18-in (457-mm) Drop] procedures [12].

The following steps were used to prepare the sample:

a. Placed plastic wrap on the baseplate for the 102-mm (4-in) compaction mold to prevent evaporation of moisture from the bottom of the sample.

b. Attached the mold to the baseplate and recorded the mass on the data sheet to the nearest 0.1 g.

c. Attached the extension collar to the mold.

d. Placed a sufficient amount of the prepared soil in the mold in layers to give a total compacted depth of approximately 130 mm (5 in). The number of layers, weight of hammer, drop height, and blows per layer used depending on the compactive effort chosen are listed in table 2-2.

e. Removed the extension collar from the mold and removed the exposed compacted soil with a stiff metal straightedge until the surface was even with the top of the mold. The trimmings (i.e., excess soil when preparing the test specimen) were recovered and their moisture content determined.

f. Weighed the mold and baseplate plus wet soil to the nearest tenth of a gram.

g. Covered the sample with plastic wrap to prevent evaporation of moisture from the top of the sample during the thermal probe test.

Table 2-2. Summary of Compactive Efforts Used During Laboratory Testing Program

Description	Weight of Hammer (lbf)*	Fall (ft)*	No. of Layers	No. of Blows per Layers	Energy ft•lbf/ft^3*
Modified (ASTM D1557-78)	10	1.5	5	25	56250
Intermediate	10	1.5	3	25	33750
Standard Plus	5.5	1.0	4	27	17820
Standard (ASTM D698-78)	5.5	1.0	3	25	12375
S 12	5.5	1.0	3	12	5940
S 6	5.5	1.0	3	6	2970
S 4	5.5	1.0	3	4	1980

* NOTE:
1 lbf = 4.448 N
1 ft = 0.3048 m
1 ft•lbf/ft^3 = 47.88 J/m^3

2.3.5 Thermal Probe Tests

Laboratory thermal probe tests were performed using the thermal probes described in section 2.1.2 and the EPRI Thermal Property Analyzer described in section 2.1.3. The method of making these tests was changed slightly as experience was gained with this equipment. The procedures that finally evolved are explained below:

a. Plugged in the TPA and printer and turned power switch on. Allowed a minimum of 10 minutes for warm up.

b. Set the R/L ratio (Probe Resistance) of 610 mΩ/cm (61Ω/m) by the thumbwheel switches. This is a probe constant which did not change during the testing program.

c. Set the anticipated thermal resistivity to LOW (thermal resistivity less than 60°C•cm/watt). This setting provided the highest coefficient of determination for the moist samples tested. For the air dried samples the MEDIUM setting (thermal resistivity between 60 and 120°C•cm/watt) provided the best results.

d. Set the toggle switch to SINGLE run. SINGLE run indicates one 16 minute-45 second run at a probe power that is determined by step c. A setting of LOW provides a power of 0.359 watt/cm (35.9 w/m) while the MEDIUM setting provides a power of 0.196 watt/cm (19.6 w/m).

e. Inserted the thermal probe into the center of the soil sample using a drill press and in some cases a specially designed cap for the compaction mold to ensure good soil/probe contact. (The drill press and cap aides in preventing lateral movement of the probe as it is inserted into the soil sample.)

f. Connected the probe cables.

g. Depressed the RESET button. This initiated the thermocouple in the probe being used. (Note that up to six samples can be tested simultaneously.)

h. Waited a minimum of 20 seconds and then pressed RUN button to start the test. The RUN button initiates probe currents and data acquisition.

i. Observed the probe power, thermal resistivity and coefficient of determination for the sample(s) being tested during the run (as required) by using the Data Selector and Thermocouple Selector.

j. Noted the thermal resistivity associated with the highest value of the coefficient of determination recorded by the printer for each sample tested following the 1005 second run.

2.3.6 Moisture and Density Determinations

Moisture content and density determinations were performed after the completion of the thermal probe tests using the following approach:

a. Removed plastic wrap from top of sample and weighed the mold and baseplate plus wet soil again to determine moisture loss (gain) during the thermal probe test.

b. Removed a 25-mm (1-in) diameter core of soil from the center of the sample using a 25-mm (1-in) diameter thin wall tube and determined the moisture content of the inner soil core using ASTM D 2216-80 [Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures] procedures [12].

c. Separated the baseplate from the mold.

d. Removed a 51-mm (2-in) diameter core of soil from the center of the sample using a 51-mm (2-in) diameter soil extruder or a 51-mm (2-in) diameter thin wall tube depending on the consistency of the soil to be extruded. The thin wall tube was used for soft soil samples. The moisture content of this outer soil core was determined using ASTM D 2216-80 procedures.

e. Extruded the remaining soil from the mold using a 102-mm (4-in) diameter soil extruder and determined the moisture content of the sample using ASTM D 2216-80 procedures.

f. Compared the moisture contents for the inner core, outer core, and total sample to determine differences in moisture in the thermal probe test sample.

g. Determined the wet density of the thermal probe test sample using the wet weight of soil determined in step a. and the volume of the mold (measured at the beginning of the testing program).

h. Determined the dry mass of soil using the equation:

$$W_s = \frac{100W_t}{100+w} \qquad (7)$$

where

W_s = dry mass of soil, g
W_t = wet mass of soil, g
w = inner core moisture content, expressed in percent

i. Determined the dry density of the thermal probe test sample using the dry weight of soil determined in step h. and the measured volume of the mold.

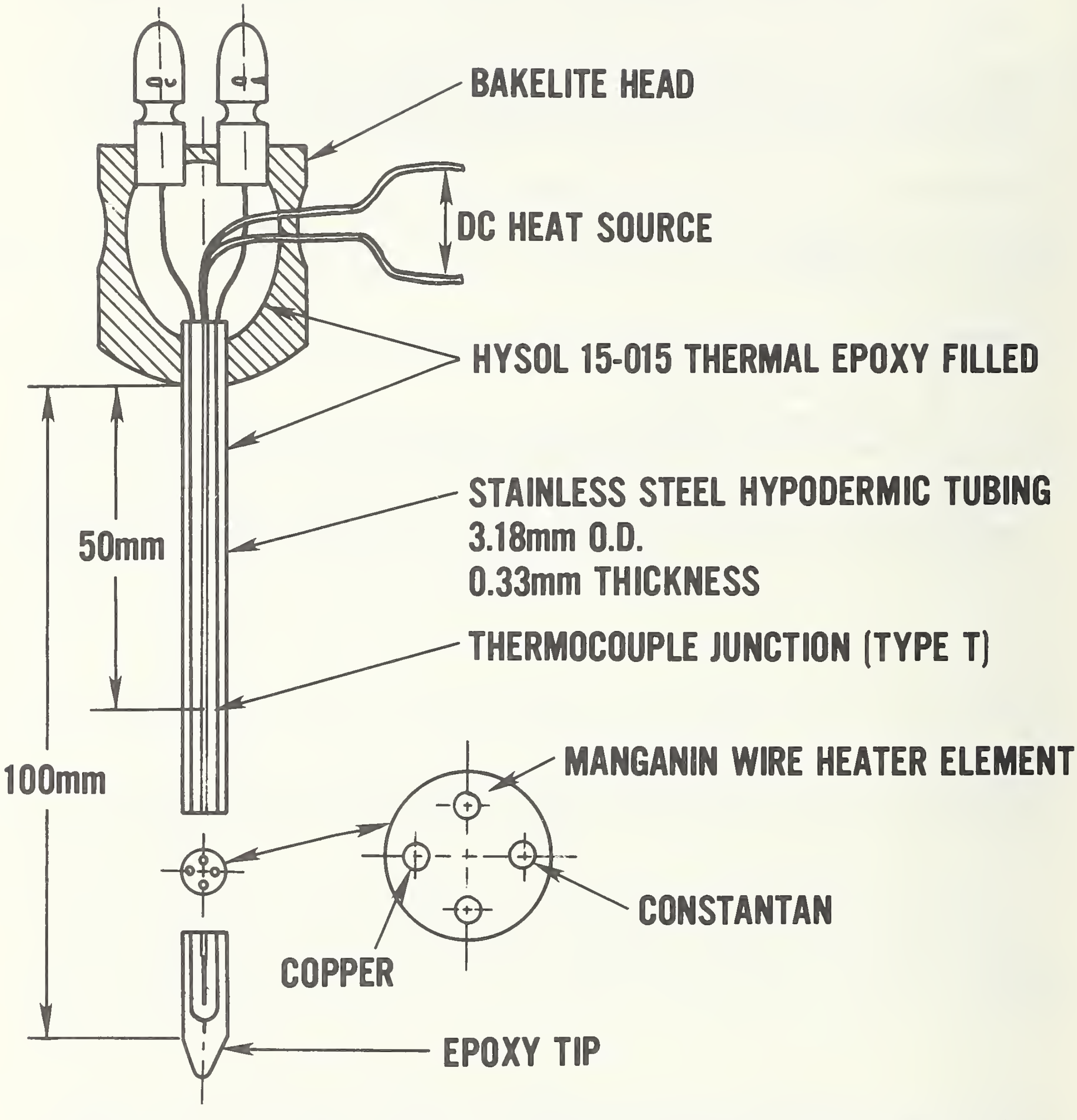


Figure 2-1. Sectional view of a laboratory thermal probe (from [27])

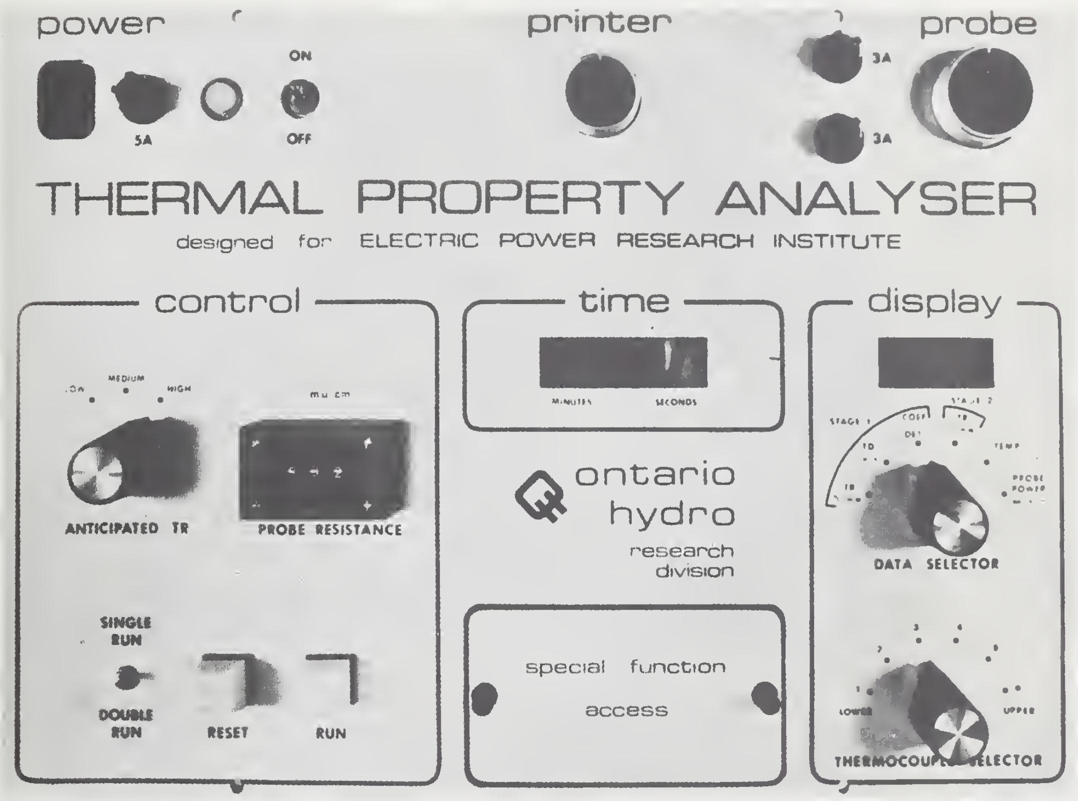
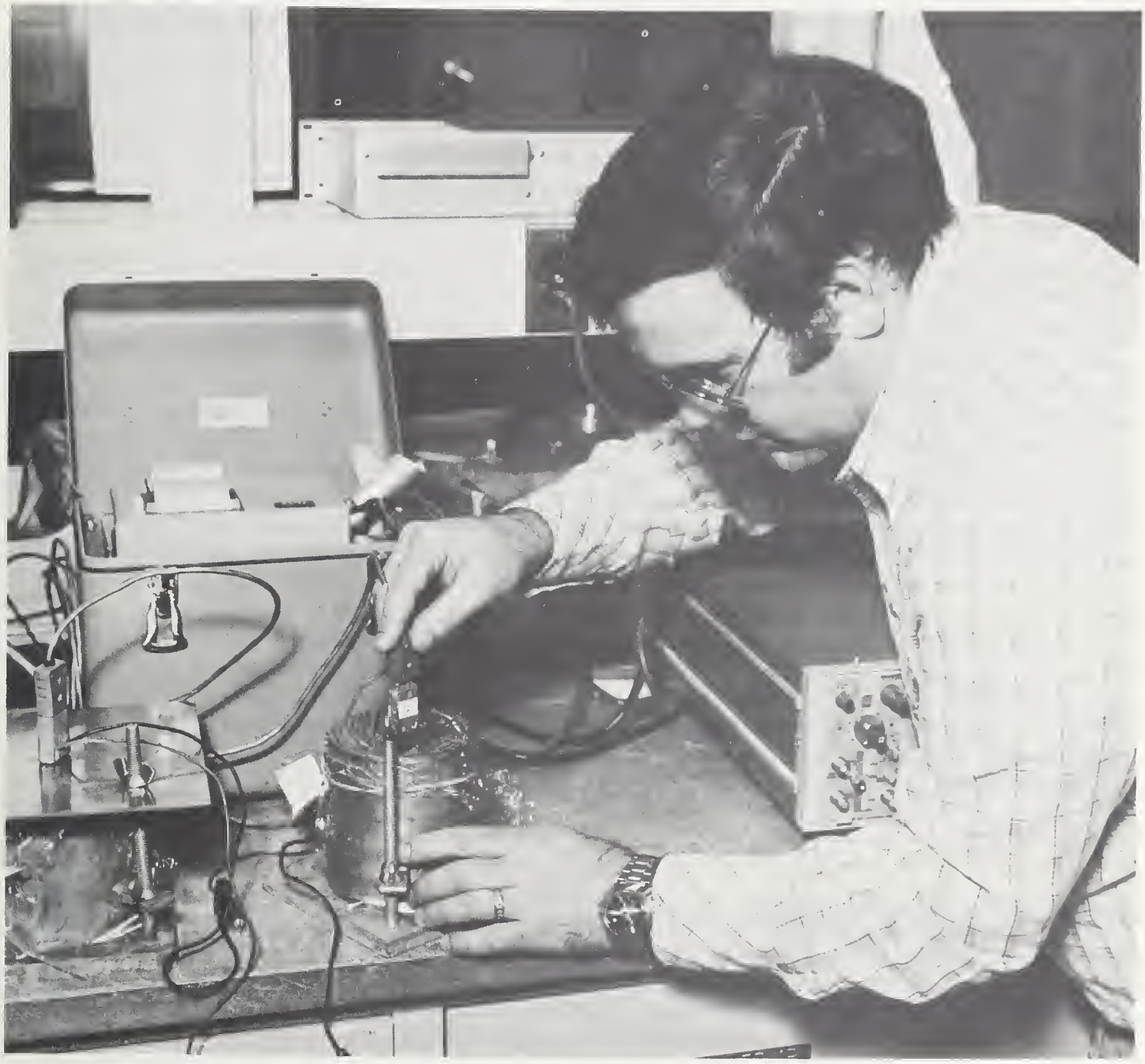


Figure 2-2. Front-panel layout of EPRI Thermal Property Analyzer (from [8])

FACING PAGE: Connecting the thermal property analyzer to the laboratory thermal probe.



3. THEORETICAL CONSIDERATIONS AFFECTING THERMAL PERFORMANCE OF SOILS

3.1 GENERAL

To provide the readers a better understanding of the findings from this study, a review of the factors affecting thermal resistivity is presented. Techniques used by agronomists and geotechnical engineers to predict soil behavior that are applicable to this study are discussed. This background information which is derived from Ref. [4] serves as the basis for the discussion of test results in section 4.

3.2 PRIMARY FACTORS AFFECTING THE THERMAL RESISTIVITY OF SOILS

The thermal resistivity of a soil is primarily influenced by the following parameters:

a. Soil composition,
b. Density, and
c. Moisture content.

The importance of these parameters is discussed below.

3.2.1 Soil Composition

Soil is a three-phase medium composed of solid materials (inorganic and/or organic), liquid (water) and gases (air). Because heat flowing through soil must flow through the solid mineral grains and the medium in which they are embedded in a complex system of series and parallel paths, the thermal resistivity of the soil depends on the thermal resistivity of its component materials and the soil structure. This point is important because of the difference in the thermal resistivity of the various components of the medium. The thermal resistivity, in thermal ohms (°C•cm/watt), of a mineral such as quartz is 11, water 165, air 4000 and for organic matter approximately twice as much as that of the mineral components. Because the resistivities of most minerals are significantly less than that of water and air, the soil mass should consist of as much solids as possible if low resistivity is desired. Another consideration is the amount of water that can be adsorbed and/or absorbed by the soil since we shall see later the importance of soil moisture on soil thermal resistivity. The amount of adsorbed water is affected by the grain size and mineral content and depends on the geometry of the soil particle surfaces and their physico-chemical character, as well as on temperature.

3.2.2 Density

Sinclair et al. [13] explained the importance of density when they stated that "In a dry soil, the solid particles form a system of series-parallel paths with each other and with the air-filled voids between them. The presence of air with its high thermal resistivity greatly increases the overall thermal resistivity of the soil as compared with its soil components because: (1) part of the heat path is necessarily 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) because the air makes for poor contact between the solid particles introducing high-thermal-resistivity air paths in series with the low-thermal-resistivity paths through the solid particles." Thus, by reducing the total void volume and improving the contact between the solid grains through densification of the soil mass a reduction in the thermal resistivity of the material will be achieved. The density of soils may be changed by artificial means such as compaction or disturbance of in situ soils (e.g., during electric cable installation) and by such natural factors as consolidation, shrinkage, or swelling. The least resistivity is achieved in the case of the greatest amount of solid material per unit volume. At porosities greater than 50 percent to 65 percent, the normal silt-clay soils in a dry state have a thermal behavior determined by the addition of the resistivities of the component phases while below porosities of 50 percent to 65 percent the thermal behavior is determined from the addition of the thermal conductivities of the component phases [14]. The transition occurs at lower porosities for well-graded crushed quartz systems and for sands used as backfill around underground cables (thermal sands). The larger the range of particle sizes, the smaller is the porosity at which this transition occurs. This transition occurs at a porosity when a contacting granular skeleton is formed by the grains of the better conducting quartz sands.

Another factor which should be considered when attempting to improve the thermal stability of a soil is its permeability which determines the potential moisture movement under thermal gradients. This movement of moisture could be critical if moisture restoration is curtailed thereby causing the thermal resistivity to increase. Consequently, an optimum thermal density which is characterized by a high amount of solid material per unit volume and yet a permeability sufficiently great to allow for moisture restoration should be used. Also, the type of fine-grained material present is a factor when attempting to reduce soil thermal resistivity because an expansive clay mineral such as montmorillonite would cause the sand particles to be forced apart during compaction by swelling action when moisture is added thereby increasing the thermal resistivity of the soil.

3.2.3 Moisture Content

Recalling the difference in the thermal resistivity between air and water, another important factor to consider is the extent to which the voids (or pore spaces) are filled with water. The terms usually used to characterize this soil property are moisture content and degree of saturation. The moisture content is defined as the mass of free water expressed as a percentage of dry mass of a given soil volume while the degree of saturation is defined as the volume of free water expressed as a percentage of the volume of voids.

The importance of soil moisture is illustrated in figures 3-1 and 3-2. As moisture is added to the soil as a thin film around the soil particles or wedges at the contacts, 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 or wedges greatly reduce the thermal resistivity of the soil.

When the moisture condition in the soil approaches the wet condition shown in figure 3-1, the effective contact area no longer increases with increasing moisture content. Consequently, the significant decrease in thermal resistivity is not evident when additional moisture is added to fill the pore space.

The moisture content at which the bridge mechanism breaks down (with a resulting disproportionate increase in the thermal resistivity with a small reduction in moisture content) has been referred to as the "critical moisture content" by Radhakrishna et al. [16]. This critical moisture content depends on the particle size distribution, particle shape and density. These trends are shown in figure 3-2.

Moisture migration is also an important consideration. Thermal gradients existing in the soil cause a redistribution of moisture in the soil thereby changing the thermal resistivity of the soil. Because moisture migration under a thermal gradient involves capillary moisture, i.e., moisture in excess of adsorbed (hygroscopic) water that is held against the force of gravity [17], the existing moisture content in the soil is an important consideration in deciding whether moisture migration is a problem. The rate of moisture migration under thermal gradients is zero outside the limits of the capillary moisture range. In the field of agronomy, the limits of the capillary moisture range are defined by the hygroscopic coefficient and the field capacity. The hygroscopic coefficient is the boundary between moist-appearing and dry-appearing soil. The field capacity represents the maximum amount of water that can be held against the force of gravity. The maximum migration rate occurs at an intermediate moisture level between the hygroscopic coefficient and the field capacity, near the wilting coefficient. The wilting coefficient is defined as the soil-moisture condition at which the ease of release of water to the plant roots is just barely too small to counter-balance the transpiration losses. The previously discussed limits are determined by measurements of soil moisture tension as given by Kohnke [18]. The soil moisture scale which provides the approximate relationship of soil moisture terms that have been referred to is presented in figure 3-3. Figure 1-1 also provides a qualitative comparison of the differences in terminology used by agronomists and geotechnical engineers, and it shows that the plastic limit of fine-grained soils is in the vicinity of the upper limit of the capillary moisture range. Hence, the plastic limit seems to coincide with the negative pressure (tension or suction) of the soil moisture at which considerable moisture migration occurs upon application of a thermal gradient [19]. Furthermore, Salomone [4] has presented data that suggest that the plastic limit defined by geotechnical engineers can be correlated with the critical moisture content. Results from this study, as discussed in section 4 provide additional insight into the relationship among the critical moisture content, optimum moisture content and the plastic limit of fine-grained soils.

In summary, we see that the primary factors affecting the thermal resistivity of soils are: soil composition, density, and moisture content. Empirical correlations between these factors and thermal resistivity are available (e.g., fig. 3-2). However, the key to improving our predictive capability in the field of thermal soil mechanics is a thorough understanding of the soil characteristics which affect thermal soil behavior. A discussion of these characteristics follows.

3.3 ASSESSING THE ENGINEERING PROPERTIES OF SOILS

Soil texture, plasticity and cohesiveness form the basis for the soil classification schemes commonly used by geotechnical engineers. Texturally, soils are classified as either coarse-grained (sands and gravels) or fine-grained (silts and clays) with the dividing line being whether the soil is retained on/or passes through the 75μm (no. 200) sieve. The particle size distribution of sands and gravels have an important influence on their engineering behavior. For fine-grained soils the engineering properties are greatly affected by the presence of water rather than by the texture alone.

The presence of water affects the plasticity and cohesiveness of fine-grained soils by affecting the interaction between the mineral grains. The plasticity and cohesion of a soil are indicators of soil type. Clays are both plastic and cohesive while sands are non-plastic and noncohesive (cohesionless). Silts are intermediate between sands and clays. Silts are fine-grained yet non-plastic and cohesionless. These relationships have been summarized by Holtz and Kovacs [3] (table 3-1).

Table 3-1. Textural and Other Characteristics of Soils (from [3])

Soil name:	Gravel, Sands	Silts	Clays
Grain size:	Coarse grained Can see individual grains by eye	Fine grained Cannot see individual grains	Fine grained Cannot see individual grains
Characteristics:	Cohesionless Nonplastic Granular	Cohesionless Nonplastic Granular	Cohesive Plastic -
Effect of water on engineering behavior:	Relatively unimportant (exception: loose saturated granular materials and dynamic loadings)	Important	Very important
Effect of grain size distribution on engineering behavior:	Important	Relatively unimportant	Relatively unimportant

By mechanical analysis the particle size distribution (texture) of a soil is obtained. Detailed procedures for this test have been specified by ASTM D 422-72 (Standard Method for Particle-Size Analysis of Soils) procedures [12]. Atterberg Limit tests [12, 20, 21] are used to measure the plasticity of fine-grained soils. The Atterberg Limits are moisture contents which represent important limit states of engineering behavior (fig. 3-4). By knowing the natural moisture content of a soil in relation to its Atterberg Limits, the engineering response of a soil can be predicted. Because Atterberg Limits are limiting moisture contents, these limits of engineering behavior can be shown on a moisture content continuum (fig. 3-5).

From figure 3-5 we see how geotechnical engineers use the results of classification tests to show: a) types of soil behavior for given ranges of moisture contents, and b) changes in the state of soil as moisture content changes. This figure serves to demonstrate the need to establish classification tests which indicate the thermal behavior of soils. Results from this study discussed in section 4 begin to meet this need for fine-grained soils.

3.4 DETERMINING THE THERMAL BEHAVIOR OF SOILS

3.4.1 General

Progress in the determination of the thermal behavior of soils has been hampered by the fact that information on thermal soil properties that is scattered in a variety of technical fields has not been consolidated, and professionals lack a common language to describe the thermal behavior of soils.

Procedures used to evaluate the thermal properties of soils are based on routine methods adopted over the years but do not necessarily reflect all the information and techniques now available in the various disciplines faced with the problem of soil characterization and the prediction of heat transfer in soils. As part of these routine procedures, heat flow problems are frequently solved using constant values of soil thermal conductivity from "handbooks" without considering the factors which affect soil thermal conductivity previously discussed. Also, researchers have not always documented their findings in terminology that is consistent nor correlated their results with the findings of earlier work [2].

Use of soil as an insulating material or a material to dissipate heat requires that progress be made in this area and a systematic approach be developed.

3.4.2 Approach

After reviewing the factors that influence the thermal resistivity of soil and the methods available to assess the type and properties of soils, the hypothesis is advanced that thermal soil behavior can be correlated with the soil limit states associated with moisture content, which in turn can be identified by methods developed by geotechnical engineers and agronomists. The program reported herein was designed to test this hypothesis for one cohesive soil and examine existing data for other fine-grained soils to determine whether the findings of the tests also apply to other materials.

The following approach was used:

1. Select one fine-grained soil whose index properties are well known. Hence, AMRL Reference Soil No. 61 described in section 2.2 was selected.

2. Investigate in detail the influence of moisture and density on the thermal resistivity of the AMRL reference soil and correlate the trends with the limit states of soil behavior (Atterberg Limits) and other index properties used by geotechnical engineers.

3. Identify the concepts, methods and tests which aid in the determination of the thermal behavior of the AMRL reference soil using the results from step 2, above.

4. Obtain index property and thermal resistivity test data for other fine-grained soils. Apply the concepts, methods, and tests identified for for the AMRL reference soil to these soils and establish whether they are also appropriate for these soils.

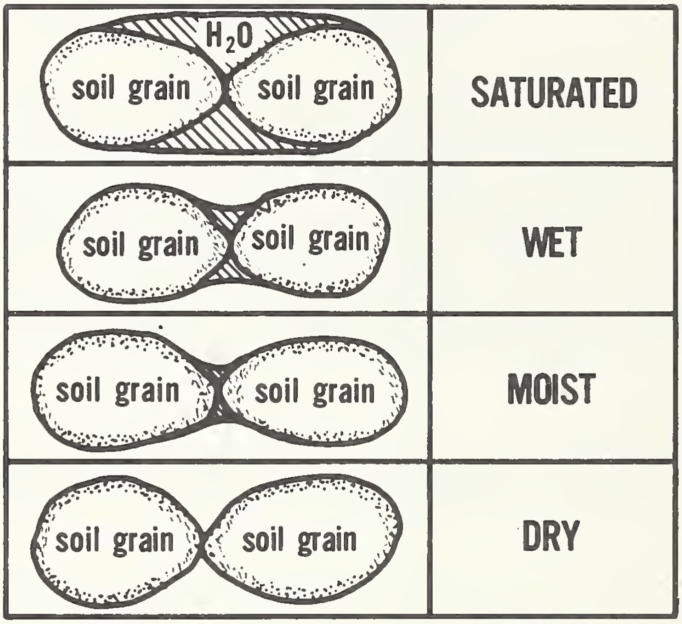


Figure 3-1. The effect of soil moisture on the heat flow path (from [4])

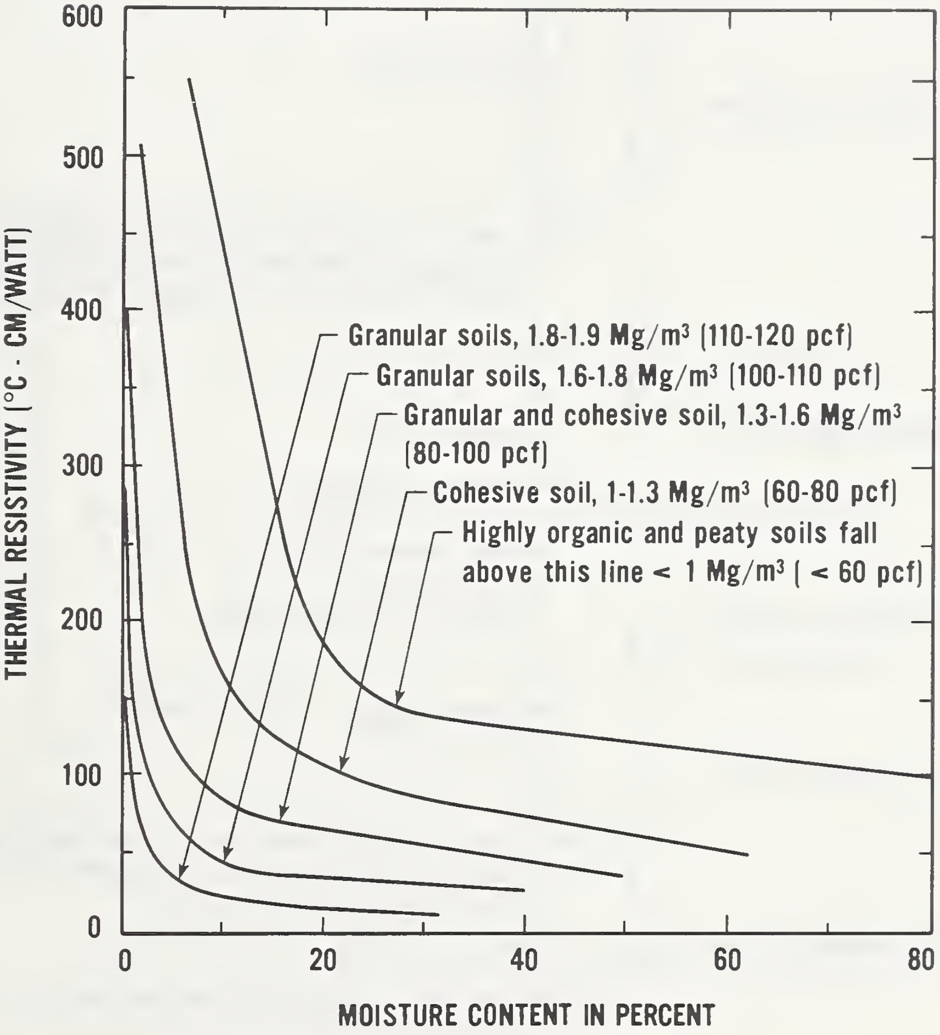


Figure 3-2. The effect of moisture content and dry density on the thermal resistivity of soils (from [15])

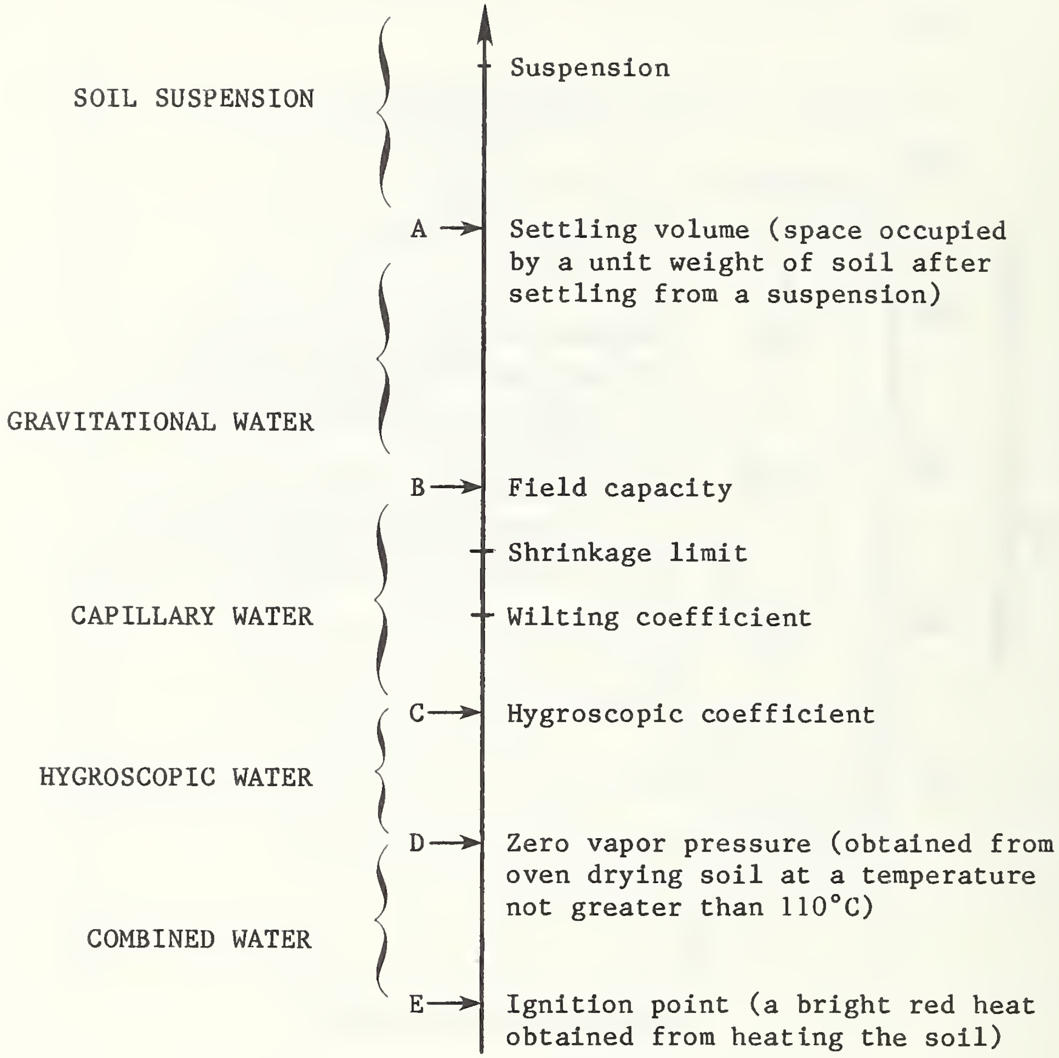


Figure 3-3. Soil moisture scale showing soil moisture terms used by agronomists (modified from [17])

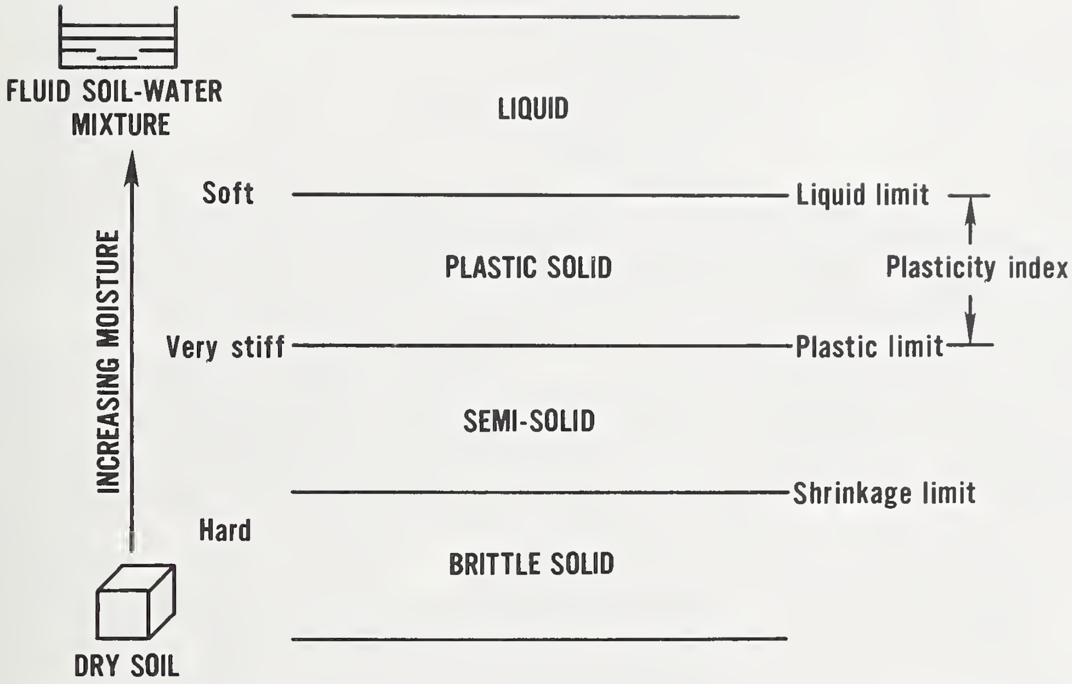


Figure 3-4. Soil moisture scale showing soil moisture terms (Atterberg Limits) used by geotechnical engineers for fine-grained soils (from [4])

FACING PAGE: The Laboratory Equipment Used to Determine the Thermal Properties of Soils.

Shown are the thermal property analyzer with printout device, and two soil samples with laboratory thermal probes inserted.

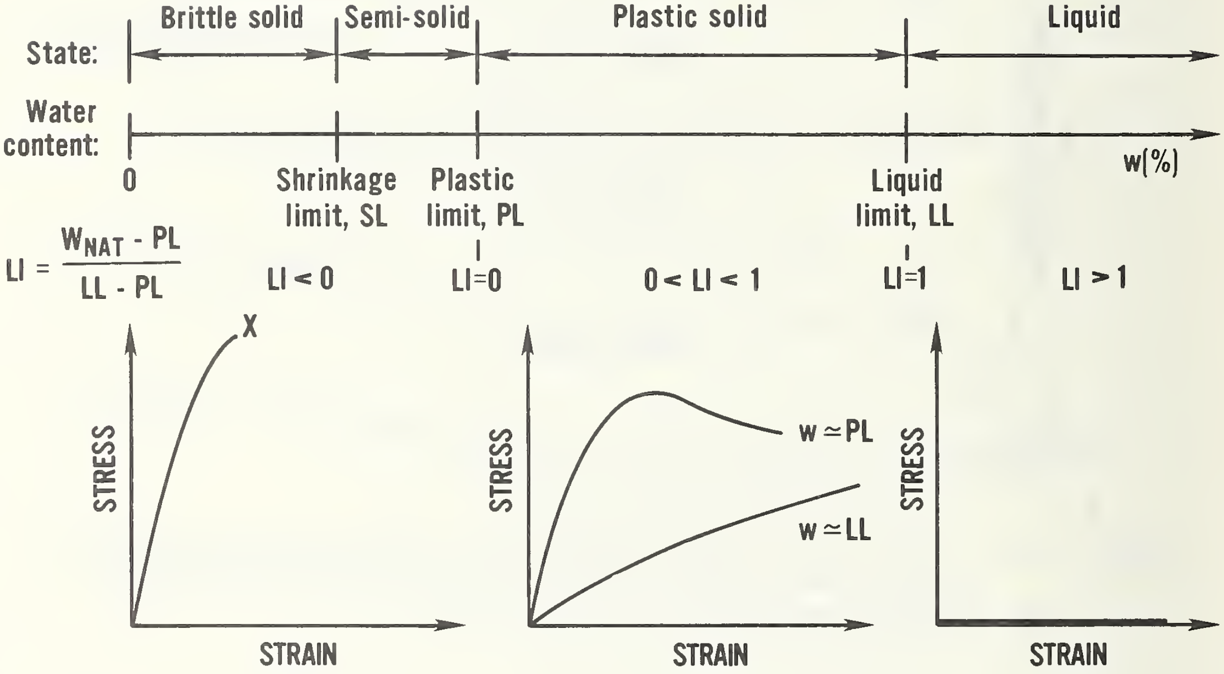
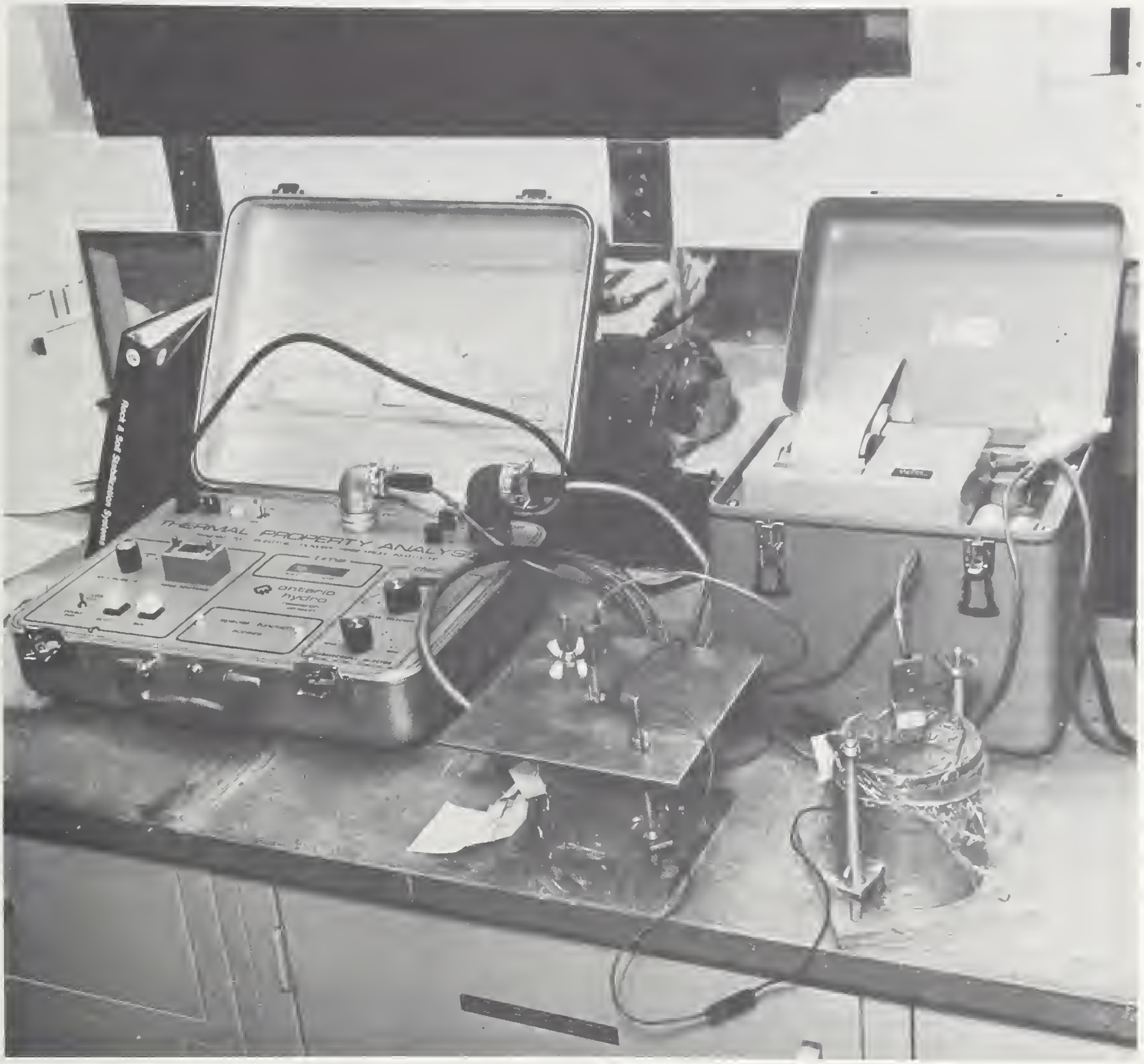


Figure 3-5. Moisture content continuum showing the various states of fine-grained soils and the generalized stress-strain response (modified from [3])



4. PRESENTATION AND DISCUSSION OF TEST RESULTS

4.1 GENERAL

The tables and figures in this section provide information on: a) the influence of density and moisture content on the thermal resistivity of the AMRL reference soil, b) the correlation of the trends observed in part a above with the compaction characteristics and the Atterberg Limits of the soil used in the study, and c) the index property and thermal resistivity test data for other fine-grained soils. A discussion of the data tabulated according to compactive effort in tables A-1 through A-8 in appendix A follows. It should be pointed out that, in most instances, no significant differences in measured values of thermal resistivity were observed for specimens compacted to the same moisture content and density. However, when comparing thermal resistivity test data from specimens remolded using S6 and S4 compactive efforts (see section 2.3.4) with thermal resistivity test data from specimens remolded using S12 compactive effort or greater, additional scatter in measured thermal resistivity were observed for specimens with the same moisture content and dry density. These differences could be caused by differences in soil fabric of the specimens tested. Voids were observed on the outer surface of the specimens compacted using the S6 and S4 compactive efforts. Therefore, the data for compactive efforts of S6 and S4 were not used in constructing figures 4-1 through 4-6.

4.2 EFFECT OF DENSITY

The influence of density on the thermal resistivity of the AMRL reference soil can be seen in figures 4-1 through 4-4. Figure 4-1 shows the variation of thermal resistivity with changes in moisture content for constant values of density. By reducing the total void volume and improving the contact between the solid grains through densification of the soil mass, a reduction in the thermal resistivity of the material can be achieved. We also see that the minimum thermal resistivity for a given density occurs as the zero air voids curve (100 percent saturation) is approached. Examination of the data for the modified and standard energies in appendix A provides additional insight into the thermal behavior of this material. The minimum and maximum thermal resistivity under saturated conditions can be approximated by measuring the thermal resistivity of two samples. One sample should be tested at the optimum moisture content* and maximum dry density* determined using the modified energy and the other sample should be tested at the liquid limit and that density which results from using standard energy. A thermal performance index can then be defined by the slope of the dashed line in figure 4-1. Eq. 8 approximates the slope of this line as follows:

$$TPI = \frac{\rho_S - \rho_M}{LL - w_{opt}} \tag{8}$$

where

TPI = thermal performance index

ρ_S = thermal resistivity of a sample prepared using standard energy (ASTM D 698-78 procedures, [12]) and a moisture content equal to the liquid limit, °C•cm/W

ρ_M = thermal resistivity of a sample prepared using modified energy (ASTM D 1557-78 procedures, [12]) and a moisture content equal to the modified optimum moisture content, °C•cm/W

LL = liquid limit as defined by ASTM D 423-72 procedures, [12], percent

w_{opt} = optimum moisture content using modified energy (ASTM D 1557-78 procedures, [12]), percent.

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* The terms optimum moisture content and maximum dry density are explained in section 4.4.

For the AMRL reference soil, the thermal performance index is: $\frac{75 - 48}{45 - 14} = 0.87 \approx 1$. The Thermal Performance Index, TPI, provides an indication of the thermal performance of the ARML reference soil under saturated conditions. It measures the change in thermal resistivity per unit change in moisture content over the range of densities expected under natural or artificial (man-made) field conditions. By taking into account the compaction characteristics and the thermal behavior of the soil, it is expected that this index may help in comparing quantitatively the thermal behavior of other fine-grained soils. Figure 4-2 presents the effect of density on the thermal conductivity of the AMRL reference soil for the purpose of comparison with Kersten data [22]. By keeping the moisture content constant and examining the change in thermal conductivity with density, the relationships in figure 4-2 and table 4-1 are obtained.

Table 4-1. Thermal Conductivity-Density Relationships

MOISTURE CONTENT IN PERCENT	EQUATION OF CURVE FOR CONDUCTIVITY IN WATT/°C•cm*
9.5	$k = 0.00007144(10)^{1.304\rho_d}$
13.0	$k = 0.001448(10)^{0.597\rho_d}$
17.0	$k = 0.002803(10)^{0.472\rho_d}$
22.5	$k = 0.01802$
27.0	$k = 0.01657$

* For k in W/m•°K multiply by 100

In general, in accordance with Kersten [22], the thermal conductivity varied with density according to the following equation:

$$k = A10^{B \cdot \rho_d} \tag{9}$$

where

k = thermal conductivity in watt/°C•cm
ρ_d = dry density, Mg/m^3
A and B = soil constants.

The results in figure 4-2 are in general agreement with the trends observed by Kersten [22]. However, in contrast to the Kersten [22] data, it was found that at moisture contents greater than 22.5 percent, the thermal conductivity was not significantly affected by density. Because the change in the Kersten [22] trend occurred at a moisture content close to the plastic limit (23.5 percent), the significance and validity of this finding should be confirmed with thermal probe tests on other fine-grained soils. This trend is also observed when the thermal resistivity versus dry density for constant moisture contents is plotted as shown on figures 4-3 and 4-4. The influence of density on the thermal resistivity continues to decrease until a moisture content in the vicinity of the plastic limit is reached. At moisture contents close to the plastic limit the effect of density is minimal.

4.3 EFFECT OF MOISTURE CONTENT

The influence of moisture content on the thermal resistivity of the AMRL reference soil is shown in figures 4-1 and 4-5 and table 4-2. Figure 4-1 shows that for a given density the thermal resistivity decreases with increasing moisture content until the critical moisture content (knee of the curve) is reached or, as in the case for the high densities (e.g. 1.84 Mg/m^3), until the zero air voids curve is approached. The trend in figure 4-1 suggests that if we want to explore the relationship between thermal resistivity and moisture content over a wide range of moisture contents for the purpose of correlating the observed trend with the limit states of soil behavior (Atterberg Limits), low density samples should be used. Also, a compactive effort which results in relatively constant density values over a wide range of moisture contents would be desirable to eliminate the influence of density on the test results.

Figure 4-5 is a plot of the thermal conductivity versus the logarithm of the moisture content. Such a plot ordinarily gives a straight line for that part of the data above a certain minimum moisture content. Kersten's [22] data suggests that this minimum moisture content is 7 percent for silt or clay soils. Considering this fact, straight lines for constant values of density were drawn on figure 4-5. This type of plot appears to fit the data as it did the Kersten's [22] data, and equations have been developed for the relationships shown in figure 4-5 (see table 4.2).

Table 4-2. Thermal Conductivity-Moisture Content Relationships

DRY DENSITY (Mg/m^3)	MOISTURE CONTENT RANGE IN WHICH APPLICABLE (PERCENT)	EQUATION FOR CONDUCTIVITY IN Watt/°C • cm*
1.84	12 to 17	$k = 0.0215 \log w - 0.00506$
1.72	9 to 21	$k = 0.0186 \log w - 0.00576$
1.66	14 to 23	$k = 0.0169 \log w - 0.00487$
1.54	14 to 27	$k = 0.0146 \log w - 0.00441$

* For k in W/m•°K multiply by 100

The equations are of the Kersten [22] form:

$$k = A_1 \log (W) + B_1 \tag{10}$$

where

k = thermal conductivity, W/°C•cm
A_1 = the slope of the line,
B_1 = the value of the intercept of the curve at 1 percent moisture, and
W = moisture content, expressed as a percent.

These equations allow determination of the moisture content of the AMRL soil if the thermal conductivity is measured and the approximate density is known for the purposes of selecting the appropriate equation. Once again it should be pointed out that the moisture content referred to in the preceding discussion is the inner moisture content of the center core soil sample as defined in section 2.3.6. A comparison of the inner, outer, and total moisture content and the moisture content of the trimmings is provided in tables A-9 through A-15 in appendix A. There was no significant difference observed among the inner, outer and total moisture contents. This observation is consistent with the trend expected for fine-grained, laboratory cured soil samples. Any difference between the moisture content of the trimmings with the other moisture contents determined results from the rapid rate of drying observed for the trimmings while the thermal probe test sample was being trimmed. Therefore, a lower initial weight was measured for the trimmings.

The moisture losses (or gains) of the thermal probe test samples during the thermal probe test are shown on tables A-16 through A-22. The average moisture loss was -0.04 percent. Seven samples gained moisture during the thermal probe test. The average moisture gain was 0.01 percent.

4.4 DETERMINATION OF SOIL THERMAL BEHAVIOR

After determining the influence of density and moisture content on the thermal resistivity of the AMRL reference soil, an attempt can be made to define an approach which will aid in determining the thermal behavior of fine-grained soils. Figure 4-6 constructed using the same data as figures 4-2 and 4-5 serves as an aid in estimating the thermal conductivity of the AMRL reference soil using the moisture content and dry density of the soil. It is also interesting to note that figure 4-6 can be used with the equations in tables 4-1 and 4-2 to estimate the moisture content and dry density of the AMRL reference soil if the thermal conductivity is known. This concept is important because as data on other fine-grained soils become available using the form of data presentation shown, engineers may be able to use the thermal conductivity of the soil to estimate its moisture content and dry density.

The next step in determining the thermal behavior of the AMRL reference soil is to correlate its trends in thermal resistivity versus moisture content and dry density, with its compaction characteristics and Atterberg Limits. When the dry densities of each sample are determined and plotted versus the moisture contents for each sample and compactive effort, curves called compaction curves are obtained (figure 4-7). Each data point on the curves shown represents a single compaction test for which the thermal resistivity was determined. Each curve is unique for the AMRL reference soil and the method of impact compaction and compactive effort used in the program. The peak point corresponding to the maximum dry density is an important point. It is known as the optimum moisture content. Note that the maximum dry density is only a maximum for a specific compactive effort. Increasing the compactive effort increases the maximum dry density, as expected, but also decreases the optimum moisture content. The compaction curves flatten out with a decrease in compactive effort. Note too that the compaction curves, even at higher moisture contents and compactive efforts, never actually reach the curve for "100 percent saturation" (traditionally called the zero air voids curve). Test specimens were prepared by 7 different compaction energies as described in section 2.3.4 to obtain the thermal resisitivity/conductivity data over a wide range of density and moisture.

The modified energy (ASTM D 1557-78 [Standard Test Methods for Moisture - Density Relations of Soils and Soil - Aggregate Mixtures Using 10-lb (4.54-kg) Rammer and 18-in (454-mm) Drop] procedures, [12]) and the standard energy (ASTM D 698-78 [Standard Test Methods for Moisture - Density Relations of Soils and Soil - Aggregate Mixtures Using 5.5-lb (2.49-kg) Rammer and 12-in (305-mm) Drop] procedures, [12]) are commonly used by engineers to determine the moisture-density relation of fine-grained soils. Hence, these energies were selected from the compactive efforts used to mold samples for presentation in figure 4-7. The S6 energy was selected for presentation because it met the criteria stated in section 4.3, i.e., it causes a relatively small fluctuation of density over a range of moisture contents from 10 percent to 30 percent. As we will see later, this characteristic will be helpful in correlating the thermal resistivity versus moisture content relationship of this soil with its Atterberg Limits.

The thermal resistivity of test specimens compacted at the dry density and moisture content shown on the compaction curve are shown on figures 4-8 through 4-14 for each of the compactive efforts used in this study. The minimum thermal resistivity for each compactive effort generally occurs at the point of optimum moisture content and maximum density. When a plot of minimum thermal resistivity versus compactive effort is made, the importance of compactive effort (or density) in achieving the minimum thermal resistivity during placement of this material is seen (figure 4-15).

The correlation of the thermal resistivity versus moisture content relationship of the AMRL reference soil with its Atterberg Limits is shown on figure 4-16. When the S6 energy is used to mold the test specimens, the thermal resistivity increases very rapidly with a slight reduction in moisture content below the plastic limit of the soil. Thus, the "critical moisture content" at a low density (1.4 to 1.5 Mg/m^3) can be found using the plastic limit of the soil under investigation. For those involved in soil heat transfer problems, this finding is important. Recalling from figure 1-1 and section 3.2.3 that the plastic limit generally defines the upper boundary of capillary moisture and that moisture migration under a thermal gradient involves capillary moisture, the negative pressure potential (often termed capillary potential, and more recently matric potential) of soil water defined by the plastic limit can be used to determine the thermal performance and stability of a fine-grained soil. If the measured negative pressure potential of soil water exceeds the negative pressure potential defined by the plastic limit [23], the soil would be expected to be thermally unstable and moisture migration under thermal gradients would be likely.

Because geotechnical engineers do not often measure the matric potential of soil water which results from the capillary and adsorptive forces due to the soil matrix, figure 4-17 presents an approximate approach for evaluating the thermal performance and stability of the AMRL reference soil using the moisture content of the soil. Four distinct regions shown on figure 4-17 establish the thermal performance of this soil. The regions are defined by the moisture contents shown in table 4-3. Also, the trend in thermal resistivity with increasing moisture content for each of the regions is described.

Figure 4-17 can also be used to define an index which is a measure of the thermal stability of the AMRL reference soil at a dry density of 1.4 to 1.5 Mg/m^3 and at a particular moisture content. This moisture content should be the minimum moisture content of the soil that is expected under design conditions. Note that thermal instability occurs in a moist soil as a result of significant moisture movement when the soil is subjected to thermal gradients and the moisture content of the soil falls below the critical moisture content. Therefore a large increase in the thermal resistivity occurs.

The index is called by the authors the thermal stability index and is defined as follows:

$$\mathrm{TSI} = \frac{w_D - \mathrm{PL}}{w_{SC} - \mathrm{PL}} \tag{11}$$

where:

TSI = Thermal Stability Index
w_D = minimum moisture content expected under design conditions, percent
PL = Plastic Limit as defined by ASTM D 424-71 procedures [12], percent
w_{SC} = supercritical moisture content: i.e., the moisture content at which the thermal resistivity increases with increasing moisture content, percent.

Table 4-3. Thermal Performance Regions of AMRL Reference Soil (See Fig. 4-17)

REGION OF THERMAL PERFORMANCE	DESCRIPTION OF TREND IN THERMAL RESISTIVITY	BOUNDARY MOISTURE CONSTANT
1	Rapid decrease with increasing moisture content	PT. A - Oven dry PT. B - Shrinkage limit
2	Moderate decrease with increasing moisture content	PT. B - Shrinkage limit PT. C - Plastic limit
3	No change with increasing moisture content	PT. C - Plastic limit PT. D - Supercritical moisture content
4	Moderate increase with increasing moisture content	PT. D - Supercritical moisture content PT. E - Liquid limit

Using the Thermal Stability Index, the thermal stability of this fine-grained soil can be evaluated according to table 4-4. If the supercritical moisture constant was not known, the Liquid Limit of the soil could have been substituted for the supercritical moisture content in equation 11.

Table 4-4. Thermal Stability Index for AMRL Reference Soil

THERMAL STABILITY INDEX (TSI)	DESCRIPTION OF THERMAL STABILITY
$TSI \leq 0$	- Unstable - Moisture migration under thermal gradients likely
$0 < TSI \leq 1$	- Stable - Moisture migration under thermal gradients is unlikely - Thermal resistivity of the soil is essentially constant
$TSI > 1$	- Stable - Thermal resistivity increases with increasing moisture content

4.5 THERMAL BEHAVIOR OF OTHER FINE-GRAINED SOILS

The literature was examined to obtain data on soils with known index and thermal properties. This was accomplished after the concepts, methods and tests described in the preceding sections were identified as being useful when predicting the thermal behavior of the AMRL reference soil. Because the available information is quite limited and authors measuring the thermal properties of soils often do not classify the soils tested using a common soil classification system, nor do they provide the index properties and compaction characteristics of the soil they tested, the information presented was obtained through the cooperation of other researchers. Information in the literature generally fell into two groups. Group 1 contained those soils in which stage drying of one sample was performed to determine the thermal resistivity versus moisture content relationship. Group 2 contained those soils in which the thermal resistivities of samples at different moisture contents and densities were measured. The thermal resistivity versus moisture content relationship using data from [22] had to be determined by adjusting each thermal resistivity reported for density. The Kersten equation for fine-grained soils [22] was used to adjust the measured thermal resistivity for density. The Kersten equation is:

$$\text{Thermal conductivity, } k = [0.9 \log (\text{Moisture Content}) - 0.2]10^{0.01 \times \text{Unit Wgt.}}$$

A summary of the data found in the literature is provided in tables 4-5 and 4-6 and figures 4-18 through 4-24. It should be pointed out that because the available data were quite limited, only the concepts of correlating the critical moisture content with the optimum moisture content and plastic limit was evaluated.

Table 4-5. Correlation of Critical Moisture Content and Optimum Moisture Content for Other Fine-Grained Soils

CATEGORY	SOIL DESCRIPTION	UNIFIED SOIL CLASSIFICATION	CRITICAL MOISTURE CONTENT (PERCENT)	DRY DENSITY OF SAMPLE	OPTIMUM MOISTURE CONTENT (PERCENT)	FIGURE AND REFERENCE
Group 1	Georgia Clay	ML	18	77% of standard maximum density	19 (standard energy)	4-18 Black, 1982, private communication
Group 2	Niagara Clay	CL	20	NA	20 (standard energy)	4-19, [24]
	P4505 Northway Silt Loam	ML	16	NA	16 (modified energy	4-20, [22]
	P4602 Fairbanks Silt Loam	ML	16	NA	16 (modified energy)	4-21, [22]
	P4710 Fairbanks Silty Clay Loam	ML	18	NA	18 (modified energy)	4-22, [22]
	P4708 Healy Clay	CL	17	NA	17 (modified energy)	4-23, [22]
	P4713 Ramsey Sandy Loam	CL	9	NA	9 (modified energy)	4-24, [22]
	Little Long Till	CL	12	NA	12 (standard energy)	[24]

The index property and thermal resistivity test data obtained for the other fine-grained soils shown in Table 4-5 indicate that the critical moisture content of fine-grained soils can be defined by the optimum moisture content. To use the optimum moisture content to define the critical moisture content it is important to understand that:

1) a dry density must be specified when defining the critical moisture content of a soil because the critical moisture content increases as density decreases

(figure 4-1). (The dry density specified can be the in situ dry density (natural) or a dry density which is a percentage of the laboratory maximum dry density determined by some standard test, e.g. standard Proctor test (ASTM D698-78 procedures) or the modified Proctor test (ASTM D1557-78 procedures).

2) The compactive effort chosen to determine the optimum moisture content will depend on the dry density for which the critical moisture content is being defined.

3) The critical moisture content is the moisture content at which the minimum value of thermal resistivity is observed. The index property and thermal resistivity test data obtained for the other fine-grained soils shown in table 4-6 indicate that the critical moisture content of fine-grained soils can be defined by the plastic limit for marine sediments that have low natural dry densities. Hence, it appears that the critical moisture content correlates with the optimum moisture content for soils over a wide range of densities. However, as the density of the fine-grained soil decreases to densities typical of unconsolidated marine deposits, a correlation between the critical moisture content and the plastic limit is evident.

Table 4-6. Correlation of Critical Moisture Content and Plastic Limit for Other Fine-Grained Soils

Category	Soil Description	Unified Soil Classification	Critical Moisture Content (Percent)	Plastic Limit (Percent)	Reference
Group 1	Lake Erie Bottom Sediments (very soft clay)	CH	30-40	35-45	[25]
	Lake Erie Bottom Sediments (soft clay)	CH	25-30	25-30	[25]
	Atlantic City Marine Sediments	CH	30	30	[4]
	Georgia Strait Bottom Sediments	OH	66	68 (45-90)	[26]
	Malaspina Strait Bottom Sediments	OH	74	68 (45-90)	[26]

The limited amount of data in the literature, that are available to corroborate the concepts presented in this report, points to the need for researchers to consider these concepts when planning the laboratory testing programs for determining the thermal properties of soils and when reporting their findings.

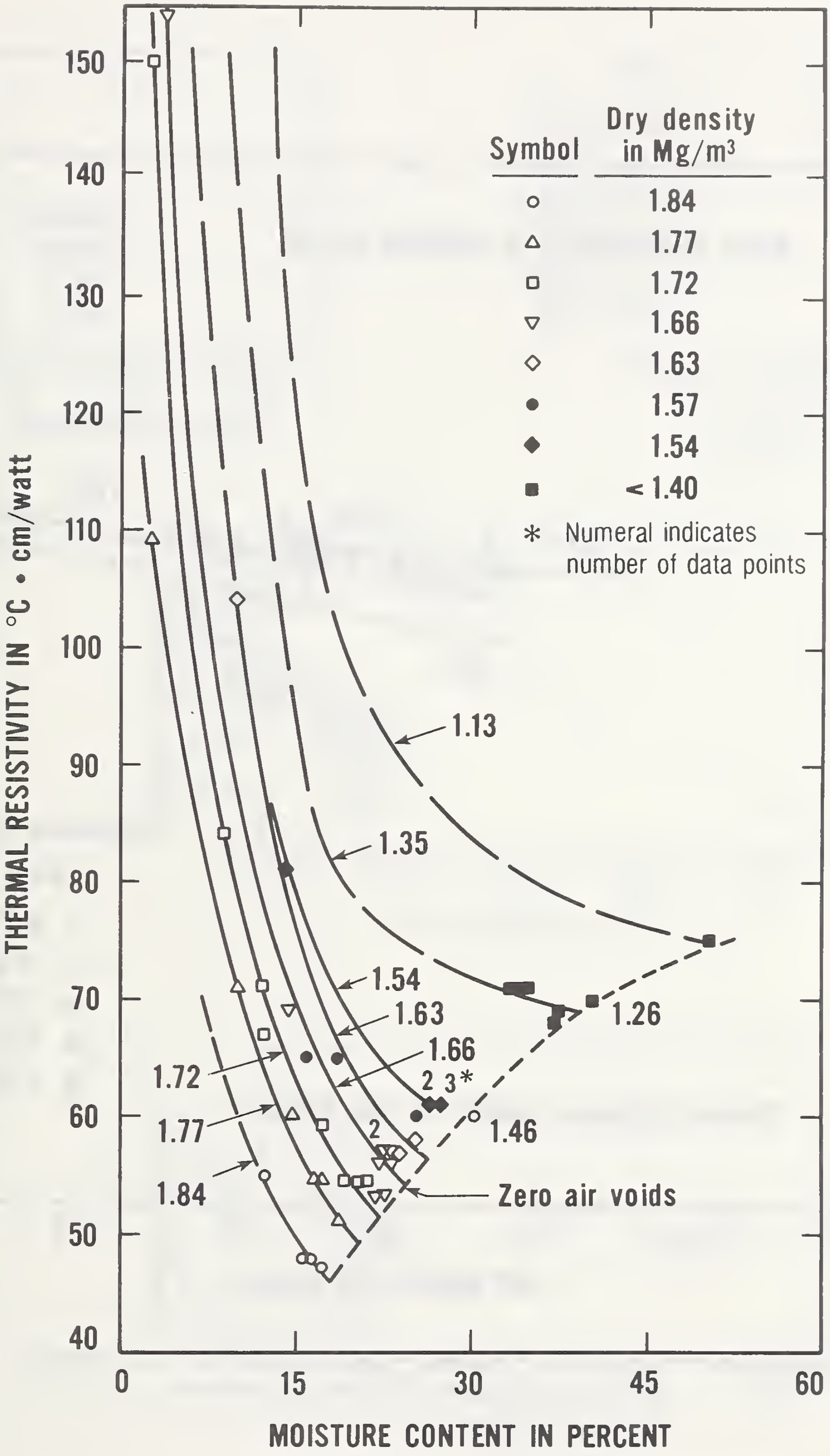


Figure 4-1. Variation of thermal resistivity with moisture content and dry density for AMRL Reference Soil

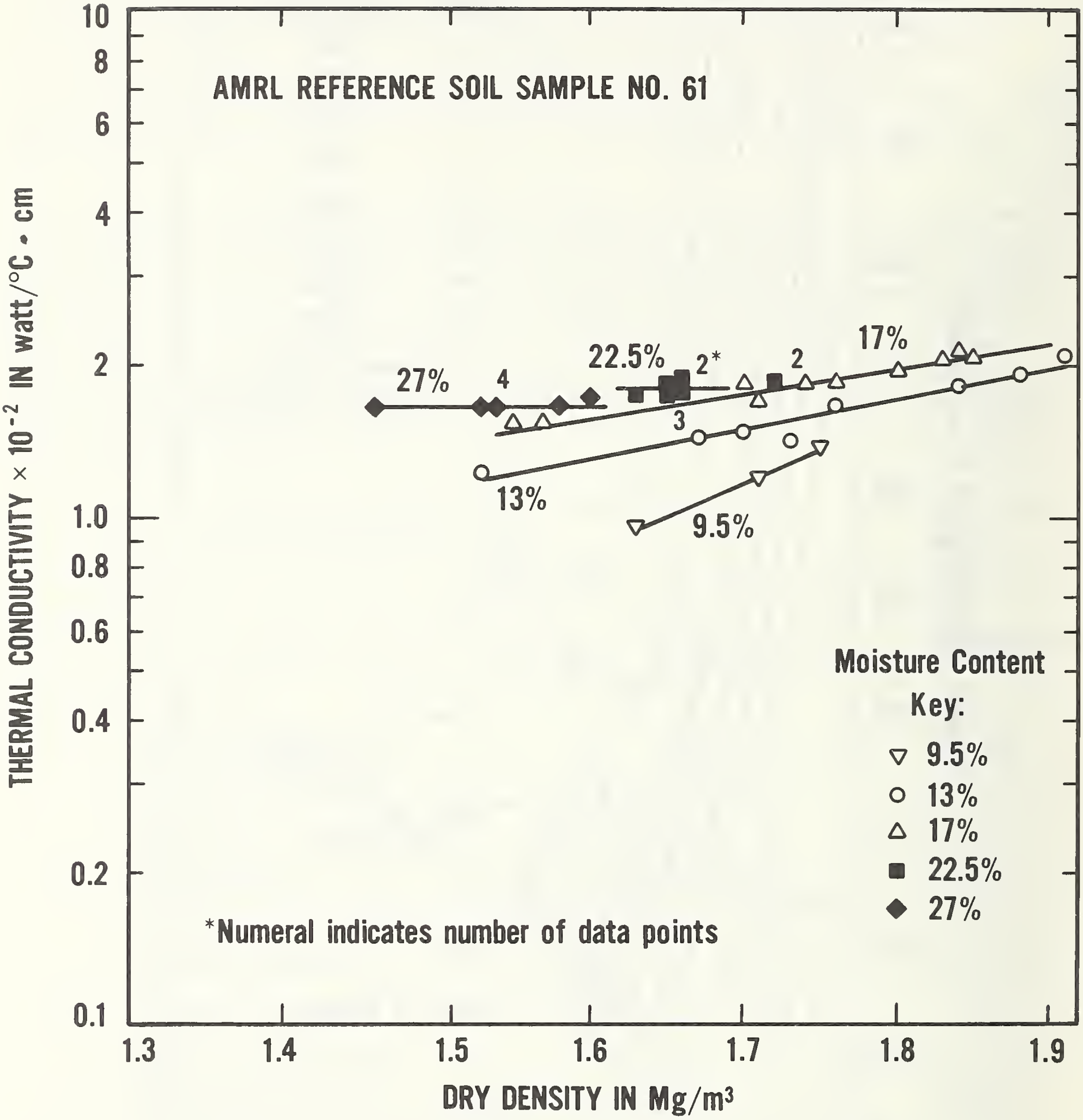
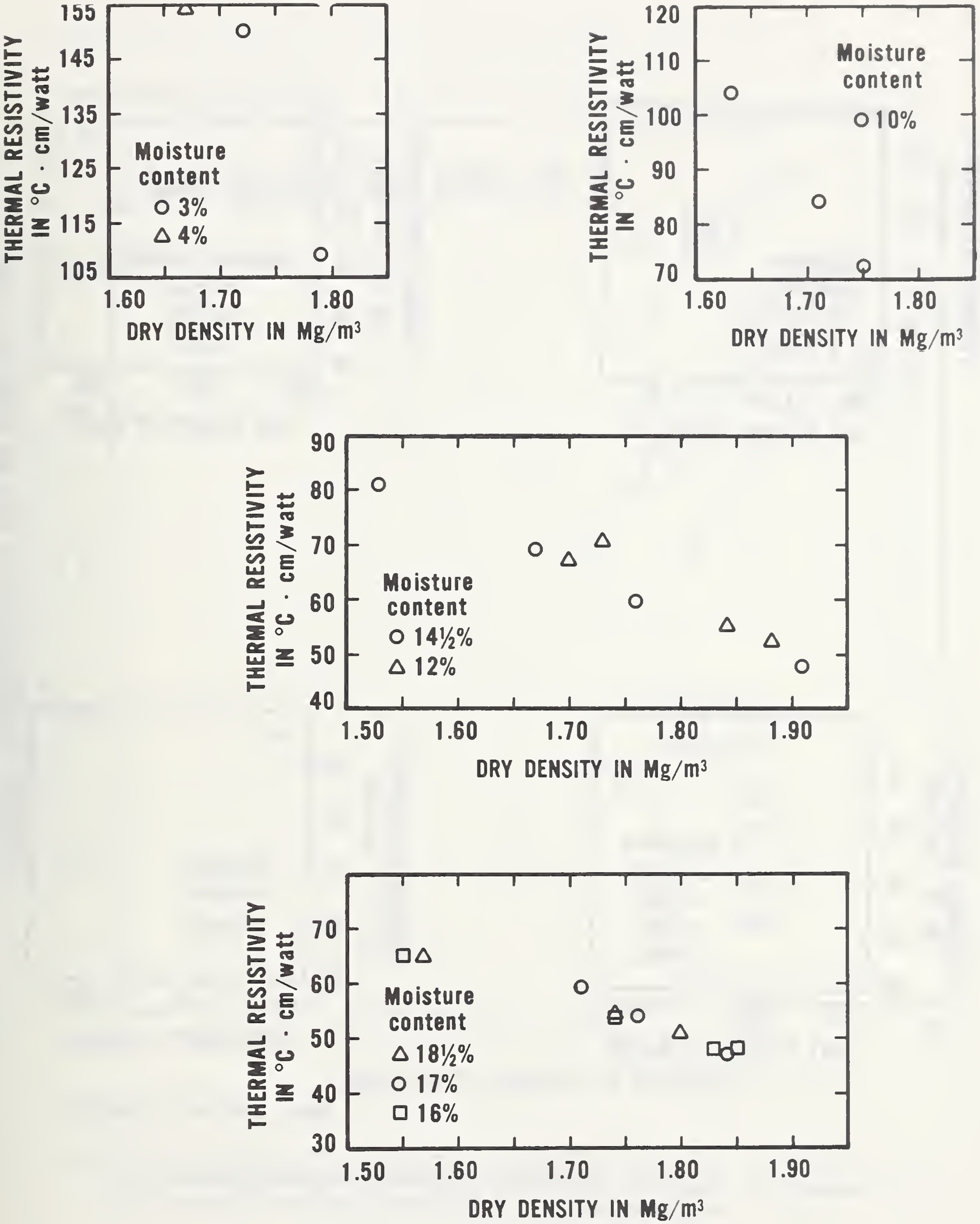
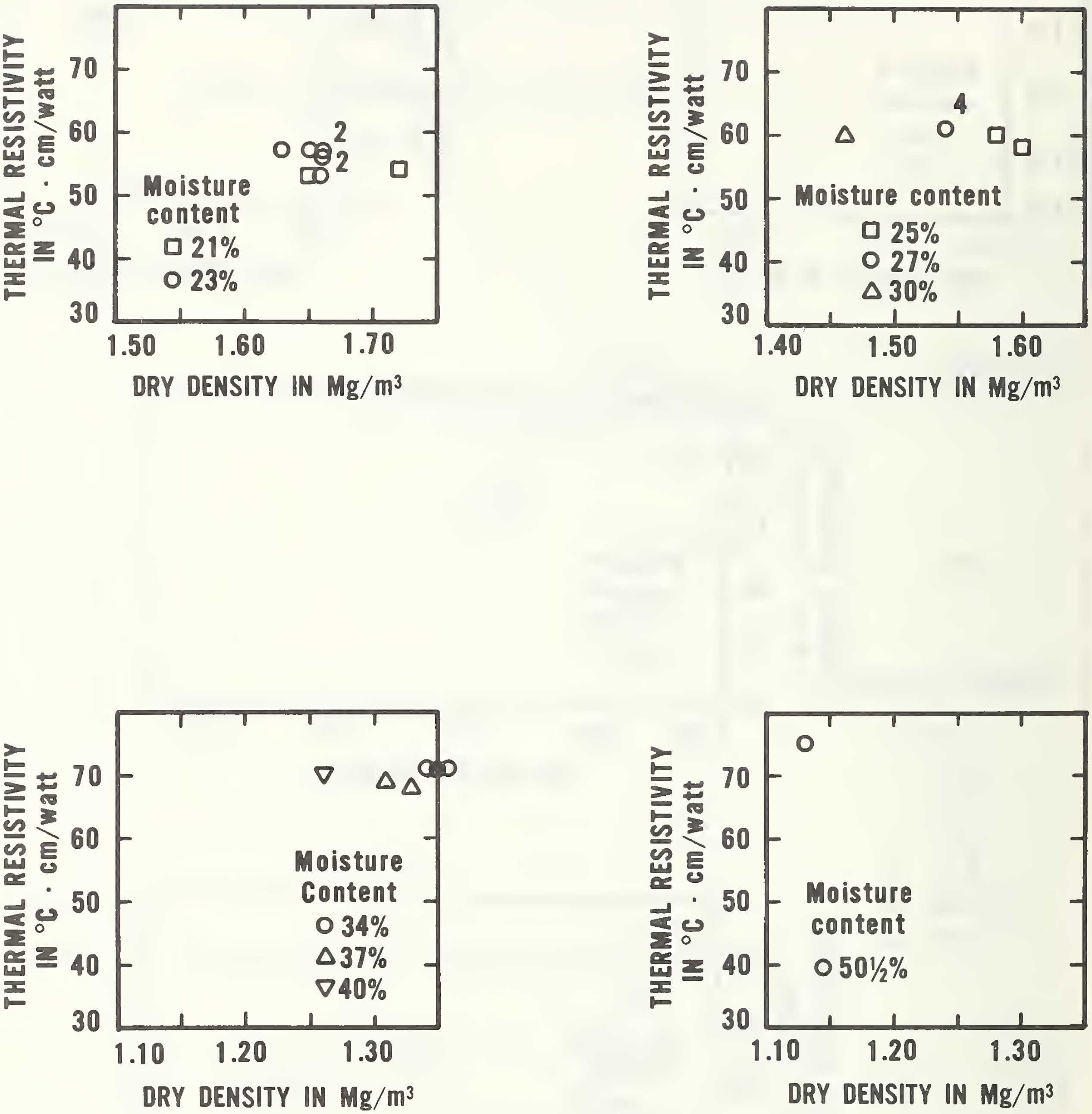


Figure 4-2. Variation of thermal conductivity with dry density for various values of moisture content



Note: 1 Mg/m3 = 62.4 PCF

Figure 4-3. Variation of thermal resistivity with dry density for moisture contents of 3 percent to 18-1/2 percent



Note: 1 Mg/m³ = 62.4 PCF

Figure 4-4. Variation of thermal resistivity with dry density for moisture contents of 21 percent to 50-1/2 percent

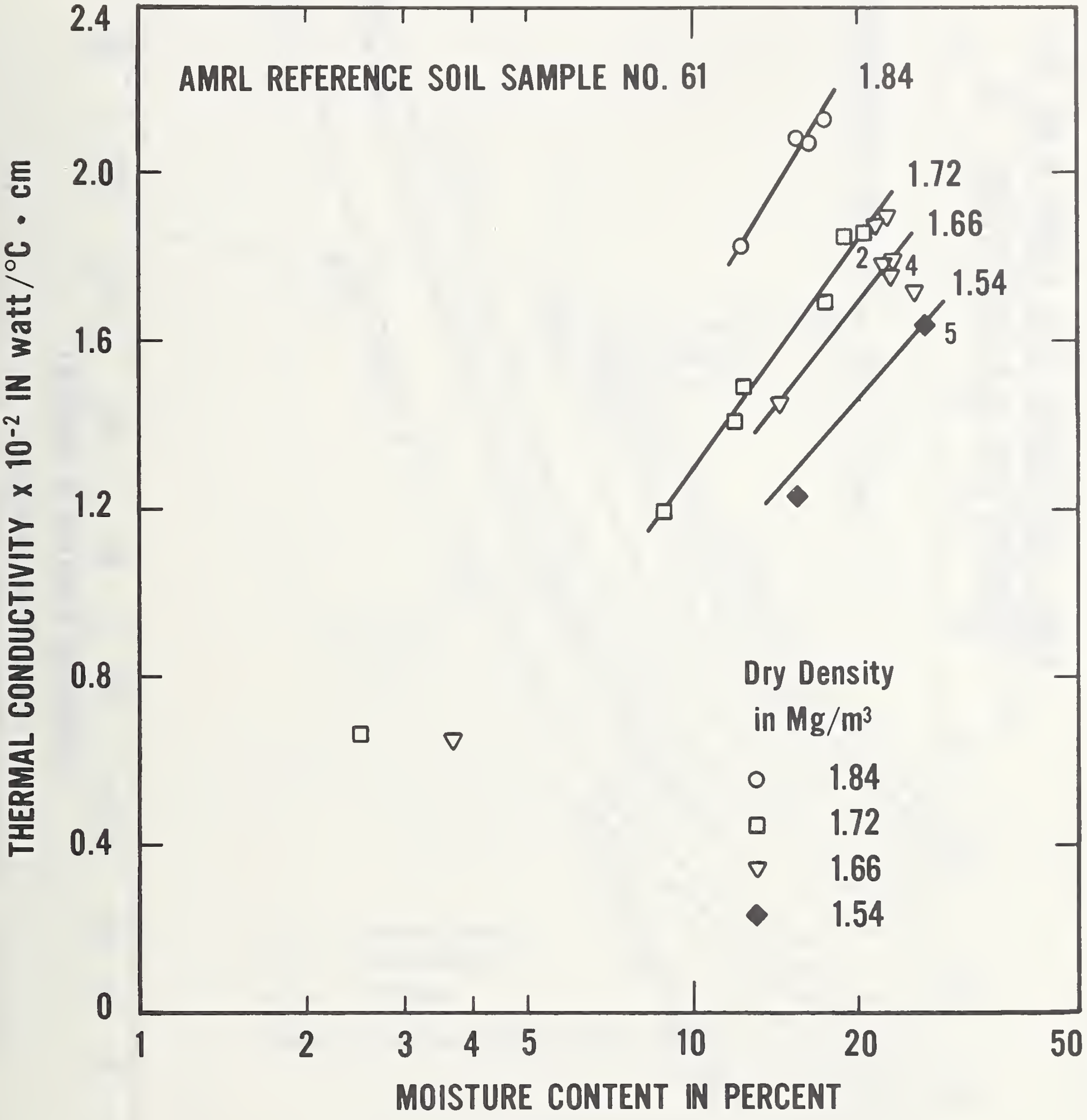


Figure 4-5. Variation of thermal conductivity with moisture content for various values of dry density

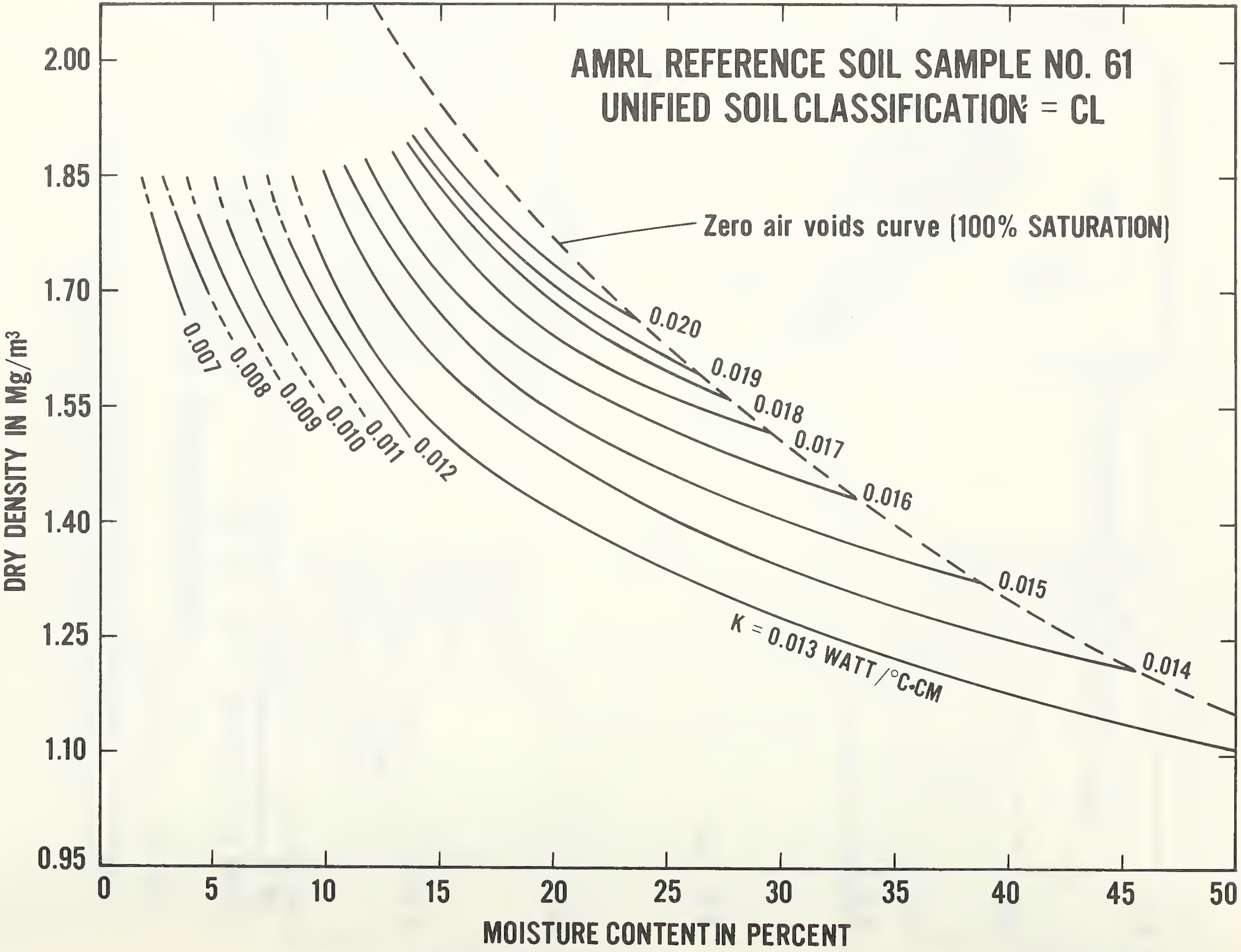


Figure 4-6. Diagram of thermal conductivity for AMRL reference soil

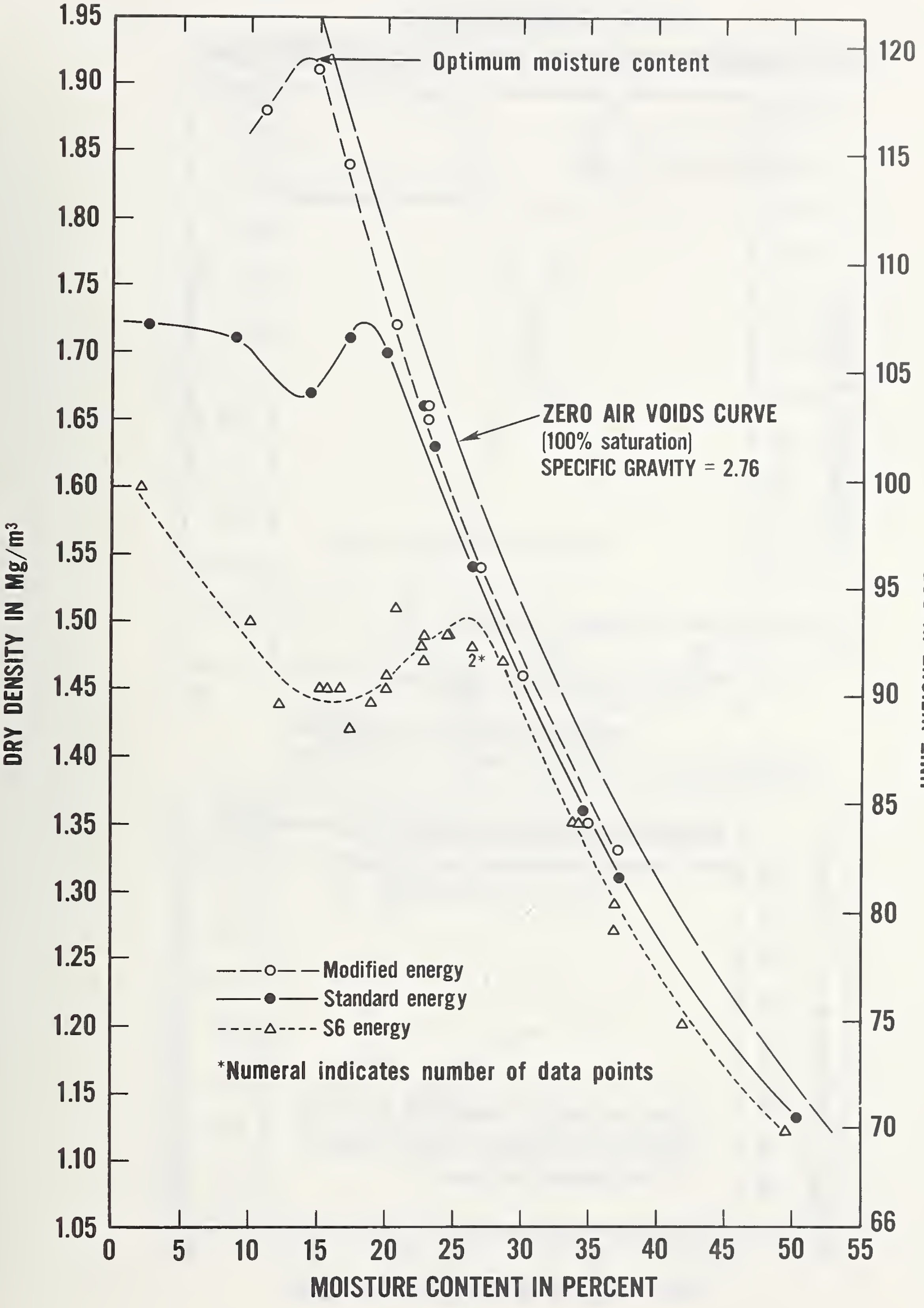
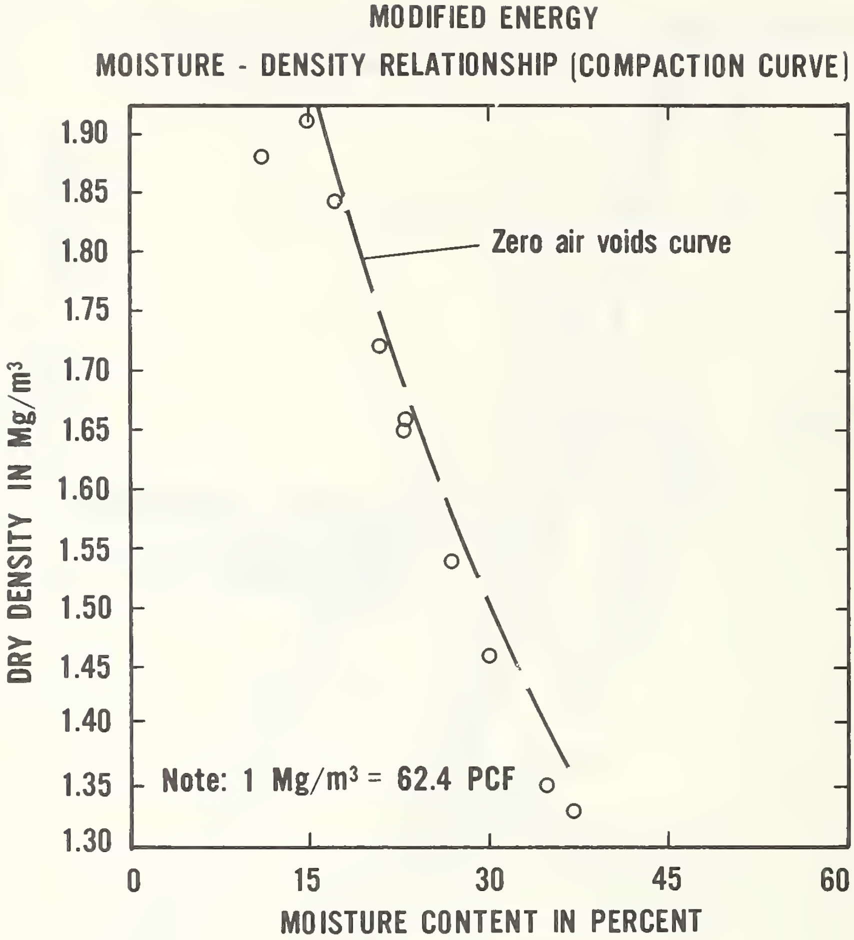


Figure 4-7. Compaction curves for modified, standard, and S6 energies



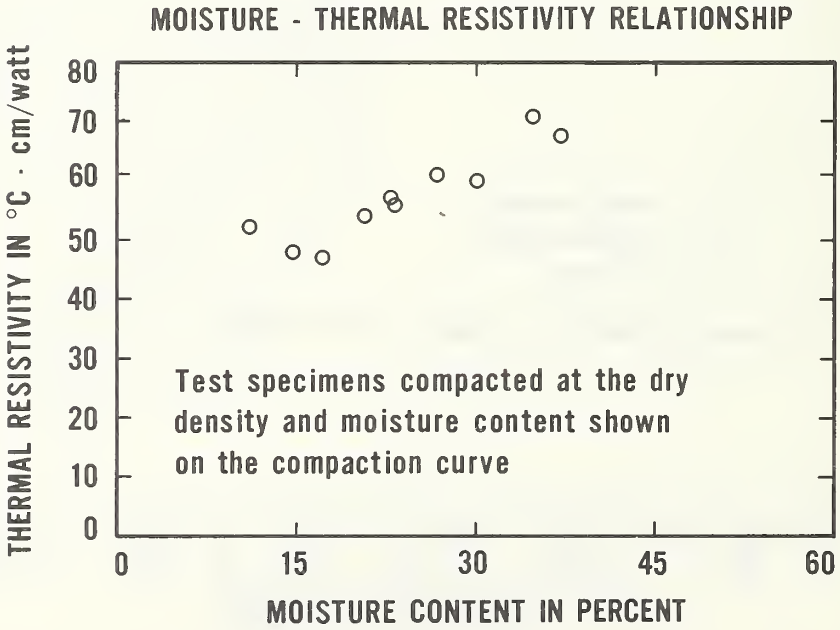


Figure 4-8. Correlation of modified energy moisture - density curve with thermal resistivity - moisture content curve

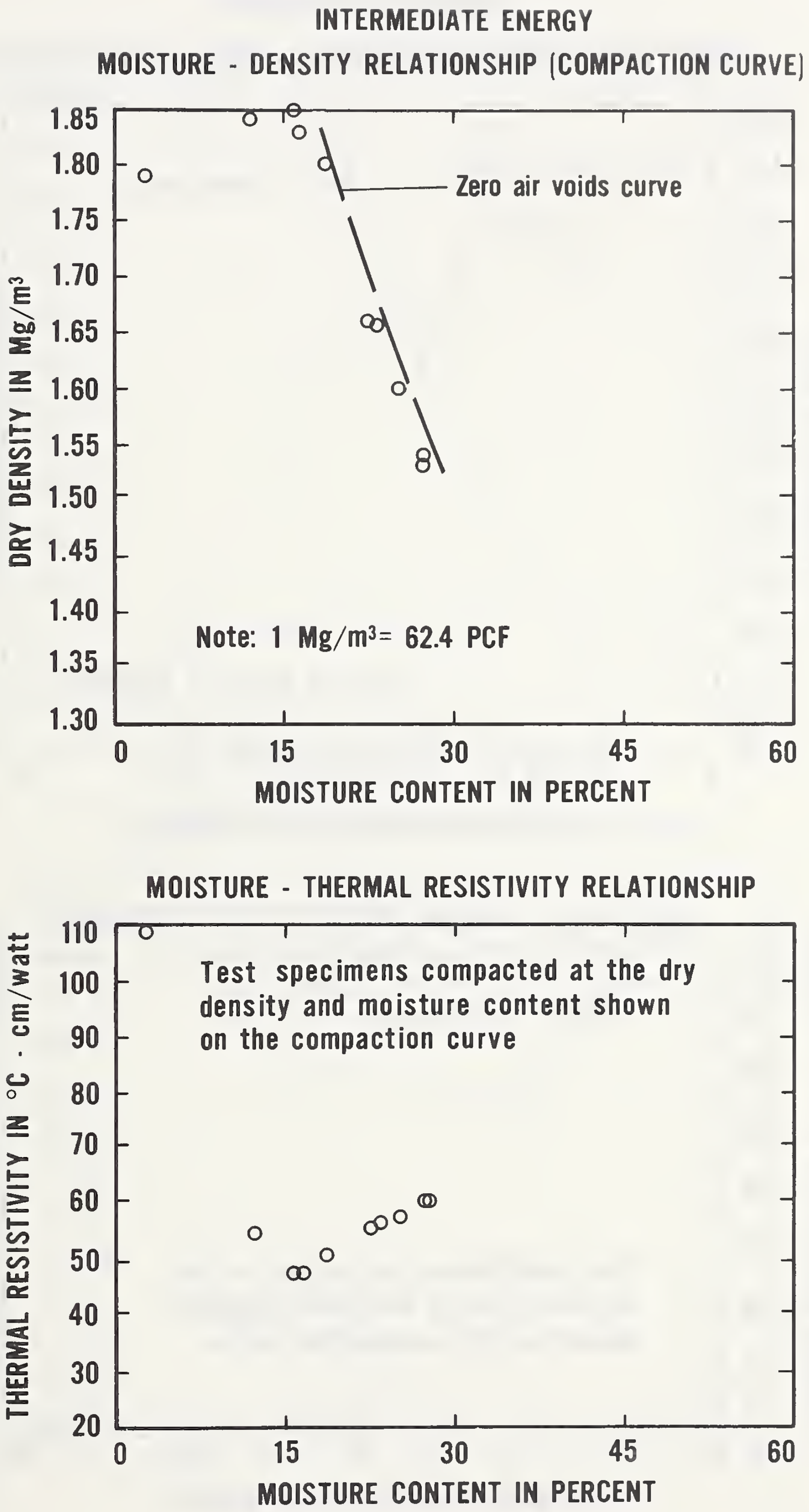


Figure 4-9. Correlation of intermediate energy moisture - density curve with thermal resistivity - moisture content curve

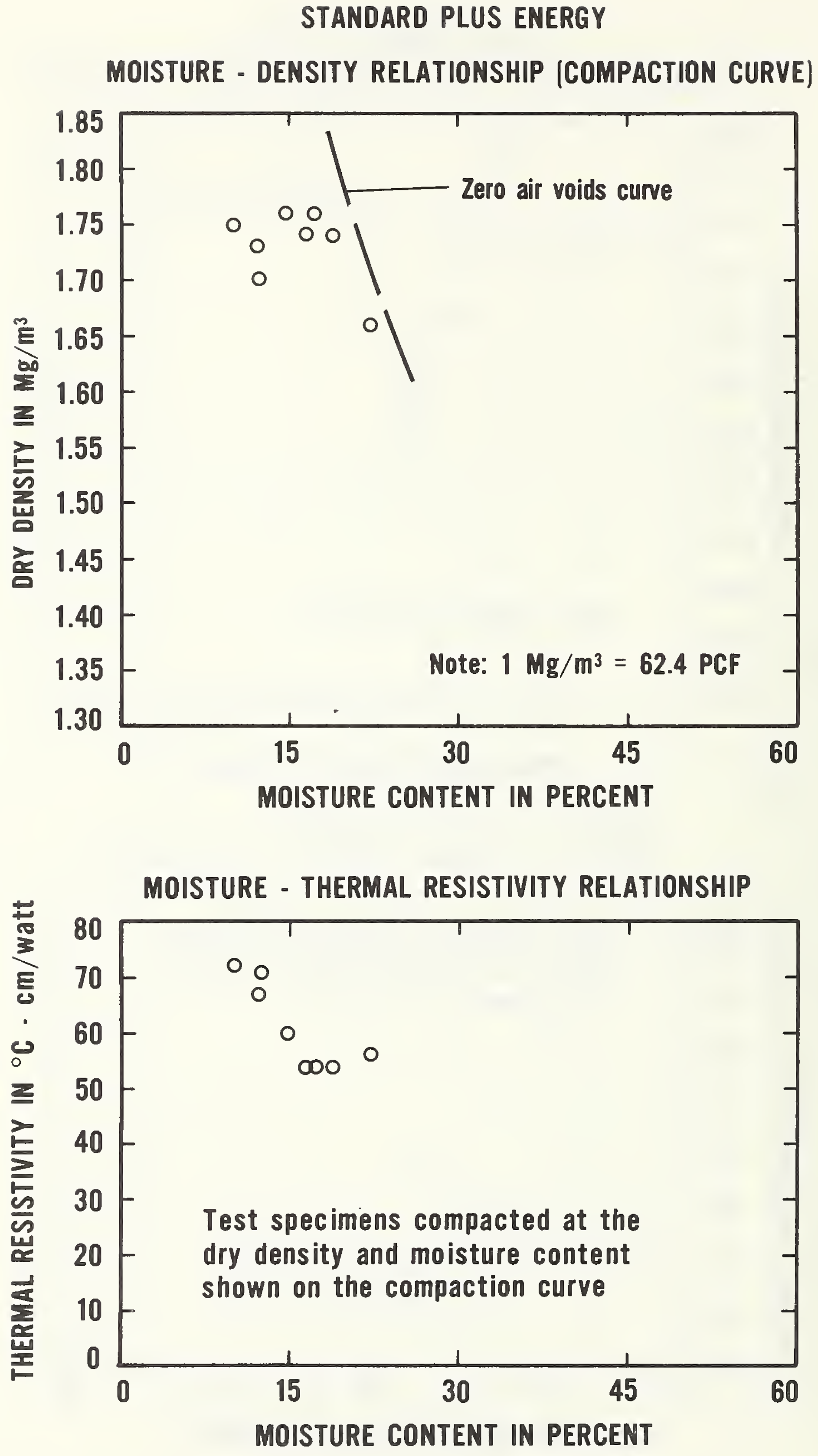
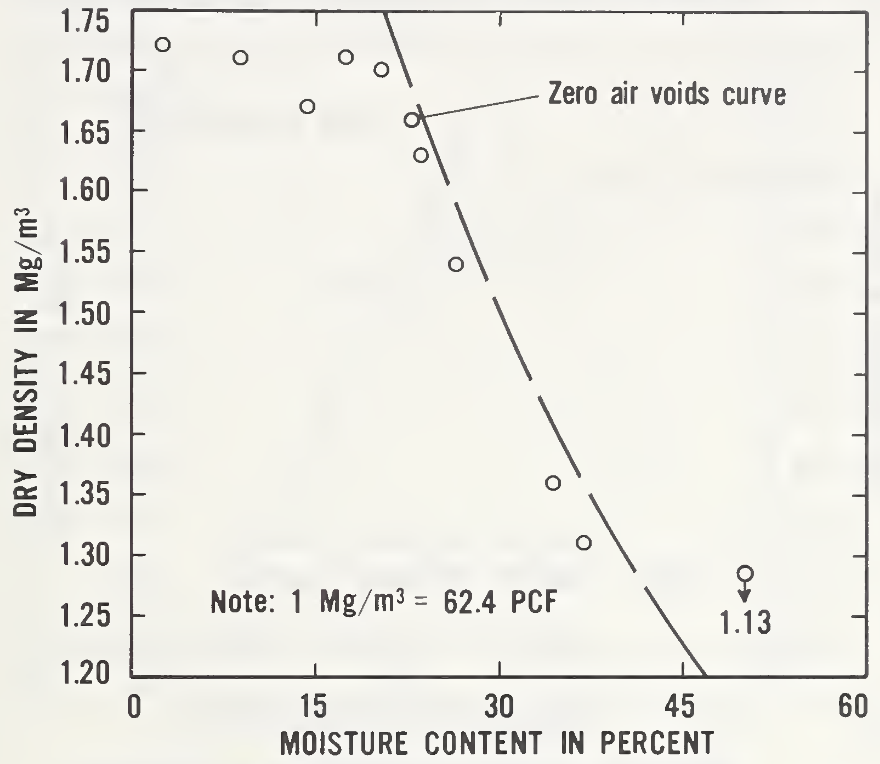
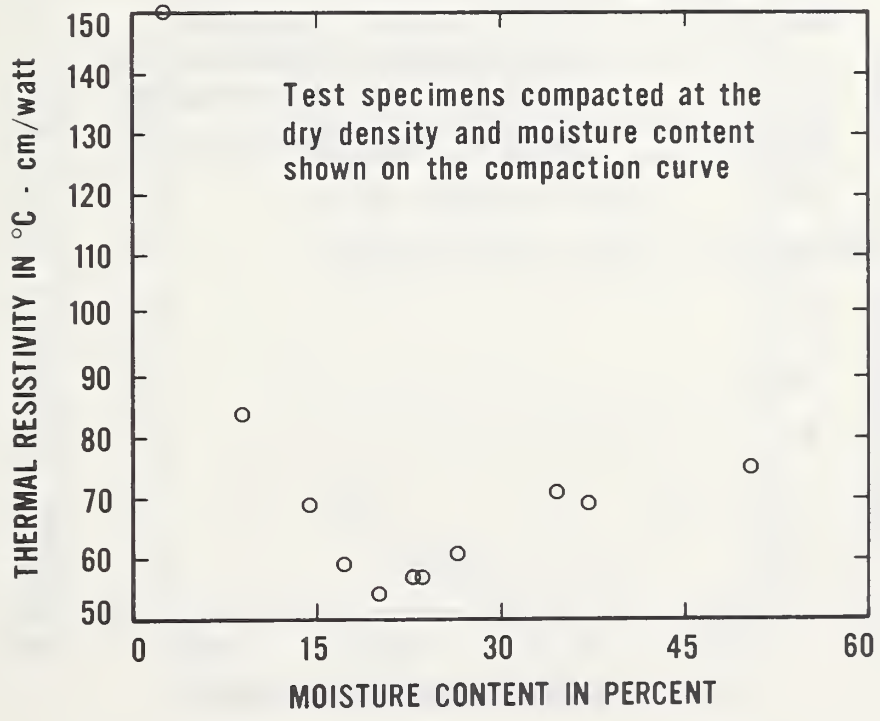


Figure 4-10. Correlation of standard plus energy moisture - density curve with thermal resistivity - moisture content curve



STANDARD ENERGY

MOISTURE - DENSITY RELATIONSHIP (COMPACTION CURVE)



MOISTURE - THERMAL RESISTIVITY RELATIONSHIP

Figure 4-11. Correlation of standard energy moisture - density curve with thermal resistivity - moisture content curve

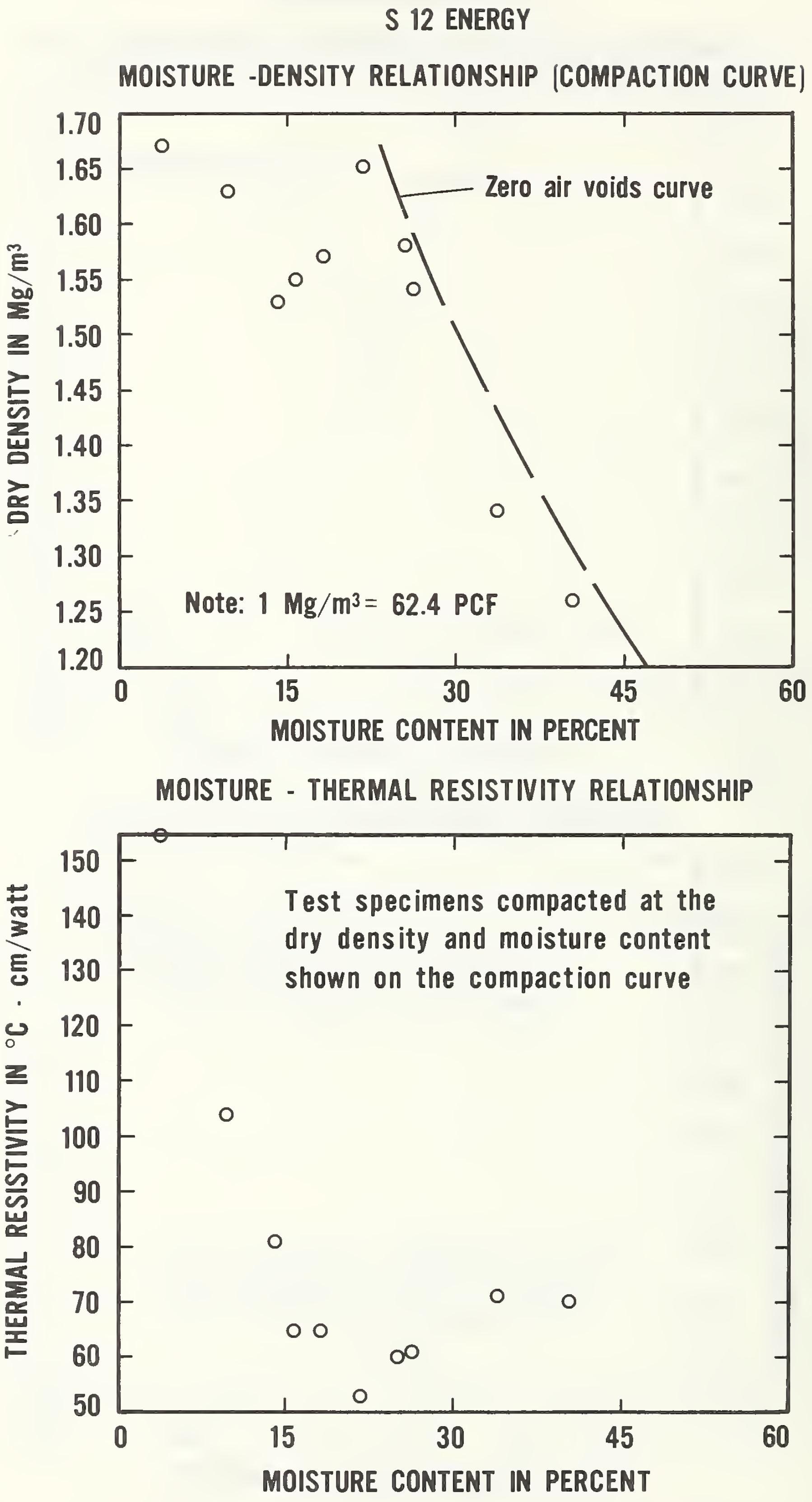


Figure 4-12. Correlation of S12 energy moisture - density curve with thermal resistivity - moisture content curve

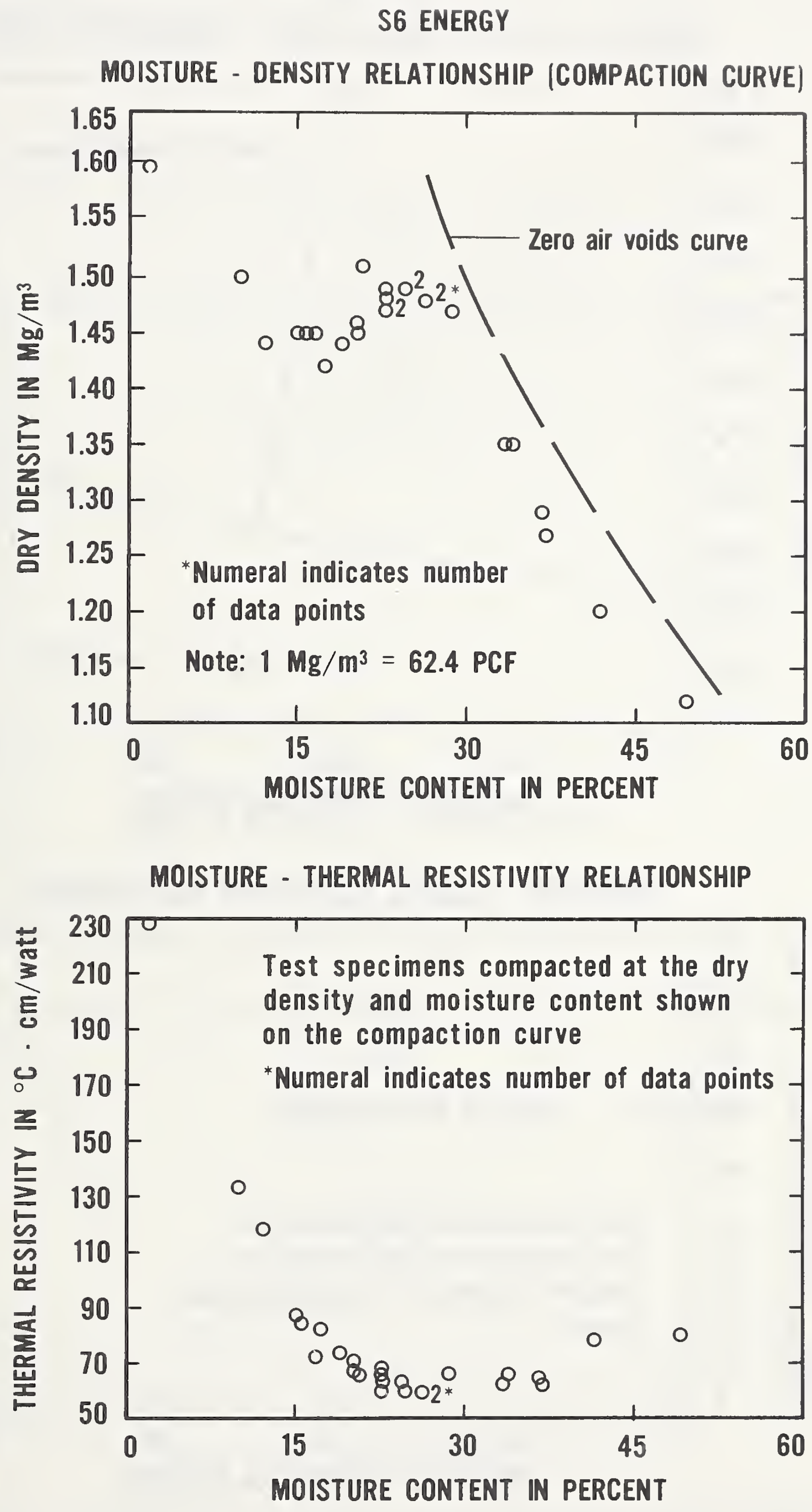


Figure 4-13. Correlation of S6 energy moisture - density curve with thermal resistivity - moisture content curve

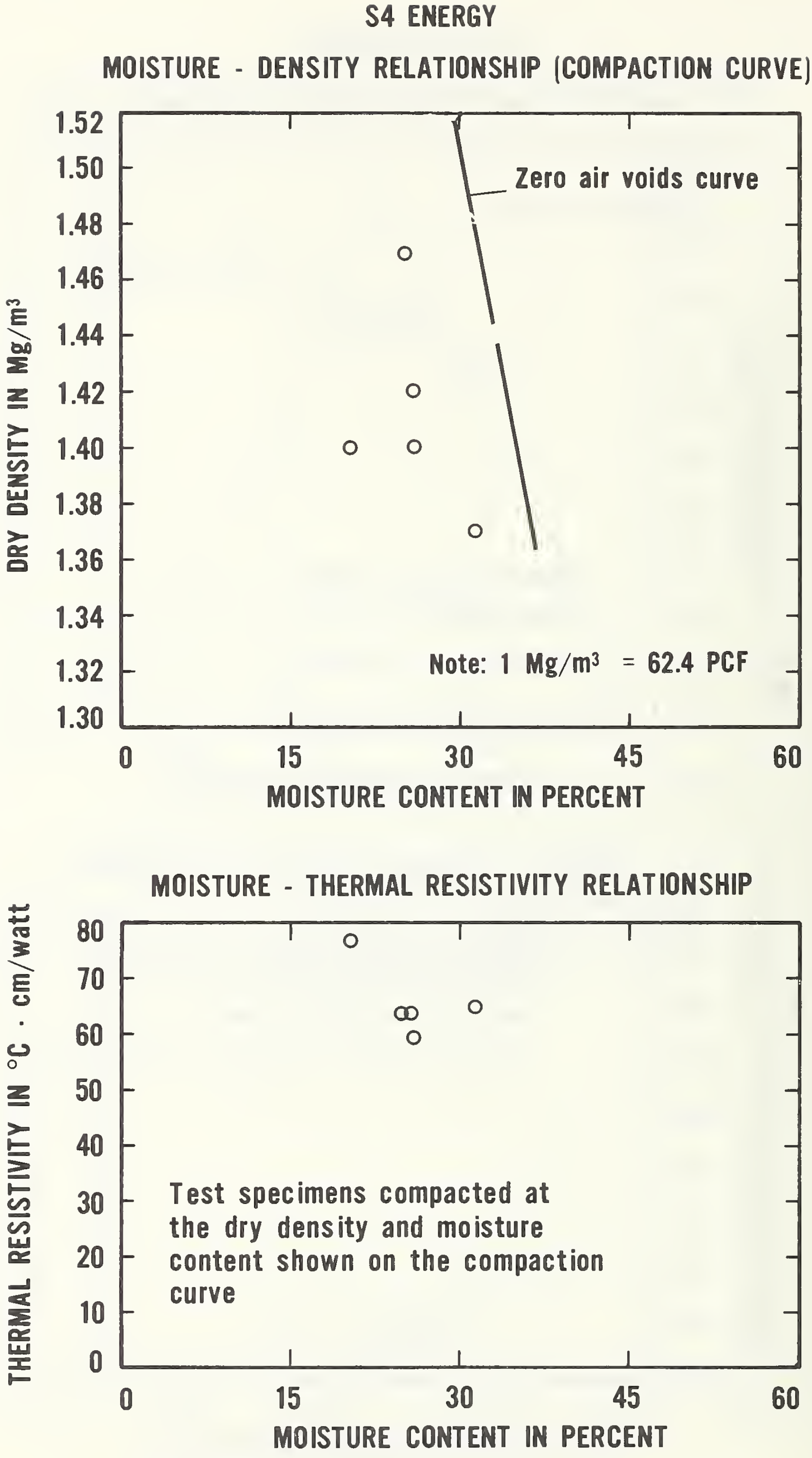


Figure 4-14. Correlation of S4 energy moisture - density curve with thermal resistivity - moisture content curve

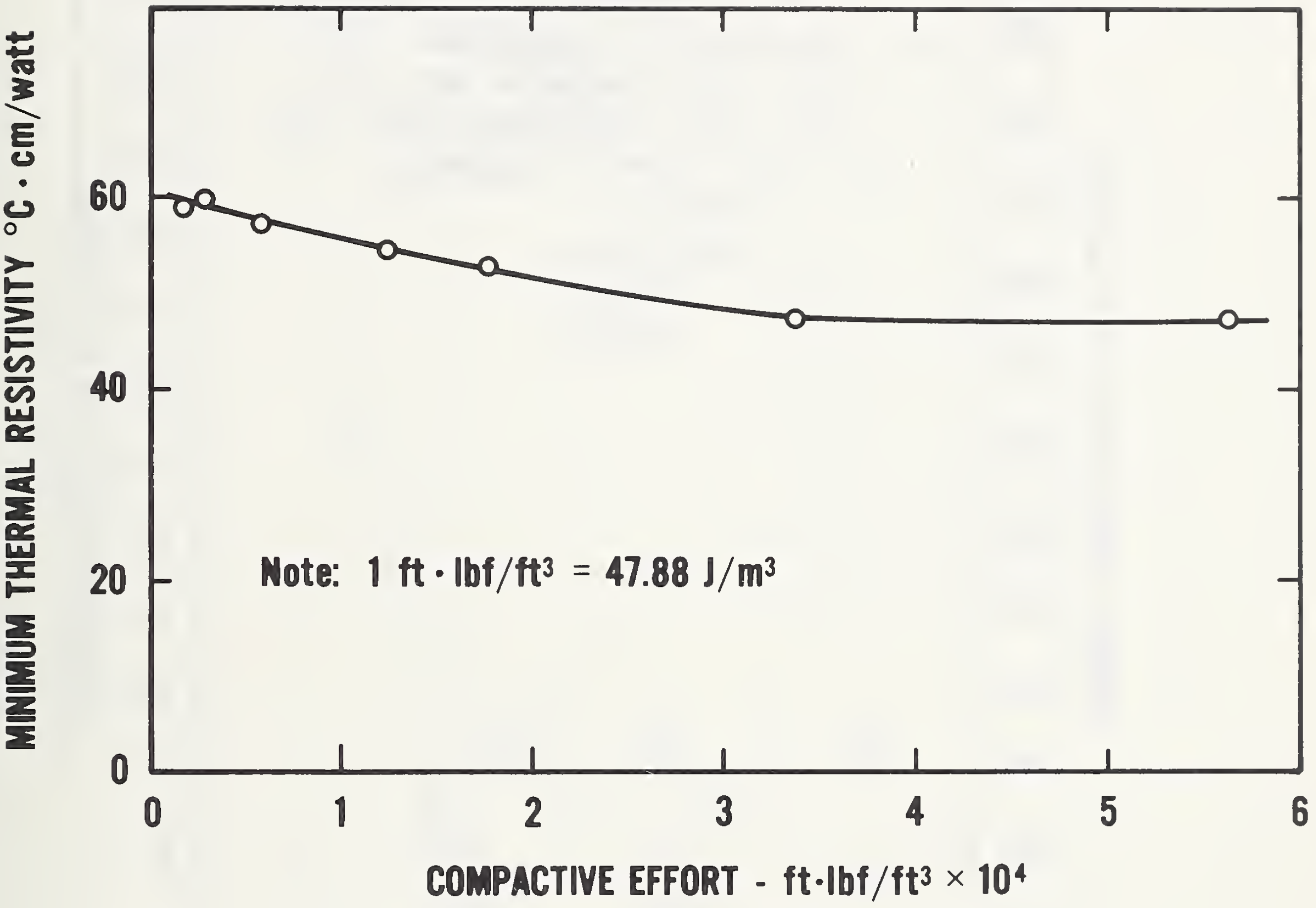


Figure 4-15. Variation of minimum thermal resistivity with compactive effort

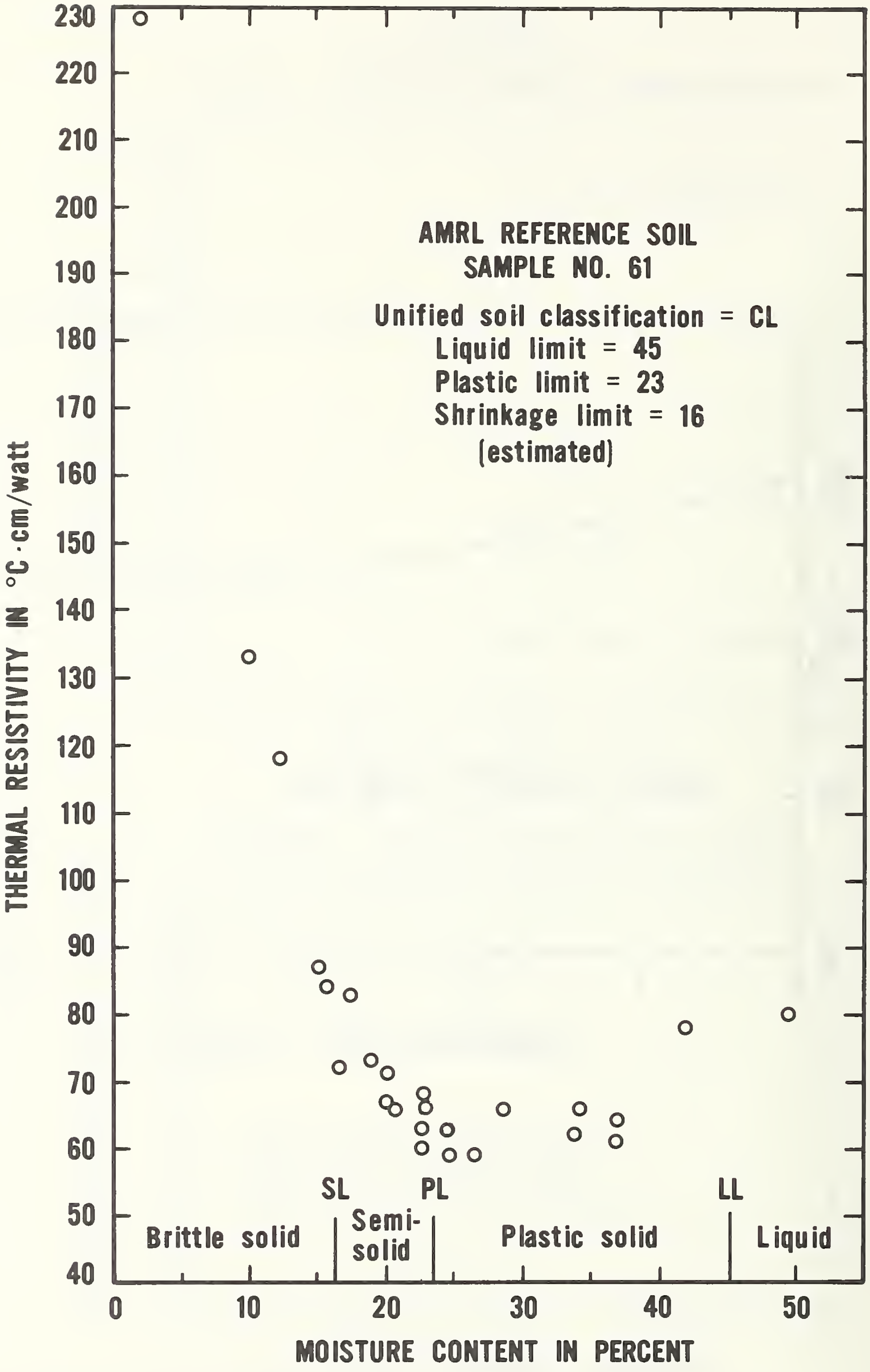


Figure 4-16. Correlation of thermal resistivity and Atterberg Limit test data using S6 compactive effort

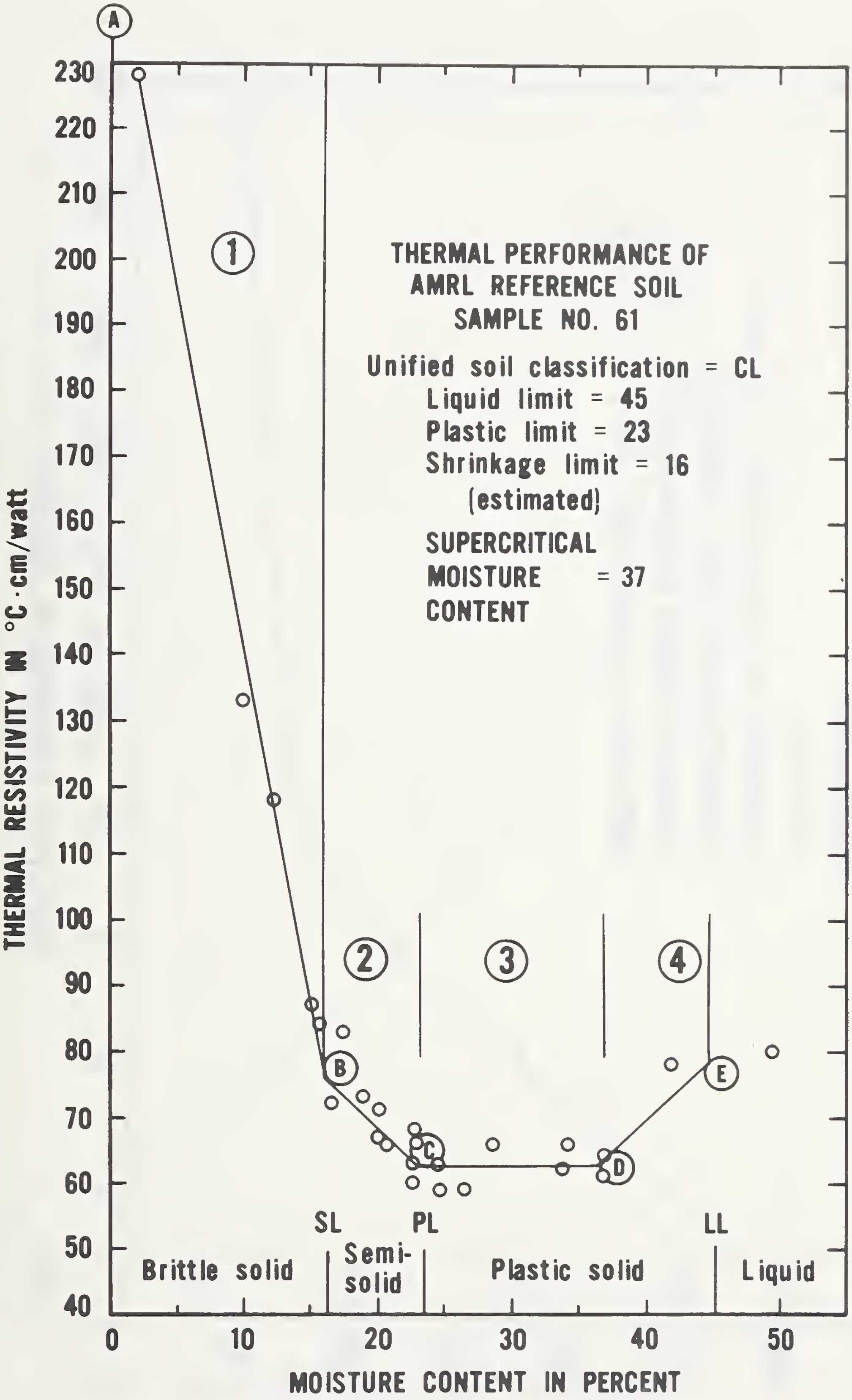


Figure 4-17. Thermal behavior of AMRL reference soil sample using S6 compactive effort

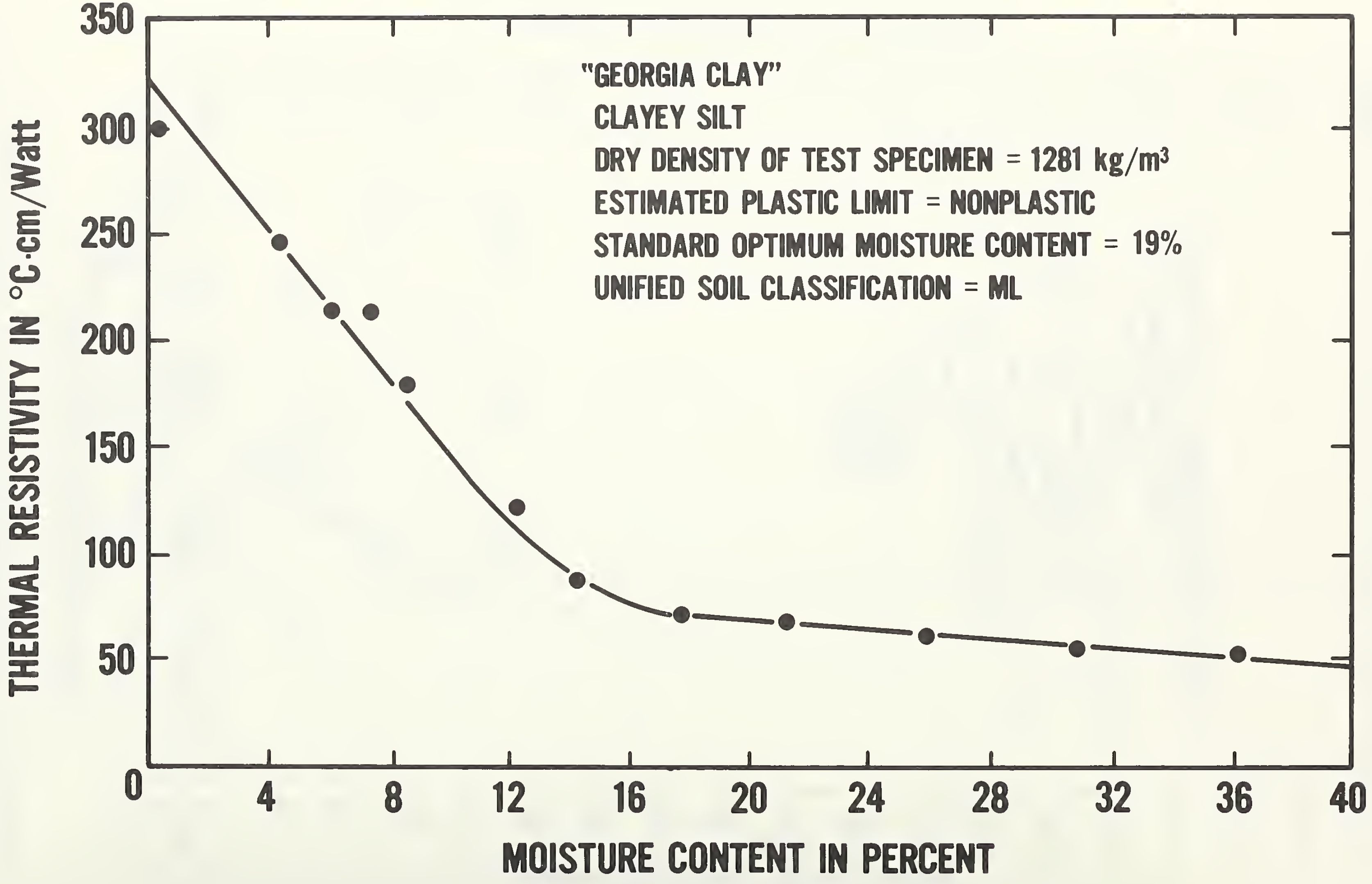


Figure 4-18. Georgia clay thermal resistivity test data [from Black, W.Z., 1982, private communication]

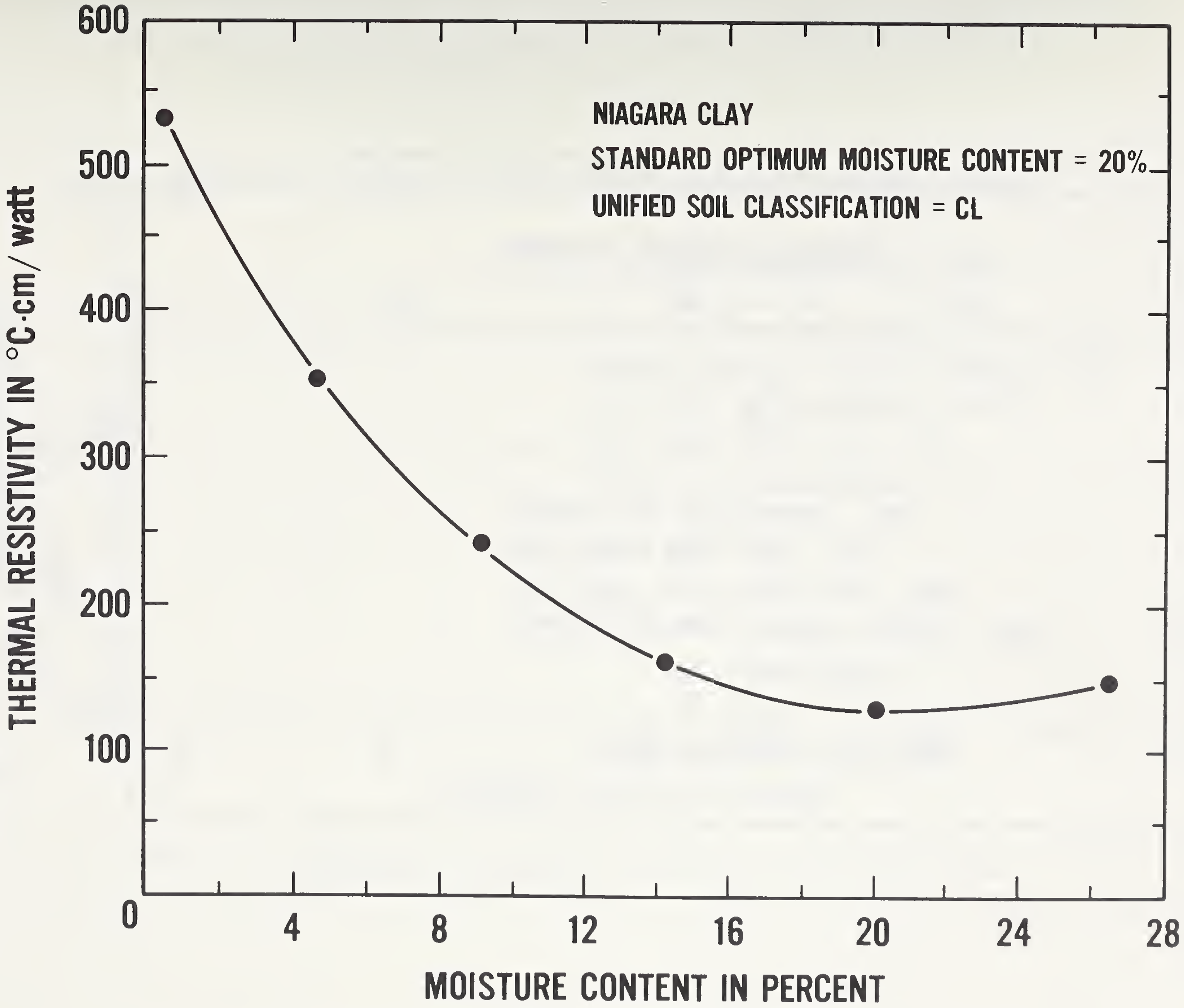


Figure 4-19. Niagara clay thermal resistivity test data (modified from [24])

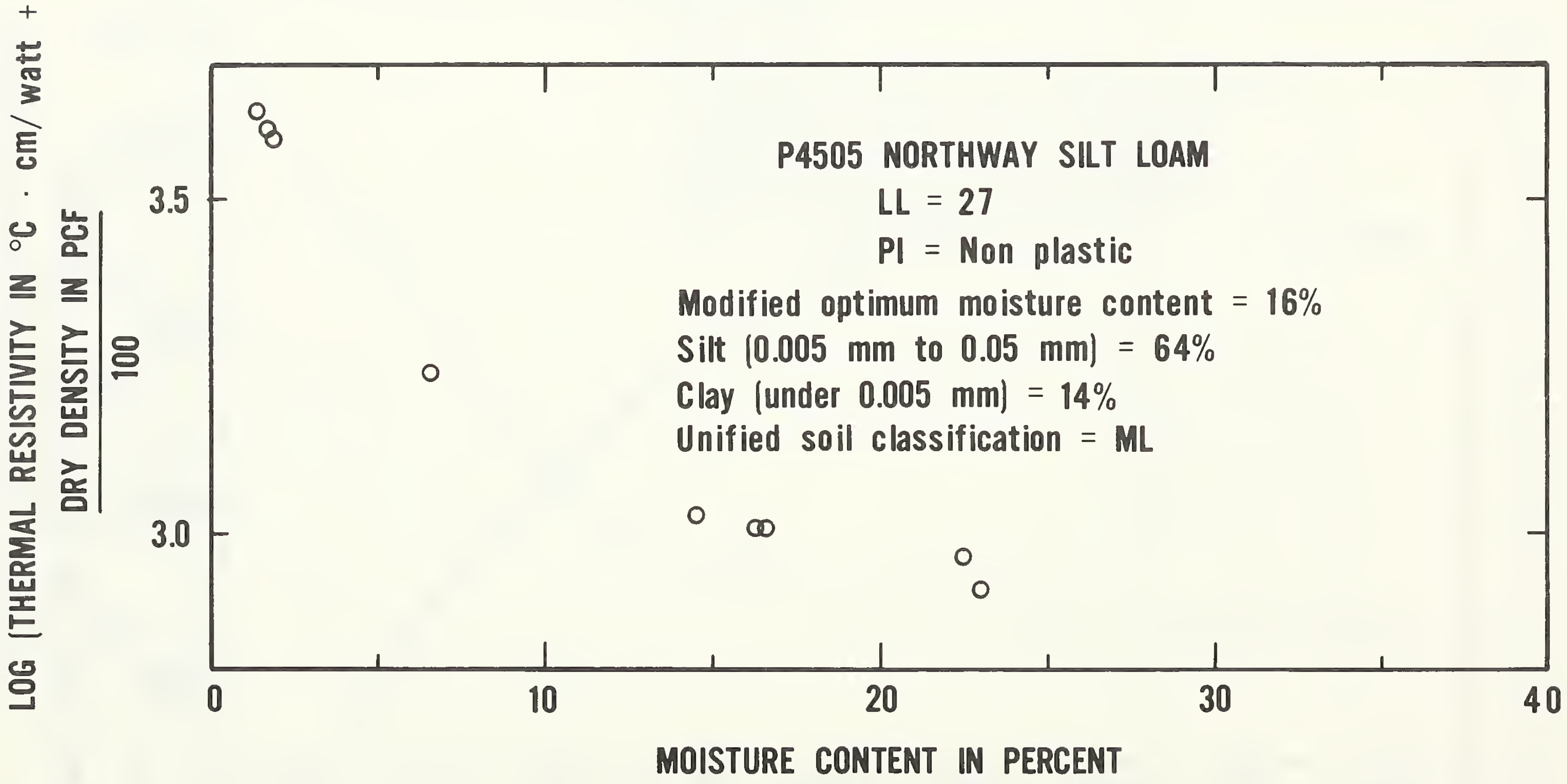


Figure 4-20. Northway silt loam thermal resistivity test data from [22] adjusted for dry density

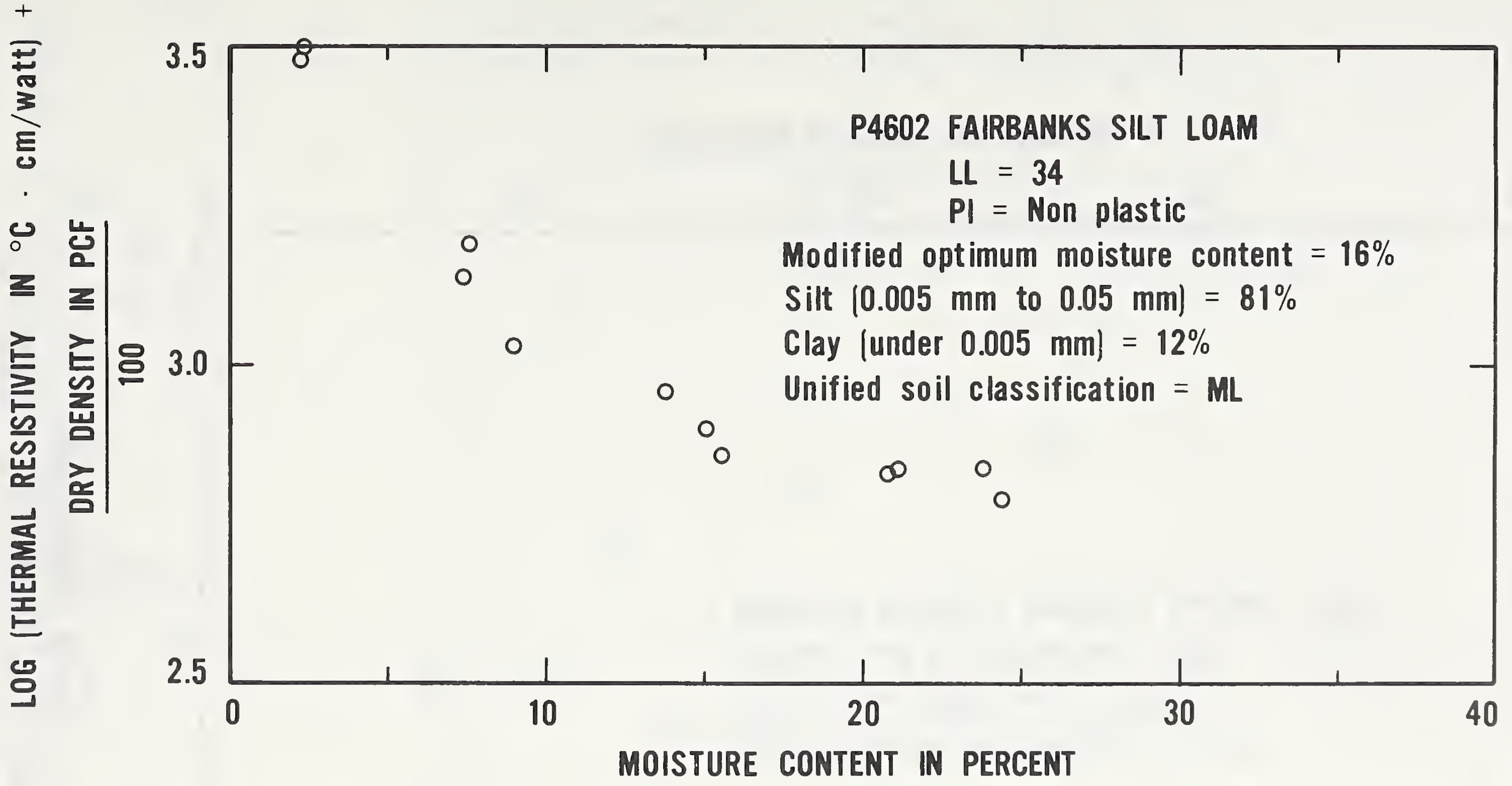


Figure 4-21. Fairbanks silt loam thermal resistivity test data from [22] adjusted for dry density

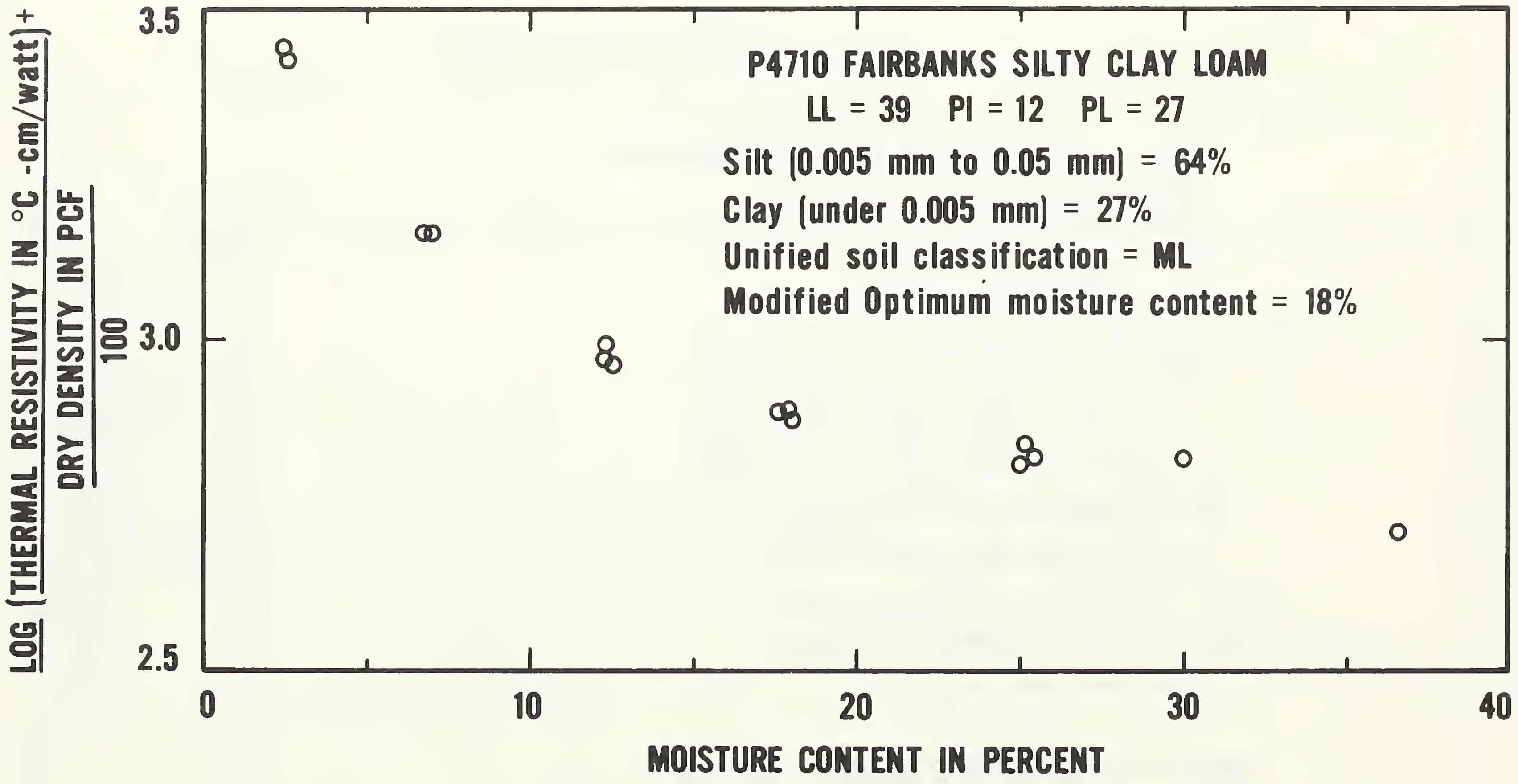


Figure 4-22. Fairbanks silty clay loam thermal resistivity test data from [22] adjusted for dry density

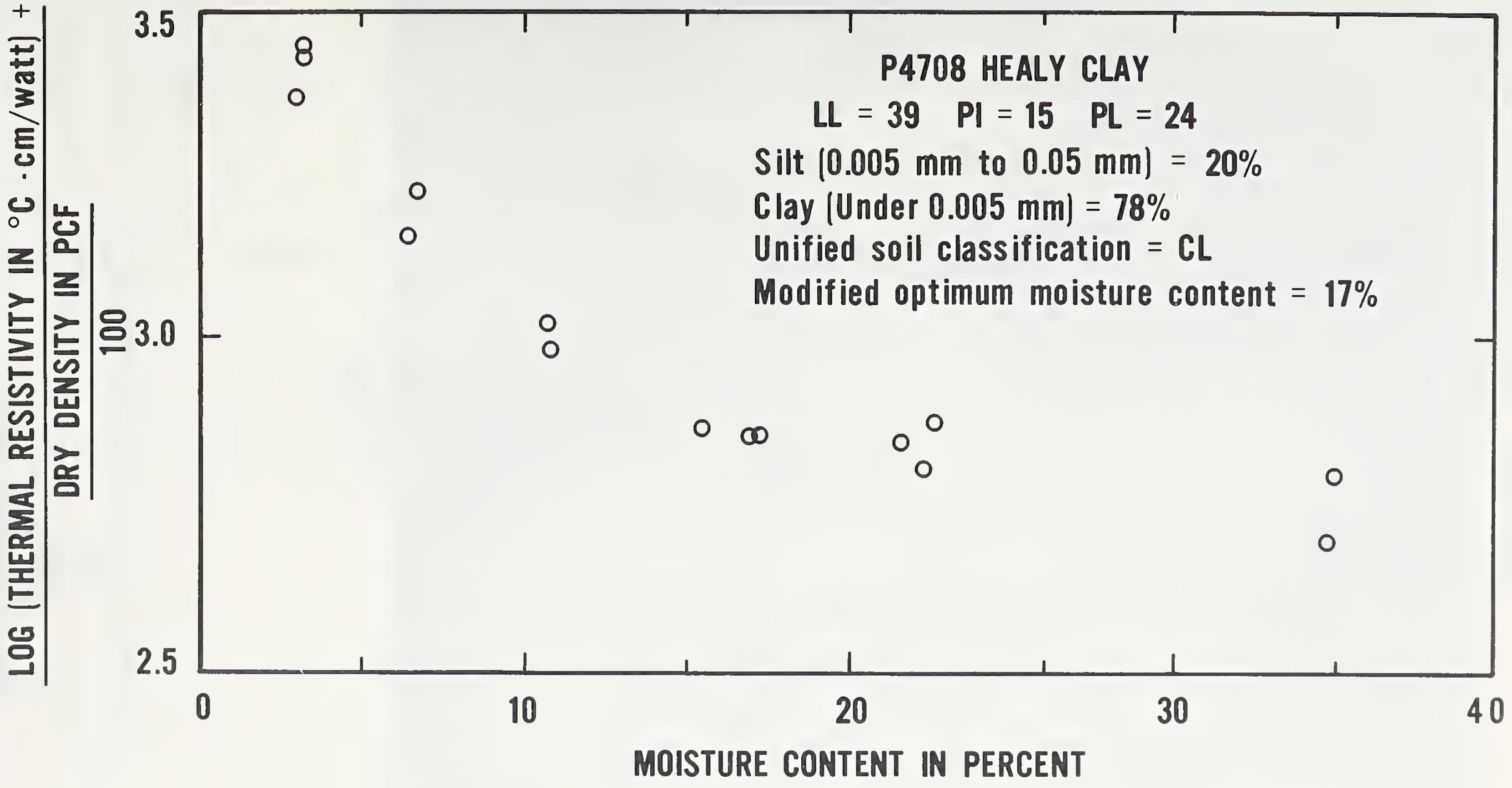


Figure 4-23. Healy clay thermal resistivity test data from [22] adjusted for dry density

FACING PAGE: Inserting a 25-mm (1-in) diameter thin wall tube to obtain the inner core moisture content sample.

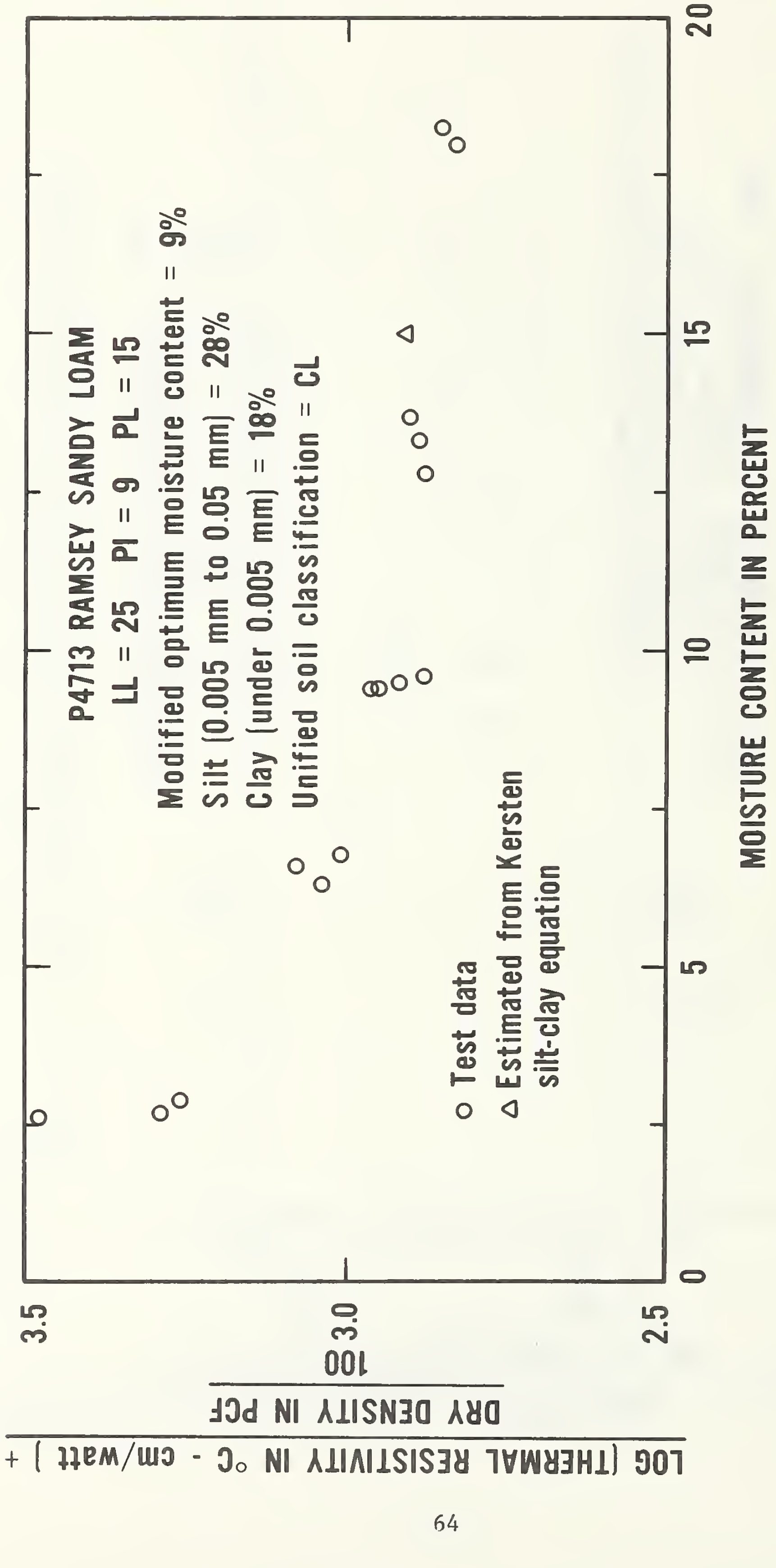


Figure 4-24. Ramsey sandy loam thermal resistivity test data from [22] adjusted for dry density

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based on this study, the following conclusions are warranted:

1) The critical moisture content increases as the dry density of the soil decreases.

2) A large increase in thermal resistivity with a small change in moisture content occurs when the moisture content of the soil is less than the critical moisture content.

3) As the compactive effort for preparing samples was decreased, a compactive effort (1.42×10^5 J/m^3) that resulted in the critical moisture content, optimum moisture content and plastic limit being approximately equal was found.

4) The index property and thermal resistivity test data obtained for the AMRL reference soil and other fine-grained soil indicate that the critical moisture content can be defined by the optimum moisture content. The compactive effort chosen to determine the optimum moisture content will depend on the dry density for which the critical moisture content is being defined.

5) The Thermal Performance Index, TPI, provided an indication of the thermal performance of the AMRL reference soil under saturated conditions. It measured the change in thermal resistivity per unit change in moisture content over the range of densities expected under natural or artificial (man-made) field conditions.

6) The Thermal Stability Index, TSI, defined in this study provided an approximate approach for evaluating the thermal stability of the AMRL soil using the moisture content of the soil expected under design conditions.

5.2 RECOMMENDATIONS

Based on this study the following recommendations are made:

1) The approach developed for this study was useful when establishing the thermal behavior of the AMRL reference soils. Because classification and thermal properties of fine-grained soils are not generally found in the literature, other researchers are encouraged to use the approach described in this study when measuring and reporting the thermal properties of soils.

2) The concepts used to establish the thermal behavior of the AMRL soil should be studied further using a wide variety of soils, and exceptions, if any, to the general trends should be identified.

3) A dry density or the compactive effort used to prepare the samples should be specified when defining the critical moisture content. The dry density specified can be the in situ dry density (natural) or a dry density which is a percentage of the laboratory maximum dry density determined by some standard test, e.g. standard Proctor test (ASTM D698-78 procedures) or the modified Proctor test (ASTM D1557-78 procedures).

4) Correlations of index properties and the thermal behavior of soils provide a cost effective method for assessing the probable thermal performance of soils in an engineering situation. These correlations should be used in conjunction with those thermal property measurements required to evaluate system performance (viz: underground power cables, heat storage, heat loss into ground and frost penetration) over the range of operating conditions expected.

FACING PAGE: Extrusion of the remaining compacted sample using soil extruder for total moisture content determination.

6. ACKNOWLEDGMENTS

The writers wish to thank J. Lichtenberg and H. Puluzzi of Potomac Electric Power Company (PEPCO) and T. Rodenbaugh of the Electric Power Research Institute (EPRI) for making the necessary arrangements which allowed us to use the EPRI Thermal Property Analyzer during the study. The useful discussions with T. Rodenbaugh of EPRI, H. S. Radhakrishna, S. Boggs, and J. Steinmanis of Ontario Hydro and D. Parmer of Geotherm, Inc. about the equipment used in the study and their experience in thermal property measurements was also greatly appreciated. The writers wish to thank those providing index and thermal property data on other types of soil: H. S. Radhakrishna of Ontario Hydro, D. Parmer of Geotherm, Inc., W. Murphy and D. Horna of Dames and Moore, W. Black of Georgia Tech, T. Nishioka of Arizona Public Service Company, and D. Slack, J. Mostaghimi and J. Ramsey of the University of Minnesota. In the case of T. Nishioka of Arizona Public Service Company and D. Slack of the University of Minnesota, obtaining the required index property data involved performing additional index property tests. Their special effort is greatly appreciated by the writers.

The writers also acknowledge the assistance of O. W. McIntosh of the AASHTO Materials Reference Laboratory who made the necessary arrangements for obtaining the required quantities of soil used in the testing program and W. Liggett of the NBS Statistical Engineering Group for his assistance in analyzing the thermal resistivity test data. H. S. Radhakrishna of Ontario Hydro reviewed the report. His comments and suggestions are greatly appreciated. A special thanks is also given to Brenda Thompson for typing this report.

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APPENDIX A - TABULATION OF DATA

Table A-1. Summary of Laboratory Test Data

Modified Compaction Energy

Modified Energy 2.93×10^5 J/m^3, 56250 ft•lbf/ft^3	Sample Identification No.	Moisture Content %	Porosity	Dry Density		Thermal Resistivity °C•cm/watt	Degree of Saturation %	Volumetric Water Content %	Void Ratio
				Mg/m^3	PCF				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
10.0-lb hammer, 1.5-ft drop, 5 layers, and 25 blows/layer	13.0 M	10.96	.319	1.88	117.3	52	64.6	20.6	.468
	17.5 M	14.80	.309	1.91	119.0	48	91.4	28.2	.447
	20.5 M	17.23	.332	1.84	115.1	47	95.9	31.8	.496
	23.5 M	20.84	.375	1.72	107.6	54	95.7	35.9	.601
	25.0 M	23.10	.400	1.66	103.4	56	95.7	38.3	.666
	26.5 M	22.95	.401	1.65	103.1	57	94.5	37.9	.670
	29.5 M	26.92	.441	1.54	96.2	61	94.0	41.5	.790
	32.5 M	30.01	.471	1.46	91.1	60	93.0	43.8	.890
	35.0 M	34.90	.509	1.35	84.5	71	92.8	47.2	1.038
	40.0 M	37.07	.519	1.33	82.9	68	95.0	49.3	1.077

Table A-2. Summary of Laboratory Test Data

Intermediate Compaction Energy

Intermediate Energy 16.16×10^5 J/m^3, 33750 ft•lbf/ft^3	Identification No. (1)	Moisture Content % (2)	Porosity (3)	Dry Density		Thermal Resistivity °C•cm/watt (6)	Degree of Saturation % (7)	Volumetric Water Content % (8)	Void Ratio (9)
				Mg/m^3 (4)	PCF (5)				
	Air Dried I	2.89	.351	1.79	111.8	109	14.8	5.2	.540
10.0 lb-hammer, 1.5-ft drop, 3 layers, and 25 blows/layer	14.5 I	12.21	.332	1.84	115.0	55	67.7	22.5	.498
	17.5 I	15.79	.330	1.85	115.4	48	88.6	29.2	.492
	19.0 I	16.12	.336	1.83	114.4	48	88.1	29.6	.505
	20.5 I	18.56	.348	1.80	112.3	51	95.9	33.4	.534
	23.5 I	22.46	.397	1.66	103.8	53	94.1	37.3	.659
	25.0 I	22.81	.397	1.66	103.8	57	95.5	37.9	.659
	26.5 I	25.16	.421	1.60	99.7	58	95.5	40.2	.727
	29.5 I	27.15	.444	1.53	95.8	61	93.9	41.7	.798
	32.5 I	27.38	.443	1.54	95.9	61	94.9	42.1	.796

Table A-3. Summary of Laboratory Test Data

Standard Plus Compaction Energy

Standard Plus Energy 8.53×10^5 J/m^3, 17820 ft·lbf/ft^3	Identification No.	Moisture Content %	Porosity	Dry Density		Thermal Resistivity °C·cm/watt	Degree of Saturation %	Volumetric Water Content %	Void Ratio
				Mg/m^3	PCF				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
STANDARD PLUS	10 S+	9.96	.365	1.75	109.4	72	47.9	17.5	.574
5.5-lb hammer, 1.0-ft drop, 4 layers, and 27 blows/layer	14.5 S+(1/21)*	12.15	.373	1.73	108.0	71	56.4	21.0	.595
	14.5 S+(1/28) Stored	12.22	.382	1.70	106.4	67	54.5	20.8	.619
	17.5 S+	14.71	.361	1.76	110.0	60	71.7	25.9	.566
	19.0 S+	16.49	.369	1.74	108.6	54	77.7	28.6	.586
	20.5 S+	17.08	.361	1.76	110.0	54	83.3	30.1	.566
	23.5 S+	18.90	.368	1.74	108.8	54	89.5	32.9	.583
	26.5 S+	22.28	.397	1.66	103.8	56	93.3	37.0	.659

* Date thermal test was performed.

Table A-4. Summary of Laboratory Test Data

Standard Compaction Energy

Standard Energy 5.92×10^5 J/m^3, 12375 ft•lbf/ft^3	Identification No.	Moisture Content %	Porosity	Dry Density		Thermal Resistivity °C•cm/watt	Degree of Saturation %	Volumetric Water Content %	Void Ratio
				Mg/m^3	PCF				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Air Dried S	2.52	.375	1.72	107.7	150	11.6	4.4	.599
5.5-lb hammer, 1.0-ft drop, 3 layers, and 25 blows/layer	10 S	8.94	.381	1.71	106.6	84	40.1	15.3	.616
	17.5 S	14.38	.396	1.67	104.1	69	60.7	24.0	.654
	20.5 S	17.31	.380	1.71	106.7	59	77.8	29.6	.614
	23.5 S	20.08	.384	1.70	106.0	54	88.7	34.1	.625
	25.0 S	22.78	.399	1.66	103.5	57	94.7	37.8	.664
	26.5 S	23.46	.409	1.63	101.8	57	93.6	38.3	.692
	29.5 S	26.40	.441	1.54	96.3	61	92.5	40.8	.788
	35.0 S	34.49	.505	1.36	85.2	71	93.2	47.1	1.021
	40.0 S	37.33	.527	1.31	81.5	69	92.6	48.8	1.113
	55.0 S	50.45	.592	1.13	70.3	75	96.0	56.8	1.450

Table A-5. Summary of Laboratory Test Data

S12 Compaction Energy

S12 Energy 2.84×10^5 J/m^3, 5940 ft•lbf/ft^3	Identification No.	Moisture Content %	Porosity	Dry Density		Thermal Resistivity °C•cm/watt	Degree of Saturation %	Volumetric Water Content %	Void Ratio
				Mg/m^3	PCF				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Air Dry S12	3.77	.396	1.67	104.1	154	15.9	6.3	.654
5.5-lb hammer, 1.0-ft drop, 3 layers, and 12 blows/layer	10 S12	9.70	.409	1.63	101.8	104	38.7	15.8	.692
	14.5 S12	14.17	.445	1.53	95.7	81	48.8	21.7	.801
	19.0 S12	15.89	.436	1.55	97.1	65	56.7	24.7	.774
	20.5 S12	18.19	.429	1.57	98.3	65	66.8	28.6	.752
	23.5 S12	21.56	.403	1.65	102.8	53	88.2	35.5	.675
	26.5 S12	25.15	.428	1.58	98.5	60	92.8	39.7	.748
	28.0 S12	26.29	.443	1.54	95.9	61	91.2	40.4	.796
	37.0 S12	33.77	.512	1.34	84.0	71	88.8	45.4	1.050
	42.0 S12	40.40	.544	1.26	78.4	70	92.9	50.5	1.200

Table A-6. Summary of Laboratory Test Data

S6 Compaction Energy

S6 Energy 1.42×10^5 J/m^3, 2970 ft·lbf/ft^3	Identification No.	Moisture Content %	Porosity	Dry Density		Thermal Resistivity °C·cm/watt	Degree of Saturation %	Volumetric Water Content %	Void Ratio
				Mg/m^3	PCF				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
5.5-lb hammer, 1.0-ft drop, 3 layers, and 6 blows/layer	Air Dry S6	1.95	.419	1.60	100.0	228	7.4	3.1	.722
	11.5 S6	10.00	.458	1.50	93.4	133	32.7	15.0	.844
	14.5 S6	12.33	.477	1.44	90.0	118	37.2	17.8	.914
	17.5 S6	15.55	.473	1.45	90.7	84	47.7	22.6	.899
	19 S6 (2/3)*	15.13	.474	1.45	90.6	87	46.4	22.0	.901
	19 S6 (2/8)	17.36	.487	1.42	88.4	83	50.5	24.6	.948
	20.5 S6 Stored	16.60	.473	1.45	90.7	72	51.0	24.1	.899
	21.0 S6	18.94	.478	1.44	89.9	73	57.1	27.3	.916
	22.25 S6	20.10	.476	1.45	90.3	71	61.2	29.1	.907
	23.5 S6 (2/1) Stored	20.11	.469	1.46	91.5	67	62.9	29.5	.882
	23.5 S6 (2/10)	22.68	.469	1.47	91.5	68	71.0	33.3	.882
	23.5 S6 (2/12) Stored	20.68	.451	1.51	94.6	66	69.5	31.4	.821
	24.75 S6	22.60	.463	1.48	92.5	60	72.4	33.5	.862
	25.0 S6	22.56	.464	1.48	92.3	63	71.9	33.4	.866
	26.5 S6 (1/27) Stored	22.76	.459	1.49	93.1	66	73.9	33.9	.850
	26.5 S6 (2/10)	24.53	.459	1.49	93.1	63	79.6	36.6	.850
	27(26.5) S6 Stored	24.57	.459	1.49	93.2	59	80.0	36.7	.848
	28.0 S6 (2/4)	26.36	.465	1.48	92.1	59	83.6	38.9	.870
	28.0 S6 (2/8)	26.34	.465	1.48	92.2	59	83.8	38.9	.868
	31.0 S6	28.64	.468	1.47	91.6	66	89.8	42.0	.880
	35.0 S6/1	34.17	.511	1.35	84.2	66	90.2	46.1	1.045
	35.0 S6/2	33.78	.510	1.35	84.3	62	89.4	45.6	1.043
	40.0 S6/1	36.94	.532	1.29	80.6	61	89.7	47.7	1.137
	40.0 S6/2	36.86	.538	1.27	79.6	64	87.4	47.0	1.164
	47.5 S6	41.86	.564	1.20	75.1	78	89.4	50.4	1.293
	55.0 S6	49.48	.592	1.12	70.3	80	94.2	55.8	1.450

* Date thermal probe test was performed.

Table A-7. Summary of Laboratory Test Data

S4 Compaction Energy

S4 Energy 9.48 x 10^4 J/m^3, 1980 ft·lbf/ft^3	Identification No.	Moisture Content %	Porosity	Dry Density		Thermal Resistivity °C·cm/watt	Degree of Saturation %	Volumetric Water Content %	Void Ratio
				Mg/m^3	PCF				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
S4 5.5-lb hammer 1.0-ft drop 3 layers 4 blows/layer	22 S4	20.30	.494	1.40	87.2	77	57.5	28.4	.975
	26 S4	24.87	.467	1.47	91.8	64	78.4	36.6	.876
	27 S4	25.74	.484	1.42	88.9	64	75.8	36.7	.937
	28 S4	25.89	.494	1.40	87.1	59	73.1	36.1	.977
	32 S4	31.30	.502	1.37	85.8	65	85.8	43.1	1.007

Table A-8. Computed Values for the Zero Air Voids Curve for $G_s = 2.76$

(100% Saturation)

Moisture Content % (1)	Dry Density Mg/m^3 (2)	Dry Density PCF (3)
6.8	2.32	145
8.4	2.24	140
10.0	2.16	135
11.8	2.08	130
13.7	2.00	125
15.8	1.92	120
18.1	1.84	115
20.5	1.76	110
23.2	1.68	105
26.2	1.60	100
29.5	1.52	95
33.1	1.44	90
37.2	1.36	85
41.8	1.28	80
47.0	1.20	75
53.0	1.12	70
59.8	1.04	65
67.8	0.96	60
77.3	0.88	55
88.6	0.80	50

Table A-9. Summary of Moisture Content Data

Modified Compaction Energy*

Identification No. (1)	Trimmings (Percent) (2)	Inner (Percent) (3)	Outer (Percent) (4)	Total (Percent) (5)
13.0 M	10.58	--	--	10.96
17.5 M	14.77	14.80	14.77	14.86
20.5 M	18.46	17.23	17.34	17.50
23.5 M	21.80	20.84	20.88	20.60
25.0 M	23.05	23.10	22.91	23.03
26.5 M	23.81	22.95	22.99	22.90
29.5 M	26.17	26.92	26.59	26.62
32.5 M	29.57	30.01	29.85	29.85
35.0 M	34.59	34.90	34.74	34.57
40.0 M	36.64	37.07	36.96	36.77

* 10.0-lb hammer, 1.5-ft drop, 5 layers, and 25 blows/layer.

Table A-10. Summary of Moisture Content Data

Intermediate Compaction Energy*

Identification No. (1)	Trimmings (Percent) (2)	Inner (Percent) (3)	Outer (Percent) (4)	Total (Percent) (5)
Air Dried I	2.29	2.89	--	2.81
14.5 I	12.60	12.21	--	12.00
17.5 I	15.61	15.79	15.52	15.93
19.0 I	16.63	16.12	--	16.34
20.5 I	19.68	18.56	18.28	18.67
23.5 I	23.41	22.46	22.50	23.00
25.0 I	23.51	22.81	22.82	22.86
26.5 I	24.95	25.16	25.14	25.18
29.5 I	26.51	27.15	27.15	27.06
32.5 I	26.90	27.38	27.04	27.26

* 10.0-lb hammer, 1.5-ft drop, 3 layers, and 25 blows/layer.

Table A-11. Summary of Moisture Content Data

Standard Plus Compaction Energy*

Identification No. (1)	Trimmings (Percent) (2)	Inner (Percent) (3)	Outer (Percent) (4)	Total (Percent) (5)
10 S+	8.28	9.96	--	10.10
14.5 S+(1/21)	--	12.15	12.78	12.29
14.5 S+(1/28) Stored	11.98	12.22	12.62	--
17.5 S+	13.69	14.71	--	15.15
19.0 S+	16.44	16.49	16.37	16.87
20.5 S+	18.84	17.08	--	17.37
23.5 S+	17.04	18.90	18.79	19.43
26.5 S+	23.85	22.28	22.38	22.93

* 5.5-lb hammer, 1.0-ft drop, 4 layers, and 27 blows/layer.

Table A-12. Summary of Moisture Content Data

Standard Compaction Energy*

Identification No. (1)	Trimmings (Percent) (2)	Inner (Percent) (3)	Outer (Percent) (4)	Total (Percent) (5)
Air Dried S	2.01	--	--	2.52
10.0 S	8.36	8.94	--	8.80
17.5 S	15.05	14.38	14.63	14.97
20.5 S	18.60	17.31	17.36	17.76
23.5 S	20.20	20.08	19.91	20.30
25.0 S	22.02	22.78	22.49	22.68
26.5 S	23.90	23.46	23.43	23.66
29.5 S	25.19	26.40	26.46	26.55
35.0 S	33.83	34.49	34.29	33.87
40.0 S	37.96	37.33	36.96	37.07
55.0 S	50.54	50.45	50.04	50.86

* 5.5-lb hammer, 1.0-ft drop, 3 layers, and 25 blows/layer.

Table A13. Summary of Moisture Content Data

S12 Compaction Energy*

Identification No. (1)	Trimmings (Percent) (2)	Inner (Percent) (3)	Outer (Percent) (4)	Total (Percent) (5)
Air Dried S12	3.71	--	--	3.77
10.0 S12	8.36	9.70	--	10.02
14.5 S12	14.65	14.17	--	14.07
19.0 S12	16.89	15.89	16.15	16.57
20.5 S12	19.56	18.19	18.45	18.54
23.5 S12	21.73	21.56	21.77	21.95
26.5 S12	25.45	25.15	25.31	25.16
28.0 S12	25.82	26.29	25.95	26.06
37.0 S12	33.28	33.77	33.87	33.80
42.0 S12	39.51	40.40	38.68	38.89

* 5.5-lb hammer, 1.0-ft drop, 3 layers, and 12 blows/layer.

Table A-14. Summary of Moisture Content Data

S6 Compaction Energy*

Identification No.	Trimmings (Percent)	Inner (Percent)	Outer (Percent)	Total (Percent)
(1)	(2)	(3)	(4)	(5)
Air dry S6	1.97	--	--	1.95
11.5 S6	9.85	10.00	9.97	10.29
14.5 S6	13.24	12.33	12.52	12.98
17.5 S6	14.89	15.55	15.45	15.88
(2/3)** 19.0 S6	13.37	15.13	15.46	16.01
(2/8) 19.0 S6	17.68	17.36	17.56	17.83
20.5 S6 Stored	15.28	16.60	16.68	16.95
21.0 S6	19.31	18.94	19.04	19.36
22.25 S6	20.16	20.10	20.06	20.31
23.5 S6 (2/1) Stored	19.90	20.11	19.85	20.37
(2/10) 23.5 S6	22.31	22.68	22.37	22.50
23.5 S6 (2/12) Stored	19.48	20.68	20.48	20.67
24.75 S6	22.46	22.60	22.46	22.74
25.0 S6	23.07	22.50	22.45	22.65
26.5 S6 (1/27) Stored	24.53	22.76	23.44	23.72
26/5 S6 (2/10)	23.59	24.53	24.36	24.42
27(26.5) S6 Stored	23.98	24.57	24.74	24.54
(2/4) 28.0 S6	26.24	26.36	26.54	26.33
(2/8) 28.0 S6	26.02	26.34	26.60	26.23
31.0 S6	28.42	28.64	28.98	28.20
35.0 S6/1	34.72	34.17	34.75	35.19
35.0 S6/2	33.72	33.78	33.98	33.81
40.0 S6/1	36.88	36.94	36.71	37.02
40.0 S6/2	36.96	36.86	36.92	37.02
47.5 S6	43.04	41.86	41.82	42.54
55.0 S6	52.58	49.48	49.63	51.26

* 5.5-lb hammer, 1.0-ft drop, 3 layers, and 6 blows/layer.

** Date thermal probe test was performed.

Table A-15. Summary of Moisture Content Data

S4 Compaction Energy*

Identification No.	Trimmings (Percent)	Inner (Percent)	Outer (Percent)	Total (Percent)
(1)	(2)	(3)	(4)	(5)
22.0 S4	21.23	20.30	20.52	21.14
26.0 S4	24.65	24.87	24.79	25.08
27.0 S4	25.26	25.74	26.39	25.78
28.0 S4	25.28	25.89	25.92	25.80
32.0 S4	30.46	31.30	31.22	31.38

* 5.5-lb hammer, 1.0-ft drop, 3 layers, and 4 blows/layer.

Table A-16. Moisture Loss (Gain) of the Test Samples During the Thermal Probe Test, Modified Compaction Energy*

Identification No.	Mass of mold and base plate plus wet soil (g)		Moisture loss (gain) (g)	Percent moisture loss (gain)
	Before thermal probe test	After thermal probe test		
(1)	(2)	(3)	(4)	(5)
13.0 M	6318.8	6318.2	-0.6	-0.03
17.5 M	6396.2	6395.2	-1.0	-0.05
20.5 M	6389.4	6389.5	-0.1	-0.005
23.5 M	6314.1	6313.5	-0.6	-0.03
25.0 M	6270.2	6269.8	-0.4	-0.02
26.5 M	6265.4	6265.1	-0.3	-0.02
29.5 M	6169.4	6168.5	-0.9	-0.05
32.5 M	6137.8	6137.1	-0.7	-0.04
35.0 M	6044.8	6044.3	-0.5	-0.03
40.0 M	6062.7	6063.0	+0.3	+0.02

* 10.0-lb hammer, 1.5-ft drop, 5 layers, and 25 blows/layer.

Average loss -0.03 percent
Average gain +0.02 percent

Table A-17. Moisture Loss (Gain) of the Test Samples During the Thermal Probe Test, Intermediate Compaction Energy

Identification No.	Mass of mold and base plate plus wet soil (g)		Moisture loss (gain) (g)	Percent moisture loss (gain)
	Before thermal probe test	After thermal probe test		
(1)	(2)	(3)	(4)	(5)
Air Dried I	6088.3	6087.6	-0.7	-0.04
14.5 I	6297.9	--	--	--
17.5 I	6370.8	6370.6	-0.2	-0.01
19.0 I	6355.6	6355.8	+0.2	+0.01
20.5 I	6335.5	6335.3	-0.2	-0.01
23.5 I	6271.0	6271.0	0.0	0.0
25.0 I	6250.3	6249.5	-0.8	-0.04
26.5 I	6209.6	6209.6	0.0	0.0
29.5 I	6191.7	6191.3	-0.4	-0.02
32.5 I	6168.4	6166.2	-2.2	-0.12

* 10.0-lb hammer, 1.5-ft drop, 5 layers, and 25 blows/layer.

Average loss -0.03 percent
Average gain +0.01 percent

Table A-18. Moisture Loss of the Test Samples During the Thermal Probe Test, Standard Plus Compaction Energy

Identification No.	Mass of mold and base plate plus wet soil (g)		Moisture loss (gain) (g)	Percent moisture loss (gain)
	Before thermal probe test	After thermal probe test		
(1)	(2)	(3)	(4)	(5)
10.0 S+	6169.1	--	--	--
(1/21)** 14.5 S+	6155.3	6152.8	-2.5	-0.14
14.5 S+ Stored (1/28)	6159.6	6155.1	-4.5	-0.25
17.5 S+	6255.4	6254.8	-0.6	-0.03
19.0 S+	6261.9	6261.9	0.0	0.0
20.5 S+	6271.4	6268.9	-2.5	-0.13
23.5 S+	6305.9	6305.7	-0.2	-0.01
26.5 S+	6242.7	6242.0	-0.7	-0.04

* 5.5-lb hammer, 1.0-ft drop, 4 layers, and 27 blows/layer.

** Date thermal probe test was performed.

Average loss -0.09 percent

Table A-19. Moisture Loss (Gain) of the Test Samples During the Thermal Probe Test, Standard Compaction Energy*

Identification No.	Mass of mold and base plate plus wet soil (g)		Moisture loss (gain) (g)	Percent moisture loss (gain)
	Before thermal probe test	After thermal probe test		
(1)	(2)	(3)	(4)	(5)
Air Dried	5991.4	5989.8	-1.6	-0.10
10 S	6109.6	6105.1	-4.5	-0.25
17.5 S	6146.7	6146.7	0.0	0.0
20.5 S	6242.2	6241.9	-0.3	-0.02
23.5 S	6245.8	6245.9	+0.1	+0.005
25.0 S	6271.1	6270.6	-0.5	-0.03
26.5 S	6249.3	6247.8	-1.5	-0.08
29.5 S	6192.5	6190.6	-1.9	-0.10
35.0 S	6081.3	6081.0	-0.3	-0.02
40.0 S	6040.7	6040.8	+0.1	+0.006
55.0 S	5947.3	5946.6	-0.7	-0.04

* 5.5-lb hammer, 1.0-ft drop, 3 layers, and 25 blows/layer.

Average loss -0.07 percent
Average gain +0.005 percent

Table A-20. Moisture Loss of the Test Samples During the Thermal Probe Test, S12 Compaction Energy*

Identification No.	Mass of mold and base plate plus wet soil (g)		Moisture loss (gain) (g)	Percent moisture loss (gain)
	Before thermal probe test	After thermal probe test		
(1)	(2)	(3)	(4)	(5)
Air Dried S12	5980.2	5979.7	-0.5	-0.03
10.0 S12	6036.0	6035.2	-0.8	-0.05
14.5 S12	6001.2	6000.6	-0.6	-0.04
19.0 S12	6020.9	6020.6	-0.3	-0.02
20.5 S12	6102.3	6102.4	-0.1	-0.006
23.5 S12	6240.0	6239.6	-0.4	-0.02
26.5 S12	6185.0	6184.9	-0.1	-0.005
28.0 S12	6179.1	6179.1	0.0	0.0
37.0 S12	6044.8	6044.7	-0.1	-0.006
42.0 S12	6009.9	6009.3	-0.6	-0.01

* 5.5-lb hammer, 1.0-ft drop, 3 layers, and 12 blows/layer.

Average loss -0.02 percent

Table A-21. Moisture Loss (Gain) of the Test Samples During the Thermal Probe Test, S6 Compaction Energy*

Identification No.	Mass of mold and base plate plus wet soil (g)		Moisture loss (gain) (g)	Percent moisture loss (gain)
	Before thermal probe test	After thermal probe test		
(1)	(2)	(3)	(4)	(5)
Air Dried S6	5885.3	5884.9	-0.4	-0.03
11.5 S6	5899.5	5898.4	-1.1	-0.07
14.5 S6	5876.0	5875.4	-0.6	-0.04
17.5 S6	5905.0	5903.9	-1.1	-0.07
(2/3)** 19.0 S6	5897.2	5896.8	-0.4	-0.03
(2/8) 19.0 S6	5888.2	5887.2	-1.0	-0.06
20.5 S6 Stored	5919.0	5918.8	-0.2	-0.01
21.0 S6	5961.0	5961.3	+0.3	+0.02
22.25 S6	5959.1	5959.3	+0.2	+0.01
23.5 S6 (2/1) Stored	6007.1	6007.1	0.0	0.0
(2/10) 23.5 S6	6045.6	6045.3	-0.3	-0.02
23.5 S6 (2/12) Stored	6073.3	6073.2	-0.1	-0.006
24.75 S6	6062.8	6062.4	-0.4	-0.02
25.0 S6	6030.6	6030.3	-0.3	-0.02
25.0 S6 (1/27) Stored	6077.6	6077.4	-0.2	-0.01
(2/10) 26.5 S6	6072.3	6072.6	+0.3	+0.02
27(26.5) S6 Stored	6099.6	6099.5	-0.1	-0.006
(2/4) 28.0 S6	6079.5	6079.4	-0.1	-0.006
(2/8) 28.0 S6	6110.2	6110.1	-0.1	-0.006
31.0 S6	6132.8	6131.1	-1.7	-0.09
35.0 S6/1	6052.0	6051.7	-0.3	-0.02
35.0 S6/2	6050.4	6049.7	-0.7	-0.04
40.0 S6/1	5988.7	5988.5	-0.2	-0.01
40.0 S6/2	5967.3	5966.8	-0.5	-0.03
47.5 S6	5930.1	5929.3	-0.8	-0.05
55.0 S6	5908.2	5907.4	-0.8	-0.05

* 5.5-lb hammer, 1.0-ft drop, 3 layers, and 6 blows/layer.

** Date thermal probe test was performed

Average loss -0.03 percent

Average gain +0.02 percent

Table A-22. Moisture Loss of the Test Samples During the Thermal Probe Test, S4 Compaction Energy

Identification No.	Mass of mold and base plate plus wet soil (g)		Moisture loss (g)	Percent moisture loss
	Before thermal probe test	After thermal probe test		
(1)	(2)	(3)	(4)	(5)
22.0 S4	5932.5	5932.3	-0.2	-0.01
26.0 S4	6083.6	6083.3	-0.3	-0.02
27.0 S4	6011.6	6010.6	-1.0	-0.06
28.0 S4	5978.1	5977.8	-0.3	-0.02
32.0 S4	6052.1	6051.8	-0.3	-0.02

* 5.5-lb hammer, 1.0-ft drop, 3 layers, and 4 blows/layer.

Average loss -0.03 percent

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11. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here*)

Laboratory thermal probe tests performed on an AASHTO standard reference material (a silty clay) showed that thermal resistivity (°C·cm/watt) varies with soil moisture content and dry density. The tests were performed to correlate soil thermal behavior with the limit states of fine-grained soils. Over 80 thermal resistivity measurements were made on specimens compacted to various densities and moisture contents.

Results are presented which indicate that the optimum moisture content of soils and the Atterberg Limits can be correlated with the thermal behavior of fine-grained soils. It was found that the minimum thermal resistivity (i.e., the critical moisture content) occurred at the optimum moisture content when the soils were compacted using various compactive efforts. The critical moisture content defines the knee of the thermal resistivity versus moisture content curve. When the soils were compacted using a compactive effort of 1.42×10^5 J/m^3 (2970 ft-lbs per cubic foot), the minimum thermal resistivity occurred at the plastic limit of the AASHTO standard reference material. Also, indices are defined which allow comparison of the thermal behavior of fine-grained soils.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

Atterberg Limit tests; compaction; compaction tests; heat flow; laboratory tests; soil moisture; soil tests; tests; thermal conductivity; thermal resistivity

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