NBSIR 84-2935

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

ABSTRACT

Laboratory thermal probe tests performed on four (4) different soils were used to study the influence of soil type and gradation on the thermal resistivity of soils. The four soils covered a wide range of gradations and included: two sands (SP and SP-SM), a silty clay (CL), and a silt (ML).

Results are presented which indicate that as the sand content increases in a silty clay (CL), the minimum thermal resistivity and the critical moisture content decrease for the range of compactive efforts studied. Increasing the medium and coarse sand fraction in a granular soil significantly increases the heat conductive properties of the soils. Also, in the stable region of each of the major soil groups (i.e., granular and fine-grained soils) the influence of soil type and density on the thermal resistivity of soils is negligible and a constant value of thermal resistivity is observed. The constant value of thermal resistivity is approximately 30 to 40°C·cm/watt and 50 to 70°C·cm/watt for granular soils and fine-grained soils, respectively.

Keywords: compaction, compaction tests, gradation, heat flow, laboratory tests, soil moisture, soil tests, soil type, tests, thermal conductivity, thermal resistivity.

Table of Contents

List of Figures

List of Tables

INTRODUCTION

Heat transfer from earth-contact surfaces (such as a basement wall/floor, slab-on grade floor, underground heat distribution system, and ground coupled heat pump) is not well understood despite recent advances in building thermal analysis. One difficulty in estimating the earth heat transfer is the uncertainty involved in the thermal conductivity of the soil.

Progress in the determination of the thermal behavior of soils for earth contact heat transfer problems has been hampered by the fact that information on thermal soil properties is scattered in a variety of technical fields, and professionals lack a common language to describe the thermal behavior of soils. Use of soil as an insulating material or as a conductor to dissipate heat requires that progress be made in this area and a systematic approach be developed for selecting appropriate values of thermal resistivity.

As an aid to selecting appropriate values of soil thermal resistivity and the calculation of heat transfer in soils, Salomone (1982) showed that the critical moisture content can be correlated with soil limit states associated with moisture content, which, in turn, can be established by methods (e.g., Atterberg Limits i.e. Shrinkage Limit, Plastic Limit and Liquid Limit shown in figure 1) used by geotechnical engineers and agronomists. The critical moisture content is the moisture content below which the thermal resistivity increases rapidly with further drying. Additional work by Salomone et al. (1982, 1984[a]) found that the critical moisture content correlates with the optimum moisture content (that will be defined later) for fine-grained soils over a wide range of densities. However, as the density of the fine-grained soil decreases to densities typical of unconsolidated marine deposits (less than 1600 kg/m^3), the correlation between critical moisture content and the plastic limit found by Salomone (1982) is evident.

These correlations, optimum moisture content versus critical moisture content and plastic limit versus critical moisture content are important because the critical moisture content is of particular interest from a thermal instability viewpoint as discussed in more detail later. Thermal instability occurs in moist soils because of significant moisture movement when the soil is subjected to thermal gradients due to the presence of a heat source (Hartley et al., 1982). Therefore, a large increase in the thermal resistivity of the soil occurs when the moisture content of the soil falls below the critical moisture content (Radhakrishna et al., 1980) (dry side of optimum). Above the critical moisture content, the thermal resistivity is fairly constant (Boggs et al., 1982) (wet side of optimum).

Salomone and Kovacs (1984[b]) present three procedures for determining the critical moisture content: 1)the critical moisture content is the moisture content at the knee or cusp of the thermal resistivity versus moisture content curve, 2)the optimum moisture content and plastic limit are physical quantities indicative of the critical moisture content in soils as explained above and 3)the upper flex point (cusp) of the soil moisture characteristics curve established the critical moisture content in soils.

This paper examines the influence of soil type and gradation on the thermal behavior of soils. An approach for establishing the influence of these factors is also presented.

BACKGROUND

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 No. 200 (75 μm) sieve. The plasticity and cohesion of a soil are also indicators of soil type. Clays are both plastic and cohesive while sands are nonplastic and noncohesive (cohesionless). Silts are intermediate between sands and clays. Silts are fine-grained yet nonplastic and cohesionless. These relationships have been summarized by Holtz and Kovacs, 1981 (table 1).

The particle size distribution of sands and gravels have an important influence on their engineering behavior. The particle size distribution (texture) of a soil is obtained by mechanical analysis. Detailed procedures for this test have been specified by ASTM D 422-72 (Standard Method for Particle-Size Analysis of Soils) procedures (ASTM, 1982).

The engineering properties of fine-grained soils are greatly affected by the presence of water rather than by the texture alone. Consequently, Atterberg Limit tests (ASTM, 1982) are used to classify fine-grained soils. The Atterberg Limits provide a measure of the plasticity of fine-grained soils and represent important limit states of engineering behavior (figure 1). Figure 1 shows the Atterberg Limits (i.e., Plastic Limit and Liquid Limit) as limiting moisture contents that are the dividing line between the types of stress-strain behavior shown. By knowing the natural moisture content of a soil in relation to its Atterberg Limits, the engineering response of a soil can be estimated. Likewise, the work of Salomone at the National Bureau of Standards (NBS) has been directed towards developing methods to establish the limit states of thermal behavior of soils so that the thermal response of a soil can be estimated using the same index and classification properties (e.g. particle size and Atterberg Limits) of soils.

The approach that is being used involves systematically testing soils in the soil groups defined by the Unified Soil Classification System (see, for example, Holtz and Kovacs, 1981) and establishing the relationship of thermal resistivity versus moisture content and density for these soils. The dividing line between significant changes in the thermal resistivity versus moisture content relationship at a given density would then be an important limit state of thermal behavior.

Table 1. Textural and Other Characteristics of Soils (from Holtz and Kovacs, 1981)

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	Cohesionless	Cohesive
	Nonplastic Granular	Nonplastic Granular	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

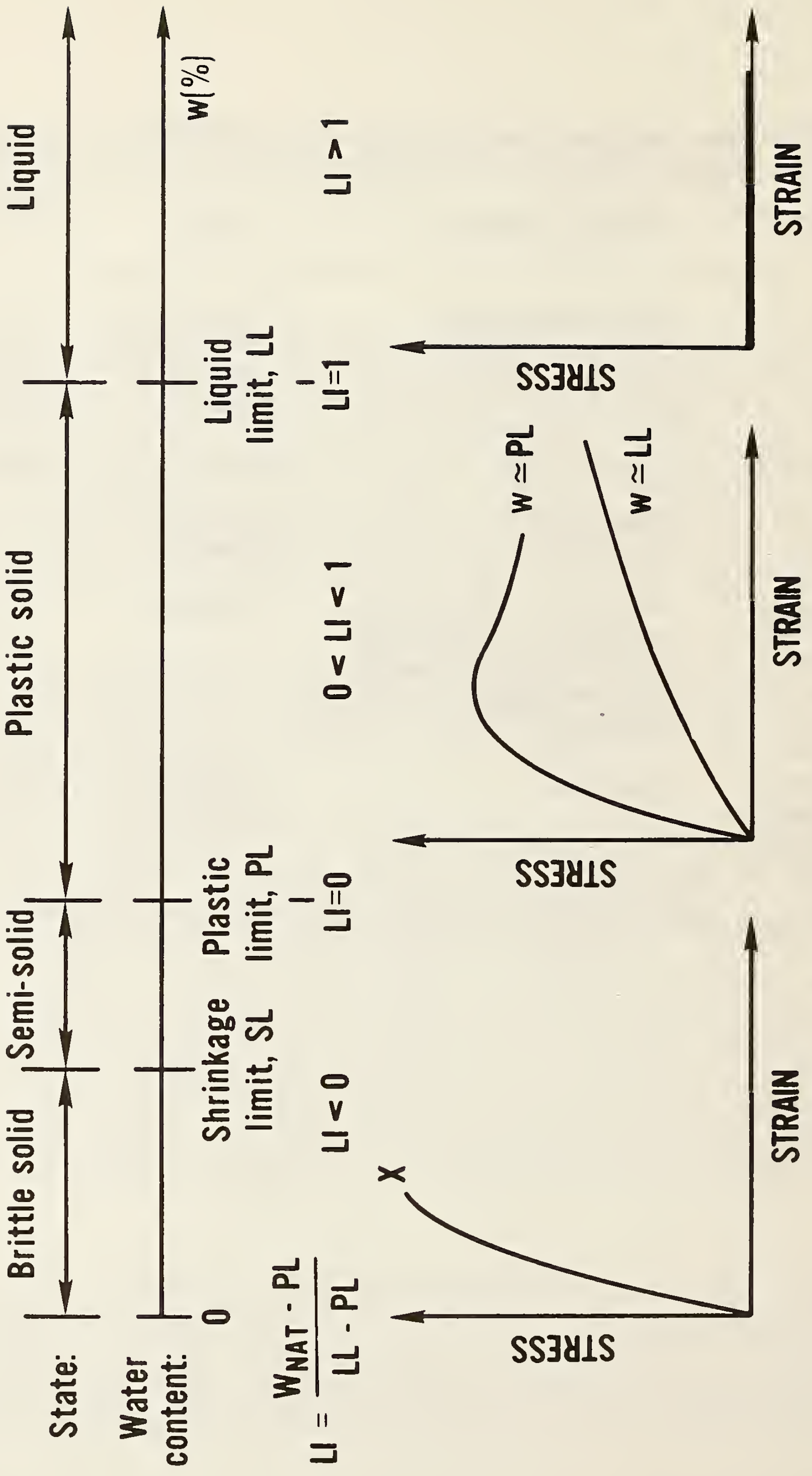


Figure 1. Moisture content continuum showing the various states of fine-grained soils and the generalized stress-strain response (modified from Holtz and Kovacs, 1981)

Figure 2 illustrates that the critical moisture content can be an important limit state of thermal soil behavior. By knowing the moisture content of a soil and the critical moisture content, the thermal resistivity of a soil can be estimated.

A large increase in thermal resistivity with a small decrease in moisture content occurs when the moisture content of the soil falls below the critical moisture content and the term "soil thermal instability" is used for this condition (Radhakrishna et al., 1980). Above the critical moisture content the thermal resistivity is fairly constant and the term "soil thermal stability" is used to describe this physical condition (Boggs et al., 1982).

APPROACH

The critical moisture content can be determined directly by using thermal probe tests to establish the thermal resistivity versus moisture content curve for a soil at the dry density anticipated for a project or indirectly by using those index properties of soils that have been found (Salomone, 1983) to correlate with the critical moisture content.

The direct method was used for this study. A thermal property analyzer was used to faciliate data acquisition and reduction from a thermal needle, the principle of which can be found in most of the heat conduction text books such as Carslow and Jaeger, 1959. The analyzer consists of an electric current (heat) source and a thermocouple reader under microprocessor control. The thermal resistivity is calculated by the microprocessor from a linear least-squares fit of the logarithms of time and temperature data obtained from the thermal needle.

Because the critical moisture content varies with dry density as shown in figure 3, the thermal resistivity versus moisture content curve was established for the soils used in the study at two or more densities. The densities selected were at least 95% of the maximum density and the minimum density of the soils. For granular soils (i.e., soils with less than 12 weight percent of soil particles passing a No. 200 (75 μm) sieve) ASTM D 2049-69 procedures were used to determine the maximum and minimum density. This method utilizes vibratory compaction to obtain maximum density and pouring to obtain minimum density. For fine-grained soils, ASTM D 698-78 and ASTM D 1557-78 procedures were used to approximate the minimum and maximum densities. These laboratory compaction methods cover the determination of the relationship between the moisture content and density of soils when compacted in a mold of a given size with a 5.5 lb (2.49 kg) rammer (ASTM D 698-78) or 10 lb (4.54 kg) rammer (ASTM D 1557-78) dropped from a height of 12 in (305 mm) (ASTM D 698-78) or 18 in (457 mm) (ASTM D 1557-78). The number of layers and the number of blows per layer were varied to obtain the moisture-density relationship at the compactive efforts shown in Table 2. Test specimens were prepared by different compaction energies to obtain the thermal resistivity data over a wide range of density and moisture. In cases where a third density was selected, some intermediate density was used.

By defining the thermal resistivity versus moisture content relationship at the minimum and maximum density, the envelope of thermal behavior is established for the soil and the influence of soil type and gradation can be studied.

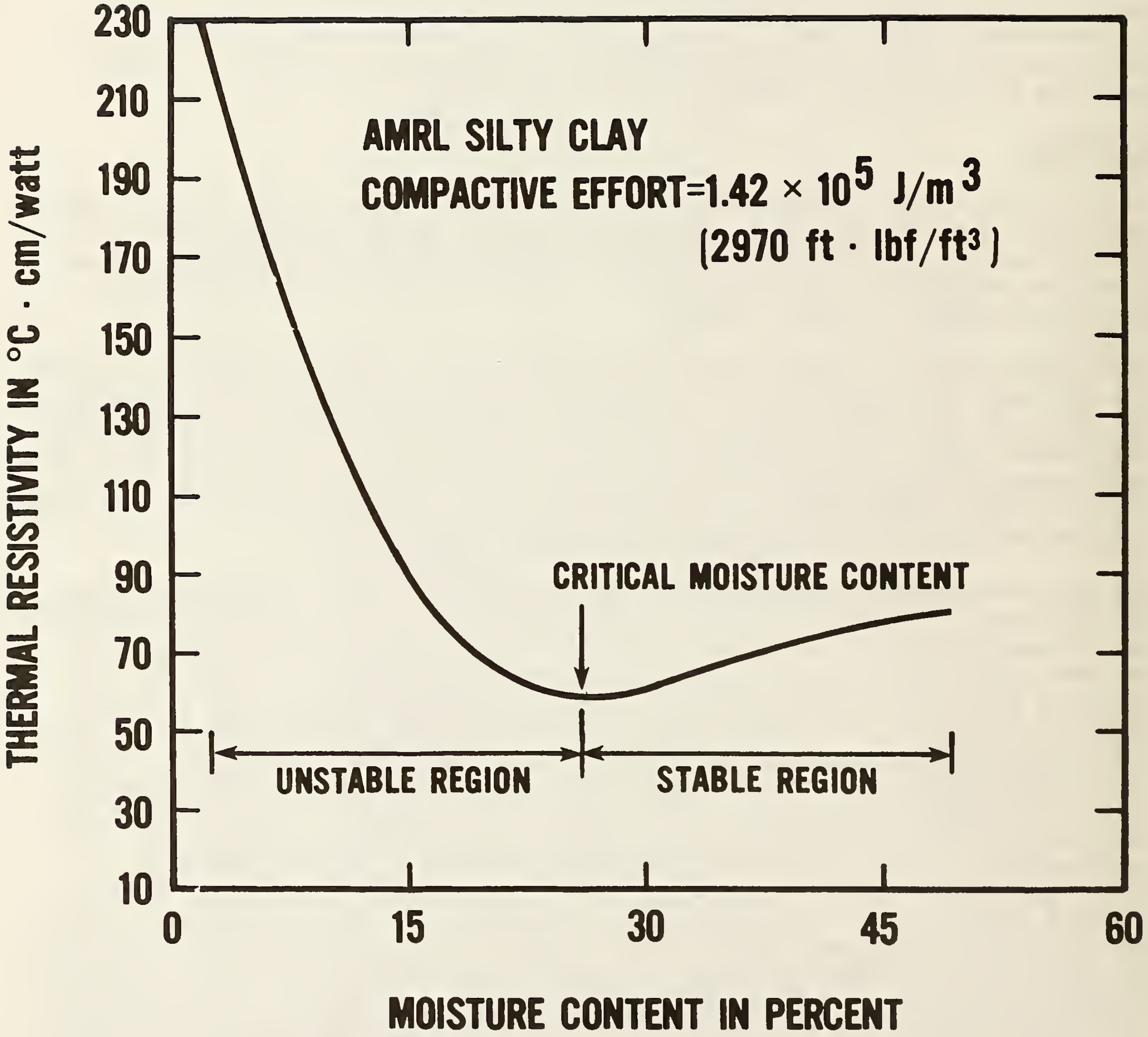


Figure 2. Variation of thermal resistivity with Moisture Content for AMRL No. 61 silty clay (Salomone and Kovacs, 1984[b])

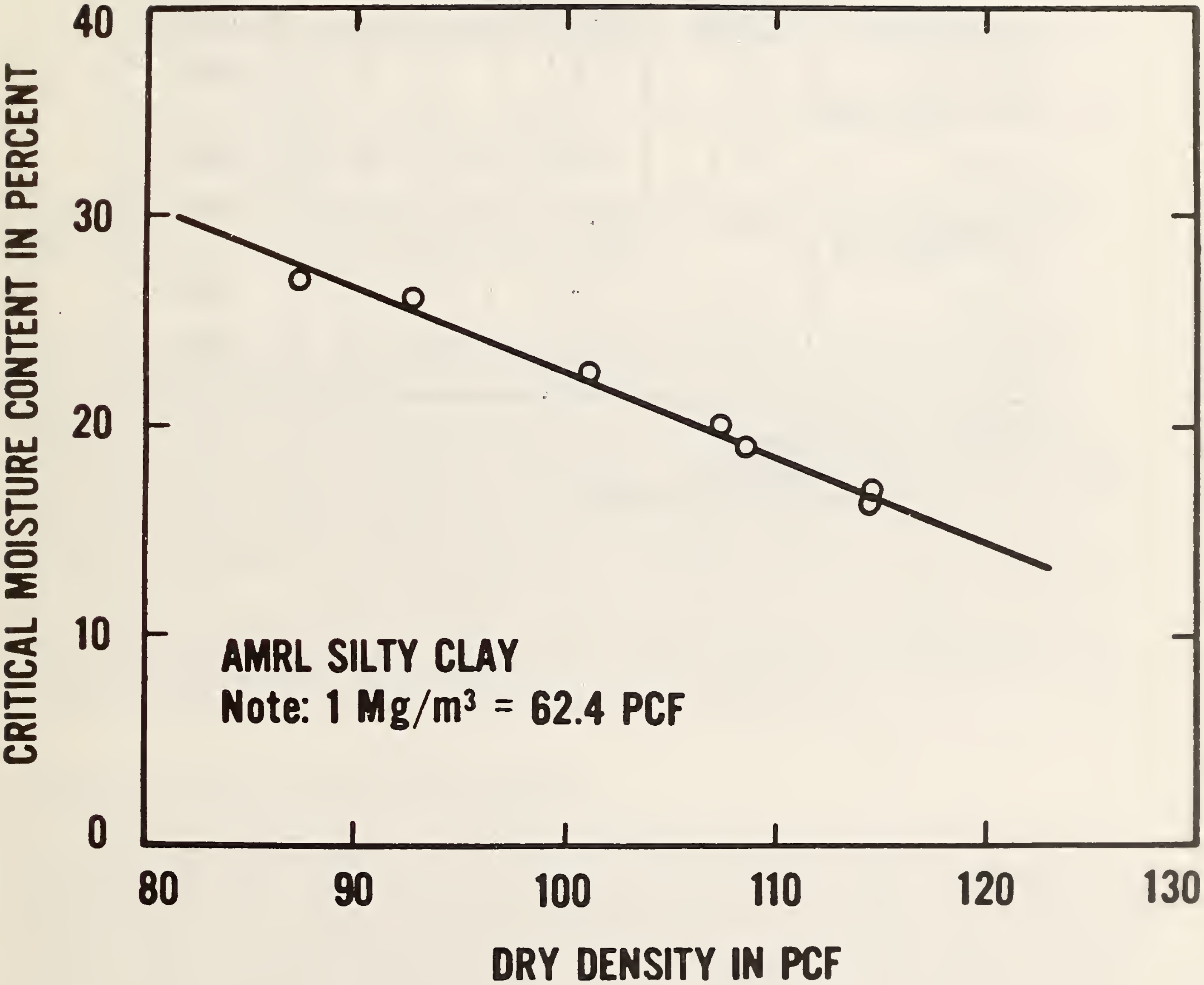


Figure 3. Influence of dry density on critical moisture content for AMRL No. 61 silty clay (Salomone and Kovacs, 1984[b])

Table 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	Compactive Energy ft•lbf/ft^3*
Modified (ASTM D1557-78)	10	1.5	5	25	56250
S 25-5	5.5	1.0	5	25	20625
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

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

DESCRIPTION OF TESTED SOILS

Soils were selected using the following criteria:

1. The gradation and plasticity characteristics of the soil were different than the other soils being studied.

2. The Unified Soil Classification symbol was different than the other soils being studied.

3. The index properties (e.g., particle size and Atterberg Limits) of the soil were well known or easily determined.

Soils meeting these criteria included in the testing are described in table 3. USCS definitions of particle size, size ranges, and symbols are presented in table 4 modified from Holtz and Kovacs, 1981.

Referring to table 3, it is important to emphasize the difference between the generic or geologic name and the soil description. The soil description and USCS symbol is more exact for classifying soils than the generic or geologic name. Each word in the soil description is used to indicate something of the gradation of the soil. The major component is stated first and adjectives such as "fine to coarse" are used to indicate particle size. Also, descriptive terms such as the word "trace" are used to indicate the amount (or proportion) in a particular size range. Use of the generic or geologic name can often be misleading. Therefore, the soil description is recommended when classifying soils.

The gradation of the soils studied are shown on figure 4. The Atterberg Limits of the fine-grained soils are also shown. Table 5 provides the compaction characteristics. Using Table 5 the densities for the thermal resistivity versus moisture content curves were selected for each of the soils.

PRESENTATION AND ANALYSIS OF TEST RESULTS

The first step in determining the thermal behavior of fine-grained soils is to correlate its trends in thermal resistivity versus moisture content with its compaction characteristics. To illustrate the procedure, figures 5 through 7 show the correlation for AASHTO Materials Reference Laboratory (AMRL) No. 71 silty clay and sand (CL) for three compactive efforts: modified, standard, and S6, respectively. When the dry densities of each sample are determined and plotted versus the moisture contents, the compaction curves are obtained. Each data point on the curves 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 and is known as the optimum moisture content. The maximum dry density varies with compactive effort. Increasing the compactive effort increases the maximum dry density and decreases the optimum moisture content as expected.

Table 3. Description of Soils Used in Testing Program

Generic Name	Letter Symbol	Soil Description
Pepco Thermal Sand	SP	Fine to coarse sand, trace silt
Florida Sand	SP - SM	Fine to medium sand, trace silt
AMRL No. 71 Silty Clay and Sand	CL	Silty clay, some fine sand, trace medium sand
Bonny Loess	ML	Silt, trace fine sand

Table 4. USCS Definitions of Particle Size, Size Ranges, and Symbols

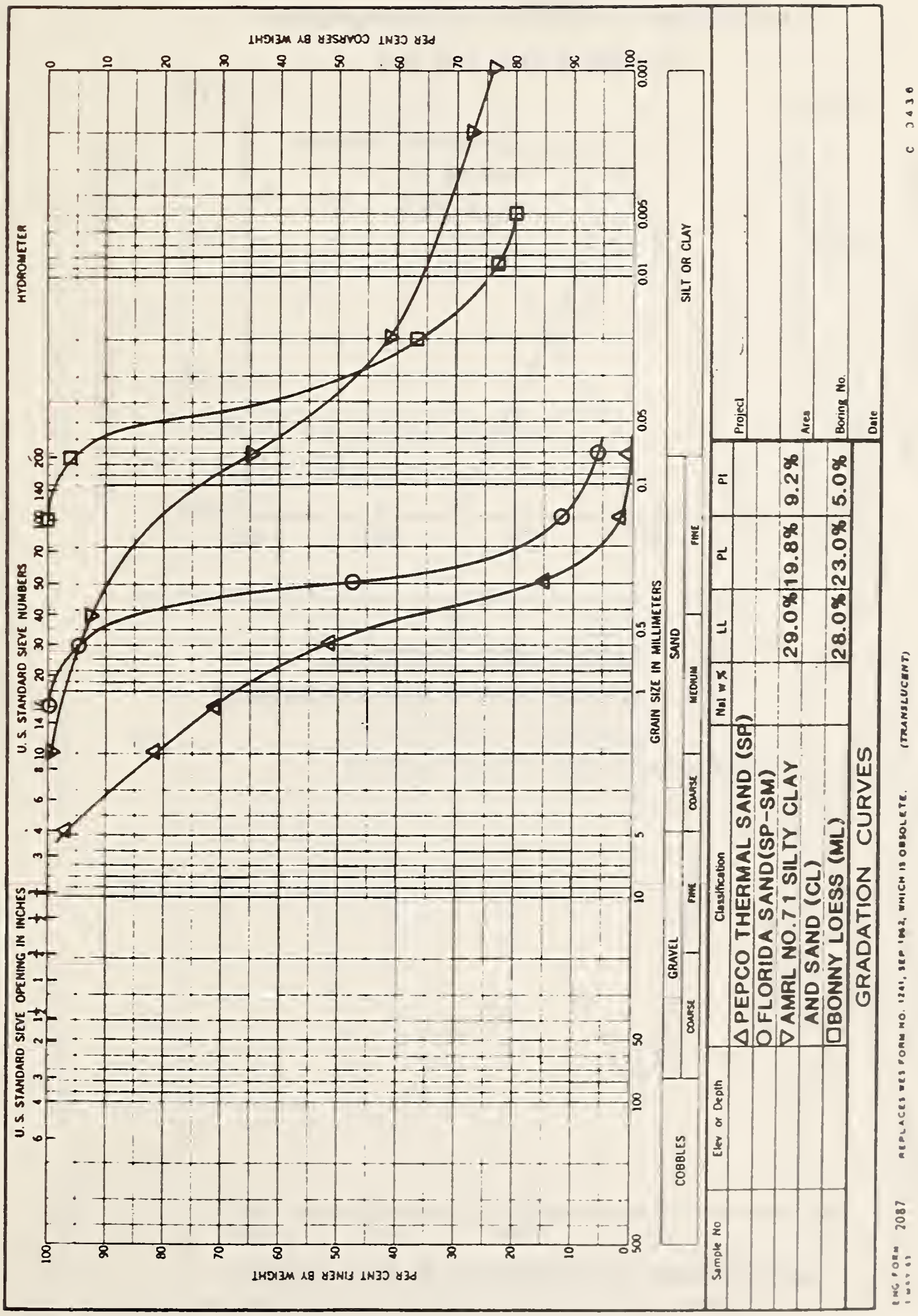
Soil Fraction or Component	Symbol	Size Range
Boulders	None	Greater than 300 mm
Cobbles	None	75 mm to 300 mm
(1) Coarse-grained soils:		
Gravel	G	75 mm to No. 4 sieve (4.75 mm)
Coarse		75 mm to 19 mm
Fine		19 mm to No. 4 sieve (4.75mm)
Sand	S	No. 4 (4.75 mm) to No. 200 (0.075 mm)
Coarse		No. 4 (4.75 mm) to No. 10 (2.0 mm)
Medium		No. 10 (2.0 mm) to No. 40 (0.425 mm)
Fine		No. 40 (0.425 mm) to No. 200 (0.075 mm)
(2) Fine-grained soils:		
Fines		Less than No. 200 sieve (0.075 mm)
Silt	M	(No specific grain size -- use Atterberg Limits)
Clay	C	(No specific grain size -- use Atterberg Limits)
(3) Organic soils:	O	(No specific grain size)
(4) Peat:	Pt	(No specific grain size)

Gradation Symbols	Liquid Limit Symbols
Well-graded, W	High LL, H
Poorly-graded P	Low LL, L

Description Term	Range of Proportion
Trace	1 - 10%
Little	10 - 20%
Some	20 - 35%
And	35 - 50%

Table 5. Compaction Characteristics

	ASTM D2049-69		ASTM D698-78	
GENERIC NAME	MINIMUM DENSITY kg/m^3 (PCF)	MAXIMUM DENSITY kg/m^3 (PCF)	OPTIMUM MOISTURE CONTENT %	MAXIMUM DENSITY kg/m^3 (PCF)
PEPCO THERMAL SAND (SP)	1578 (98.5)	1861 (116.1)	N.A.	N.A.
FLORIDA SAND (SP-SM)	1282 (80.0)	1590 (99.2)	12.5	1843 (115.0)
AMRL NO. 71 SILTY CLAY AND SAND (CL)	N.A.	N.A.	14.7	1828 (114.1)
BONNY LOESS (ML)	N.A.	N.A.	16.5	1667 (104.0)



Sample No	Elev or Depth	Classification	Nat w %	LL	PL	PI
		△ PEPCO THERMAL SAND (SP)				
		○ FLORIDA SAND(SP-SM)				
		▽ AMRL NO.7 1 SILTY CLAY AND SAND (CL)		29.0%	19.8%	9.2%
		□ BONNY LOESS (ML)		28.0%	23.0%	5.0%

Figure 4. Gradation and plasticity characteristics (Atterberg Limits) of the soils studied

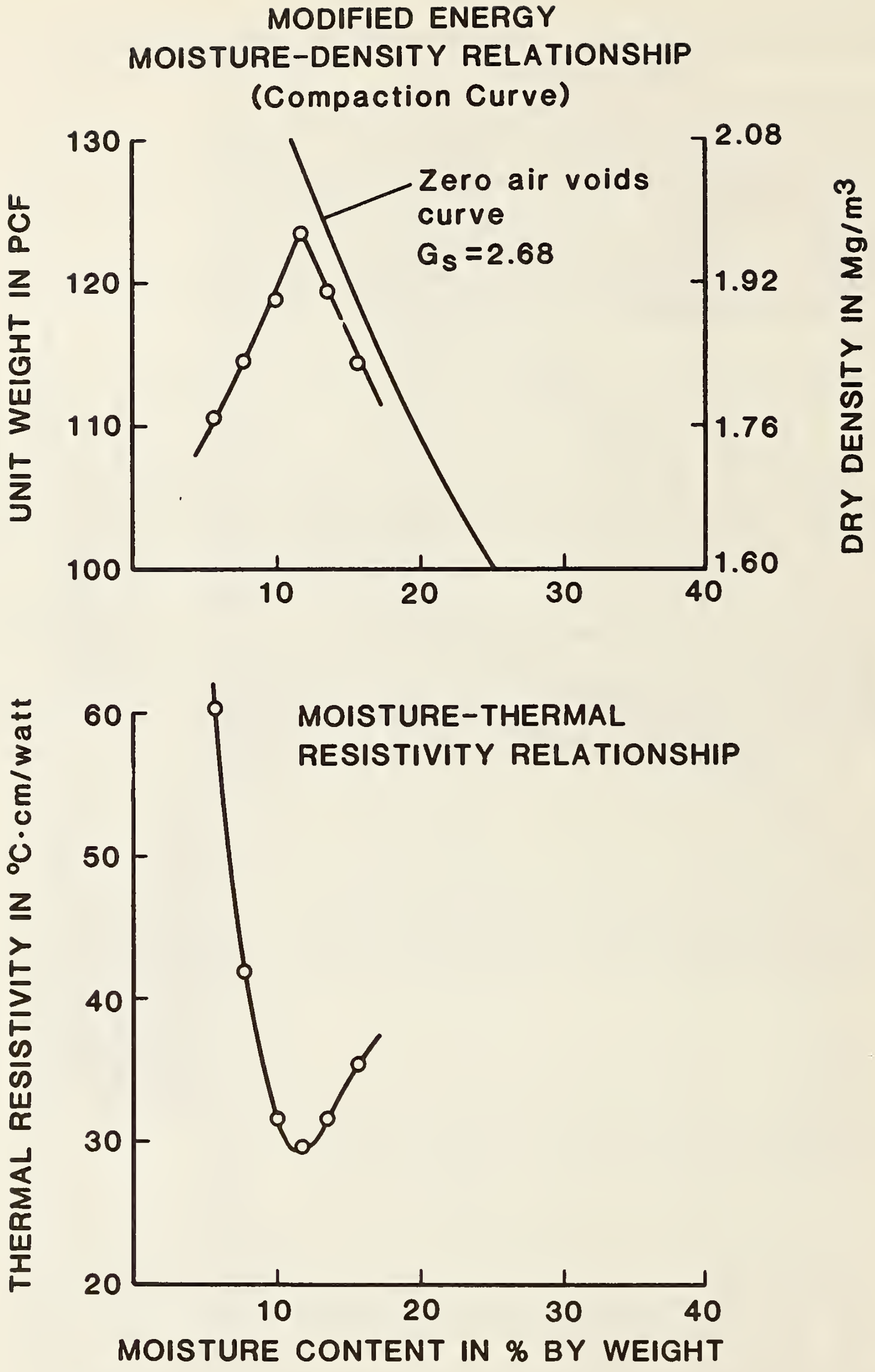


Figure 5. Relationship between dry density and thermal resistivity versus molding moisture content for modified energy (ASTM D 1557-78) for AMRL No. 71 Silty Clay and Sand (CL)

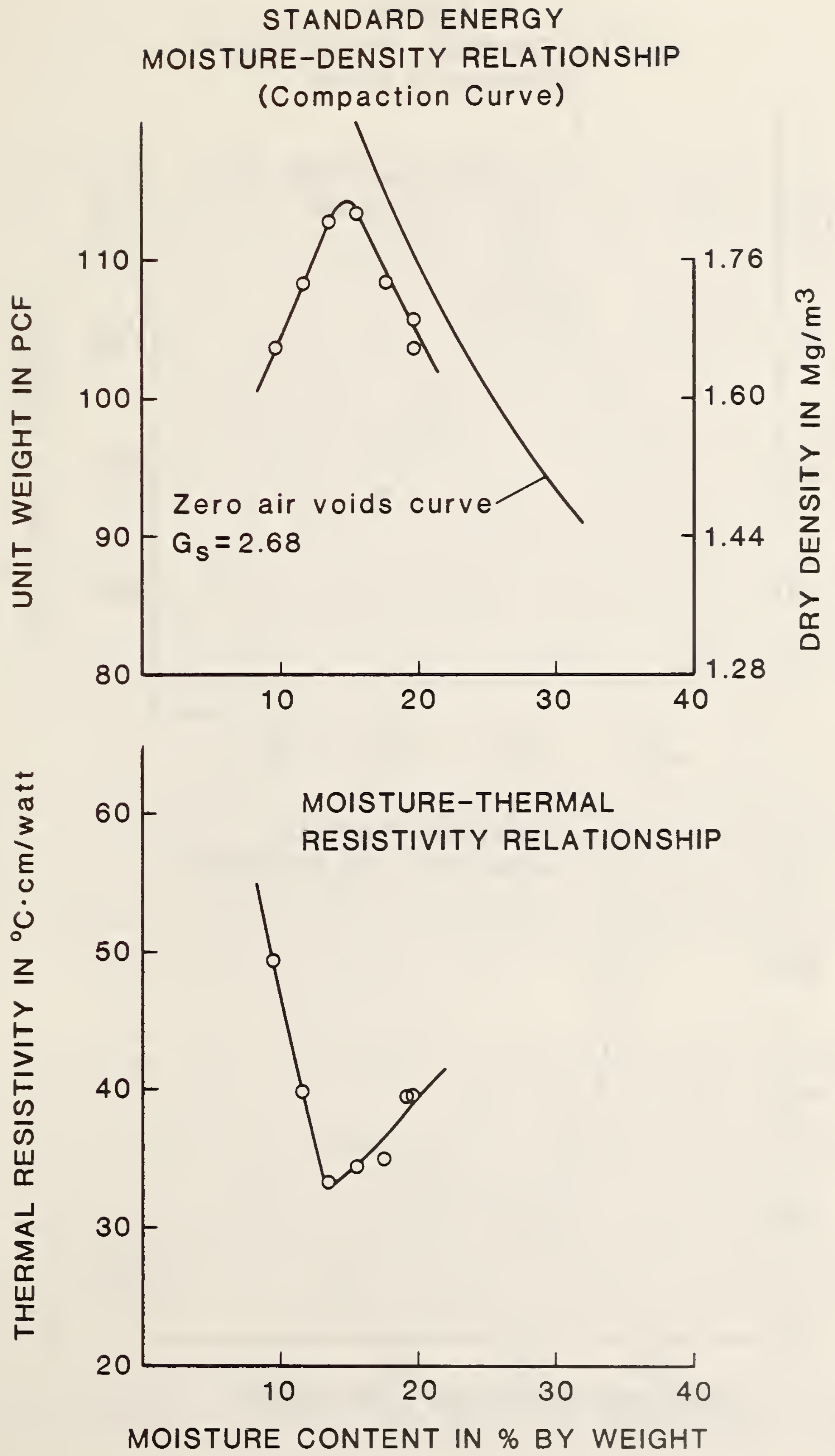


Figure 6. Relationship between dry density and thermal resistivity versus molding moisture content for standard energy (ASTM D 698-78) for AMRL No. 71 Silty Clay and Sand (CL)

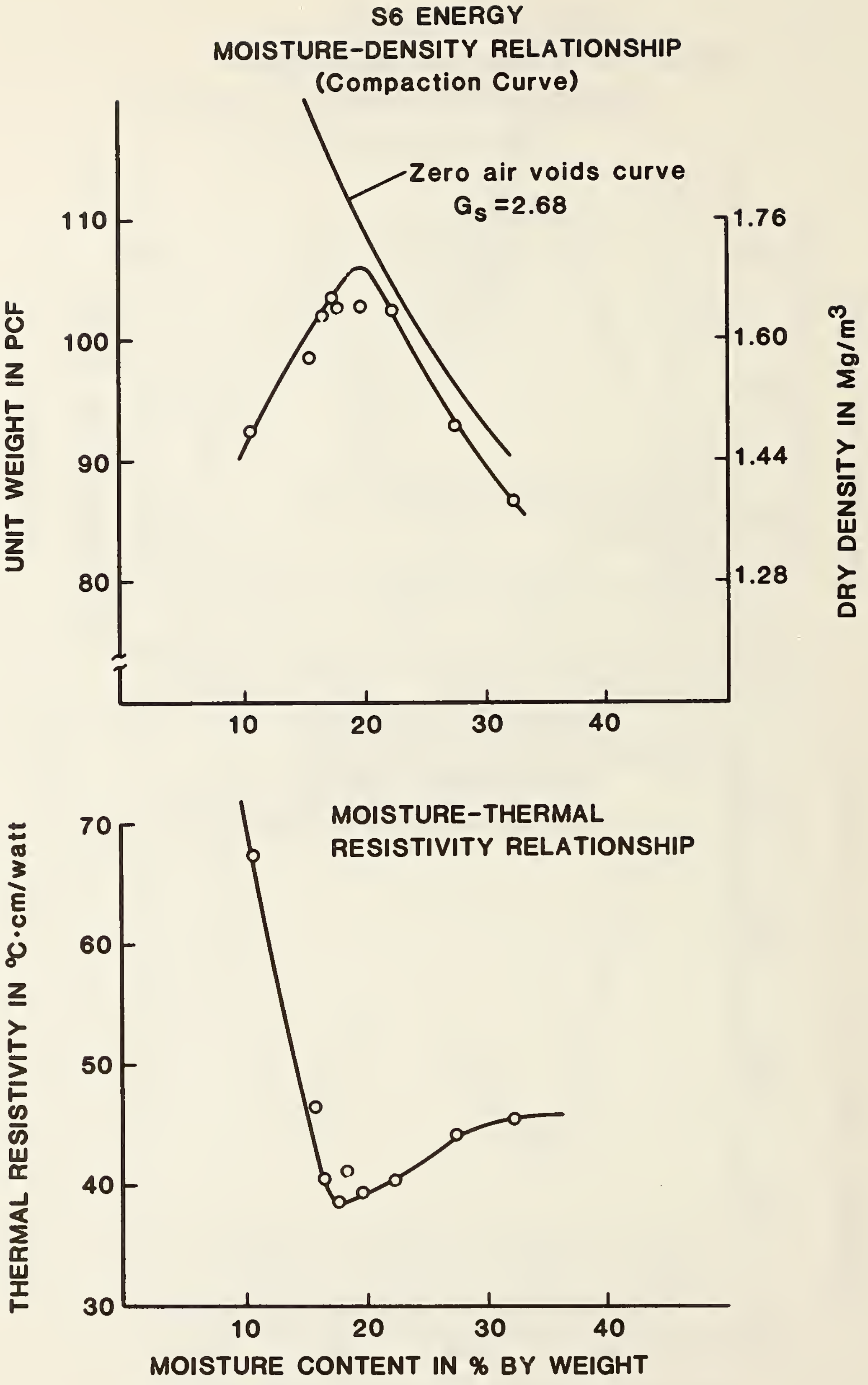


Figure 7. Relationship between dry density and thermal resistivity versus molding moisture content for S6 energy (2,970 ft·lb/cu ft) for AMRL No. 71 Silty Clay and Sand (CL)

A summary of the compaction curves and the thermal resistivity versus moisture content curves for the five compactive efforts are shown on figures 8 and 9, respectively. The minimum thermal resistivity for each compactive effort (see figures 5 through 7) generally occurs at the point of optimum moisture content (and maximum dry density). Therefore, the moisture content corresponding to the minimum value of thermal resistivity (or the critical moisture content) is approximately equal to the optimum moisture content. 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 10(a)). Using the fact that the optimum moisture content is equal to the critical moisture content, the relationship between critical moisture content and compactive efforts is shown in figure 10(b). The relationship is determined from the line of optimums, which is the line drawn through the peak points of the compaction curves at the five compactive efforts. Comparing the curve for AMRL No. 61 silty clay (CL) from Salomone and Kovacs, 1984[a] with the curve for AMRL No. 71 silty clay and sand (CL) on figure 10, one can see the influence of increasing the amount of sand in a clay soil on the relationships shown. AMRL No. 61 has 10 percent by weight sand while AMRL No. 71 has 35 percent by weight sand. As the sand content increases, the minimum thermal resistivity and the critical moisture content decrease for the range of compactive efforts studied.

The second step in determining the thermal behavior of a fine-grained soil is to use the data from plots similar to those presented on figures 5 through 7 to establish the thermal resistivity versus moisture content relationship for the range of densities anticipated for the project. The lowest density can be the minimum density anticipated for the soil and the maximum density can be the maximum density defined by ASTM D 698-78 procedures. The curves of thermal resistivity versus moisture content at the minimum and maximum density establish the envelope of thermal behavior for the soil as illustrated in figure 11 for the AMRL No. 71 silty clay and sand (CL).

The envelope of thermal behavior for a granular soil is more easily determined than for a fine-grained soil. The minimum and maximum densities are determined using ASTM D 2049 procedures (or if there is more than 12 weight % of soil particles passing a No. 200 (75 µm) sieve, ASTM D 698-78 procedures are used to determine the maximum density). Samples are then prepared at the minimum and maximum density for a full range of moisture contents and thermal probe tests are performed using the following two methods. Method 1 involves stage drying a sample at the desired dry density. Method 2 involves measuring the thermal resistivity of reconstituted soil samples at different moisture contents and at the desired dry density. The results of these thermal probe tests for the PEPCO thermal sand (SP) and the Florida sand (SP-SM) are shown in figures 12 and 13, respectively.

Comparing the envelopes of thermal behavior for the PEPCO thermal sand (SP) and the Florida sand (SP-SM) in figure 14, one can see the advantages of increasing

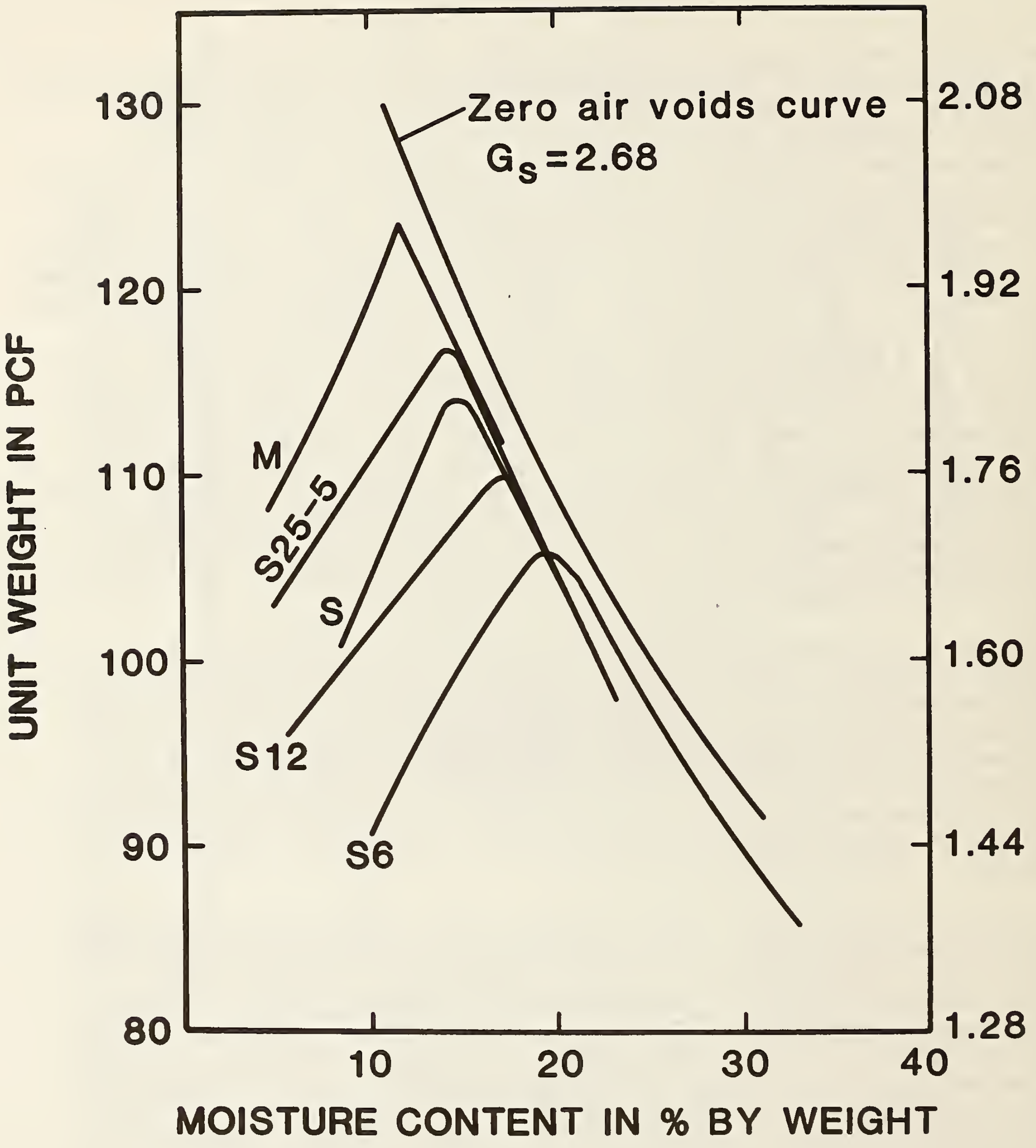


Figure 8. Summary of compaction curves for AMRL No. 71 silty clay and sand

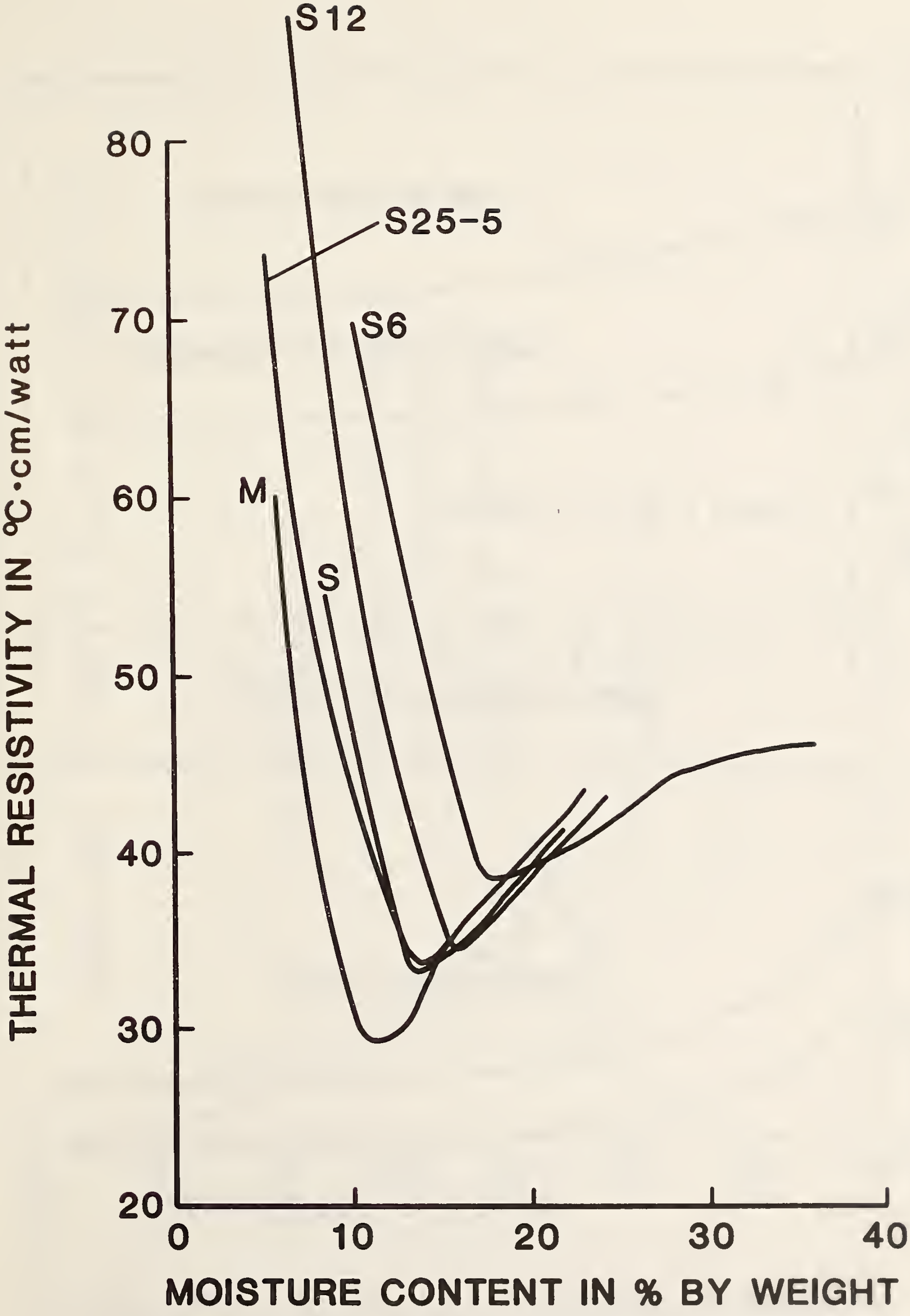


Figure 9. Summary of thermal resistivity versus moisture content curves for AMRL No. 71 silty clay and sand

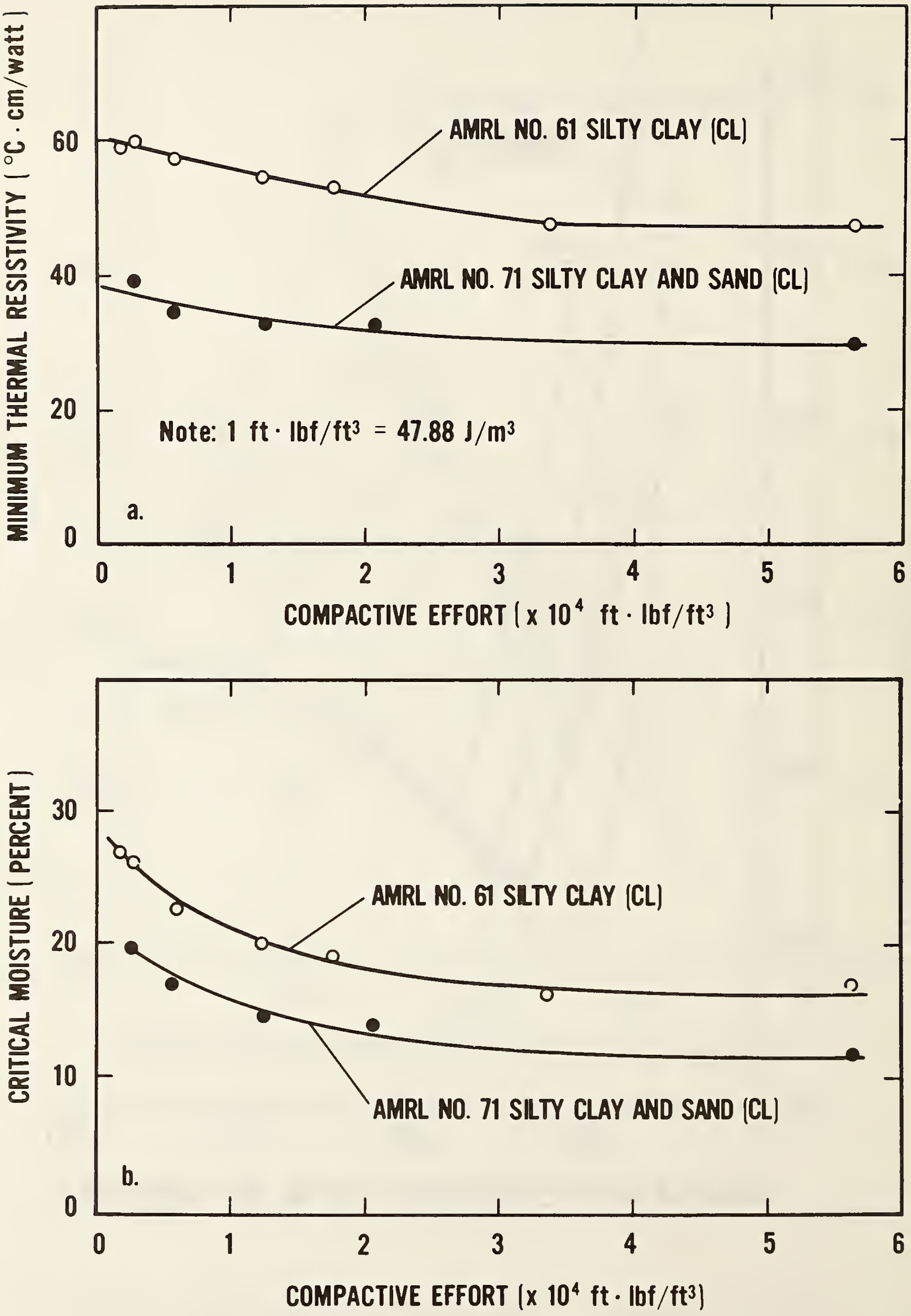


Figure 10. Plot of: (a) minimum thermal resistivity, and (b) critical moisture content versus compactive effort

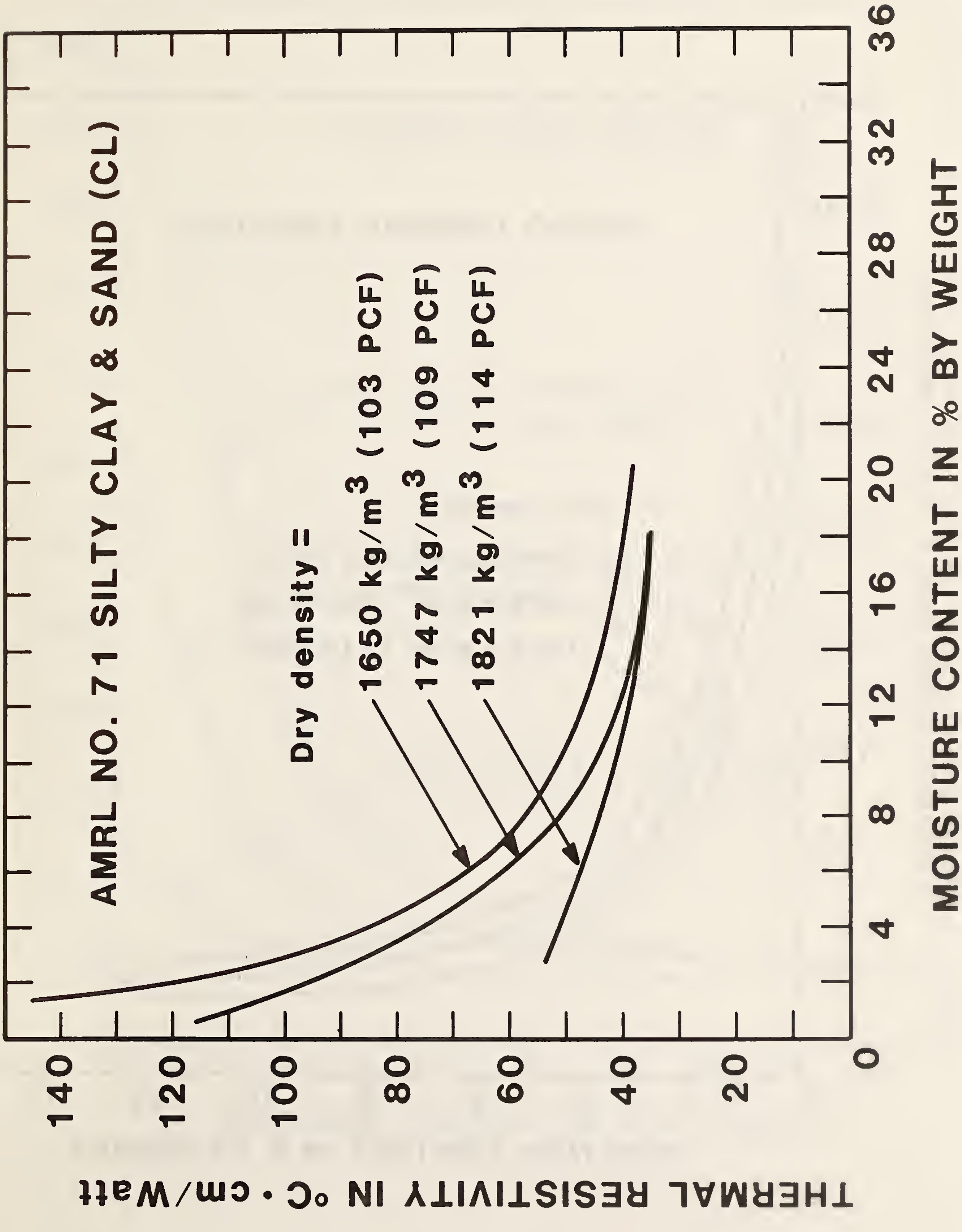


Figure 11. Envelope of thermal behavior for AMRL No. 71 silty clay and sand (CL)

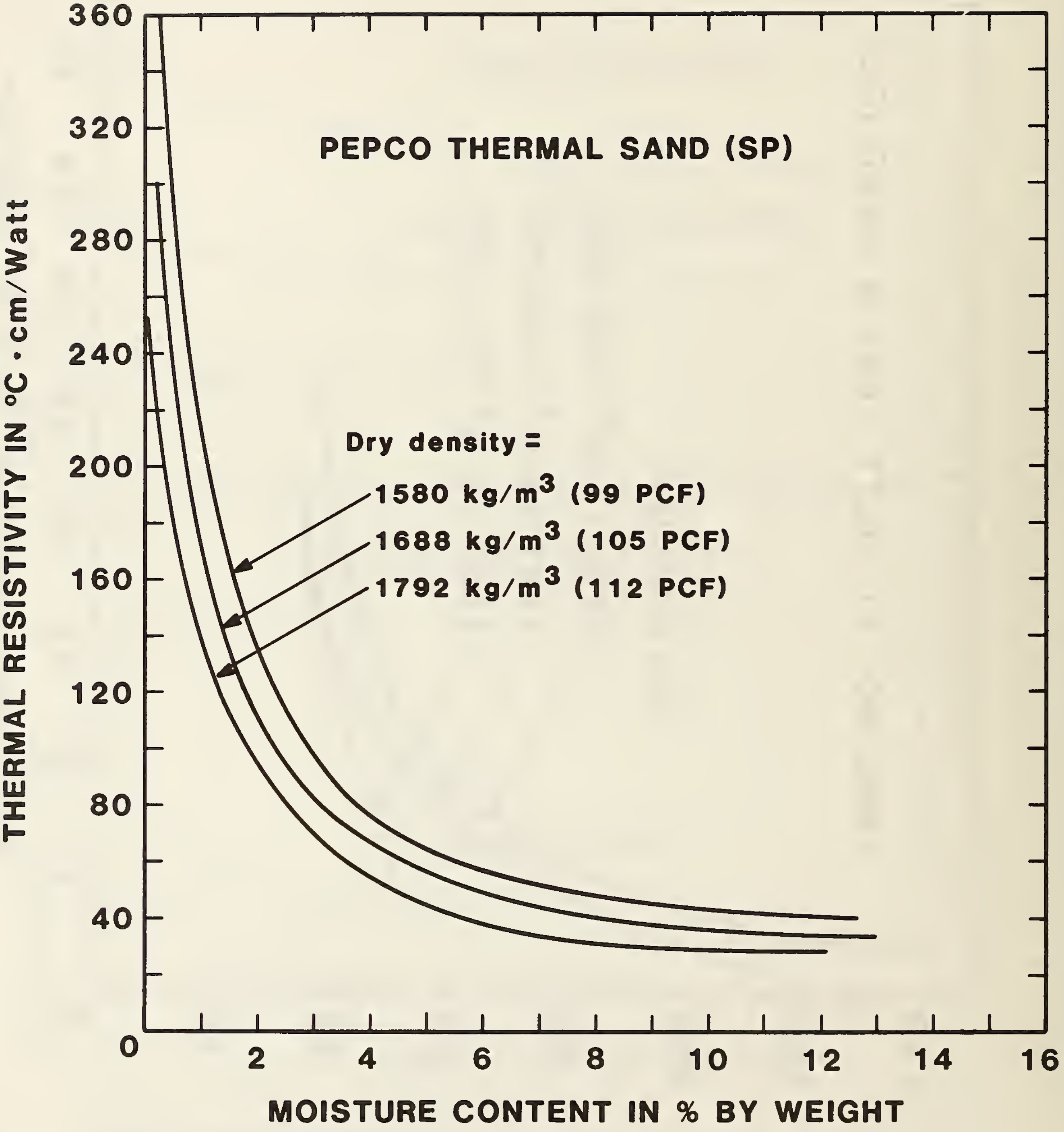


Figure 12. Envelope of thermal behavior for PEPCO thermal sand (SP)

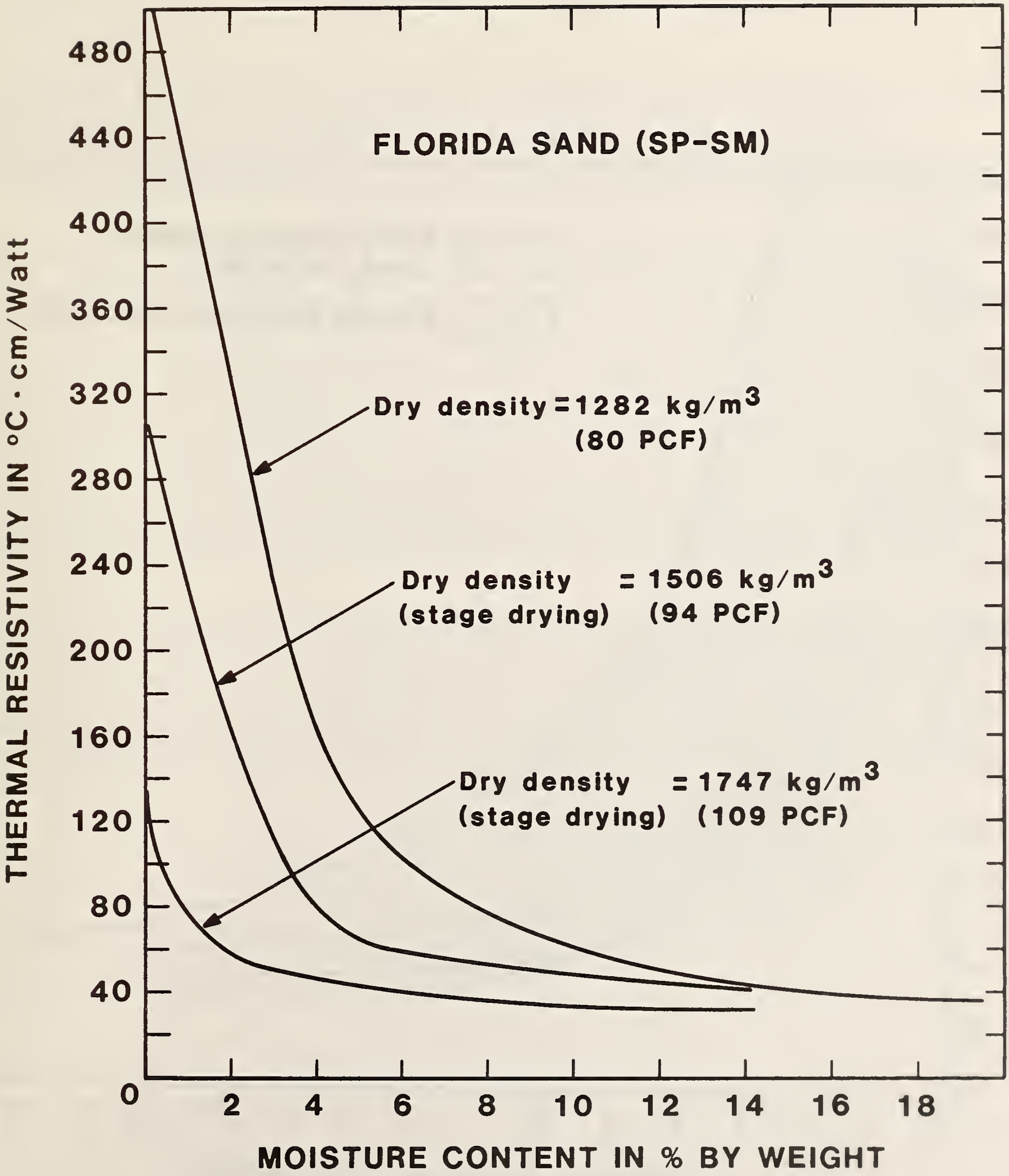


Figure 13. Envelope of thermal behavior for Florida sand (SP-SM)

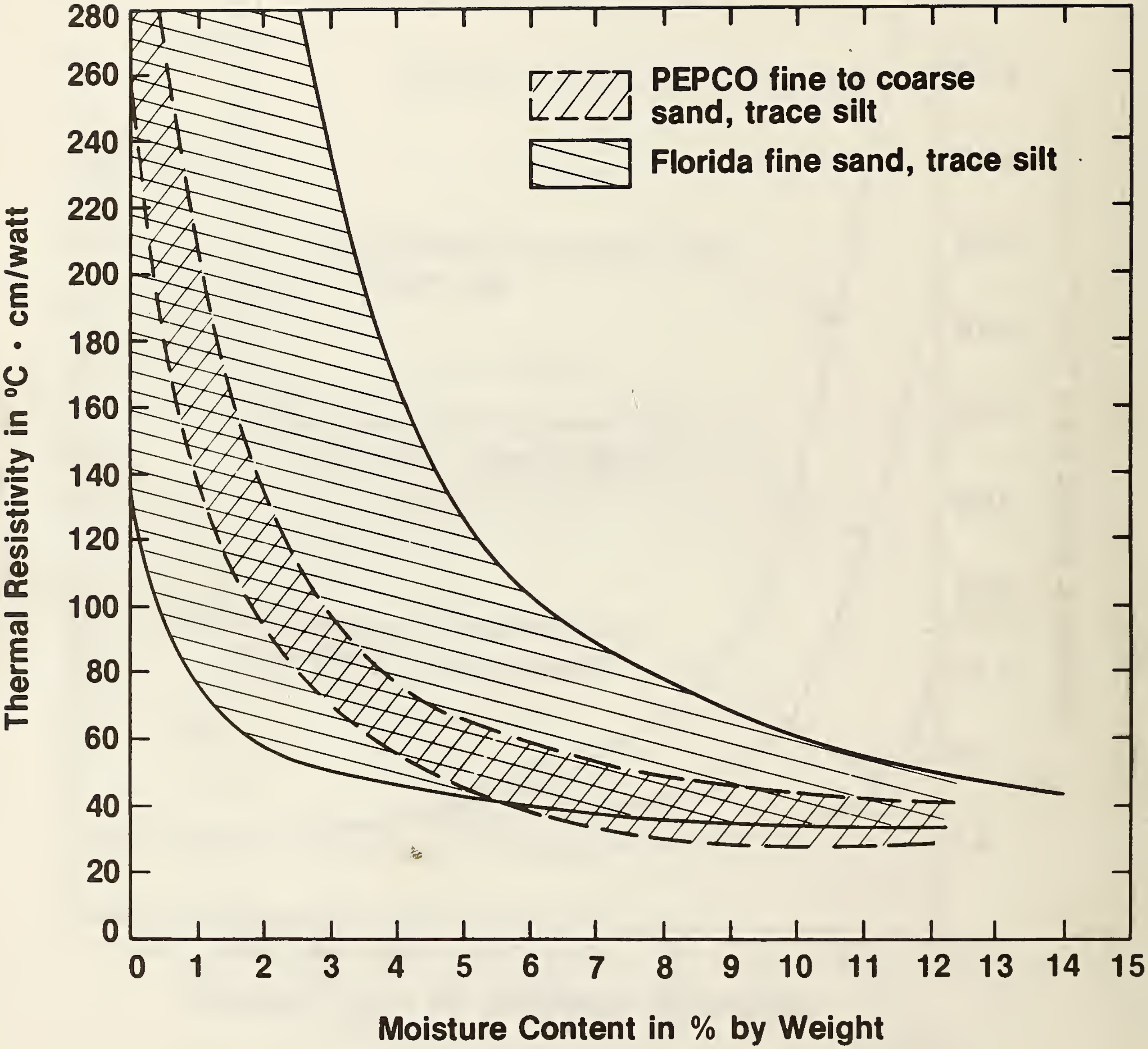


Figure 14. Comparison of envelopes of thermal behavior for PEPCO thermal sand (SP) and Florida sand (SP-SM)

the medium and coarse sand fraction in a granular soil. The envelope of thermal behavior for the PEPCO thermal sand (SP) is narrow and the upper bound is significantly lower than that for the Florida sand (SP-SM). Considering the range of densities possible (i.e. the minimum and maximum densities for these soils) the PEPCO thermal sand should be a better soil to conduct heat.

By systematically testing soils for their thermal behavior the influence of soil type and gradation was seen. To use these data to predict the thermal behavior of other granular and fine-grained soils, figures 15 through 17 were prepared. Figure 15 provides the envelope of thermal behavior for the granular soils shown. Note that in the stable region the influences of soil type and density are negligible and a constant value of thermal resistivity of approximately 30 to 40°C-cm/watt is obtained. The shapes of the curves for the various soils seem to be determined by the stable region value (approximately 40°C-cm/watt), the thermal resistivity in the dry state and the critical moisture content. The trend in figure 16 for the fine-grained soils appear to be similar except the stable region value is approximately 50 to 70°C-cm/watt. Note the stable region value should be even greater than 70°C-cm/watt for highly organic silts and clays and peaty soils if the trends continue for these traditionally more thermally resistive soils.

Figure 17 provides the relationship between critical moisture content and density for the soils studied. The relationships for the fine-grained soils (AMRL No. 61 silty clay, AMRL No. 71 silty clay and sand, and Bonny Loess) were determined using the peak points of the compaction curves and the fact that the critical moisture content is approximately equal to the optimum moisture content. The relationships are determined from the line of optimums, which is the line drawn through the peak points of the compaction curves.

For the granular soils (PEPCO thermal sand and Florida sand) the task of determining the critical moisture content is more difficult. No standard method exists for establishing the critical moisture content. Traditionally, the moisture content at the knee (or cusp) of the thermal resistivity versus moisture content curve was selected as the critical moisture content. The knee or cusp is evident for the Florida sand at densities of 1747 kg/m^3 (109 PCF) and 1506 kg/m^3 (94 PCF) (see figure 13), and these data were used to establish the relationship between critical moisture content and density for Florida sand shown in figure 17. On the other hand, it is not possible to determine the critical moisture content for the PEPCO thermal sand using the knee-of-the-curve approach. As seen in figure 12, the knee of the thermal resistivity versus moisture content curve at the three densities shown is not evident. Consequently, the critical moisture contents for the PEPCO thermal sand at densities of 1580 kg/m^3 (99 PCF), 1688 kg/m^3 (105 PCF) and 1792 kg/m^3 (112 PCF) were defined as the moisture content at which the thermal resistivity was equal to the stable region value (approximately 40°C·cm/watt). It is also important to emphasize that if this definition of critical moisture content was used for the Florida sand, the line for Florida sand would move close to the line for PEPCO thermal sand. Additional data is therefore required to esablish the appropriate definition of critical moisture content for granular soils and to confirm the trends observed. In the meantime, this figure and table 6 can aid in the estimation of critical moisture contents, i.e., the dividing line between "stability and instability."

If these trends are confirmed as more data becomes available, it would appear that the thermal resistivity versus moisture content relationship for a given dry density can be approximated by knowing:

a) stable region value of thermal resistivity,
b) critical moisture content, and
c) thermal resistivity in the dry state.

CONCLUSIONS

Based on this study, the following conclusions are warranted:

1. The fact that the critical moisture content for fine-grained soils is approximately equal to the optimum moisture content is confirmed.

2. As the sand content increases in a silty clay (CL), the minimum thermal resistivity and the critical moisture content decrease for the range of compactive efforts studied.

3. Increasing the medium and coarse sand fraction in a granular soil significantly increases its heat conductive properties as seen in figure 14.

4. In the stable region of each of the major soil groups (i.e. granular and fine-grained soils) the influence of soil type and density on the thermal resistivity of soils are negligible and a constant value of thermal resistivity is observed. The constant value of thermal resistivity is approximately 30 to 40°C-cm/watt and 50 to 70°C-cm/watt for granular soils and fine-grained soils, respectively.

5. If the trends observed during this study are confirmed as more data becomes available, it would appear that the thermal resistivity versus moisture content relationship for a soil at a given density can be approximated by: stable region value of thermal resistivity, critical moisture content and the thermal resistivity in the dry state.

ACKNOWLEDGMENT

J. Lichtenberg of Potomac Electric Power Company (PEPCO) and J. Pielert and O. W. McIntosh of the AASHTO Materials Reference Laboratory (AMRL) provided the required quantities of PEPCO thermal sand and AMRL No. 71 silty clay and sand, respectively, used in the testing program. J. Farrar of the Bureau of Reclamation supplied the Bonny Loess material. The authors wish to thank these individuals for their cooperation.

Table 6. Approximate Critical Moisture for Various Soil Types (Salomone and Kovacs, 1984[b])

Soil Description (1)	Approximate Standard Maximum Dry Unit Weight (ASTM D698-78)		Approximate critical moisture content*, as a percentage (4)
	Pounds per cubic feet (2)	Megagrams per cubic meter (3)	
Granular	120 to 135	1.92 to 2.16	<12
Silts	110 to 120	1.76 to 1.92	12 to 16
Clays	100 to 110	1.60 to 1.76	16 to 22
Organic silts and expansive clays	<100	<1.60	>22

* Critical moisture content is defined for a dry density that is 100% of standard maximum density (ASTM D 698-78)

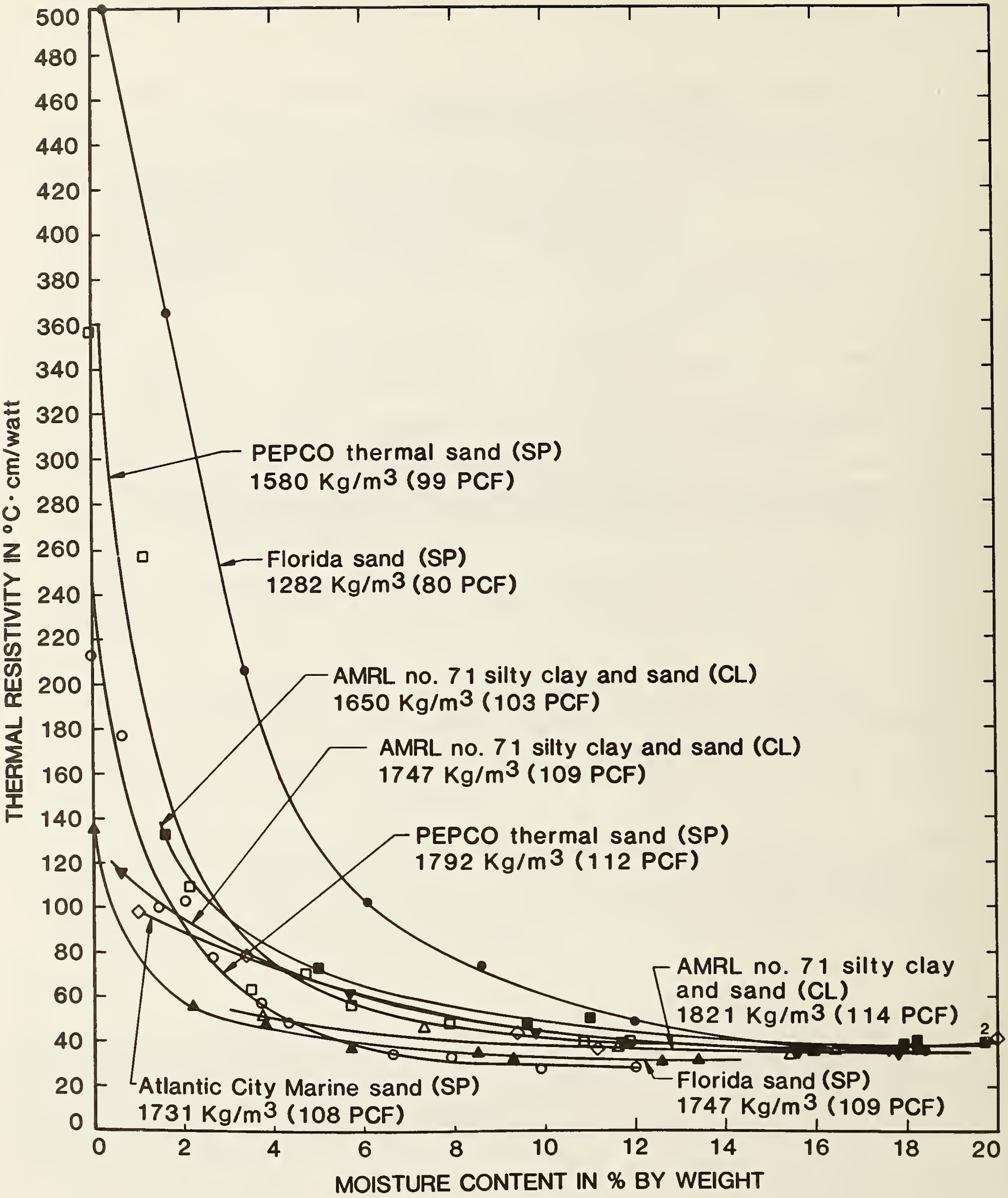


Figure 15. Envelope of thermal behavior of granular soils

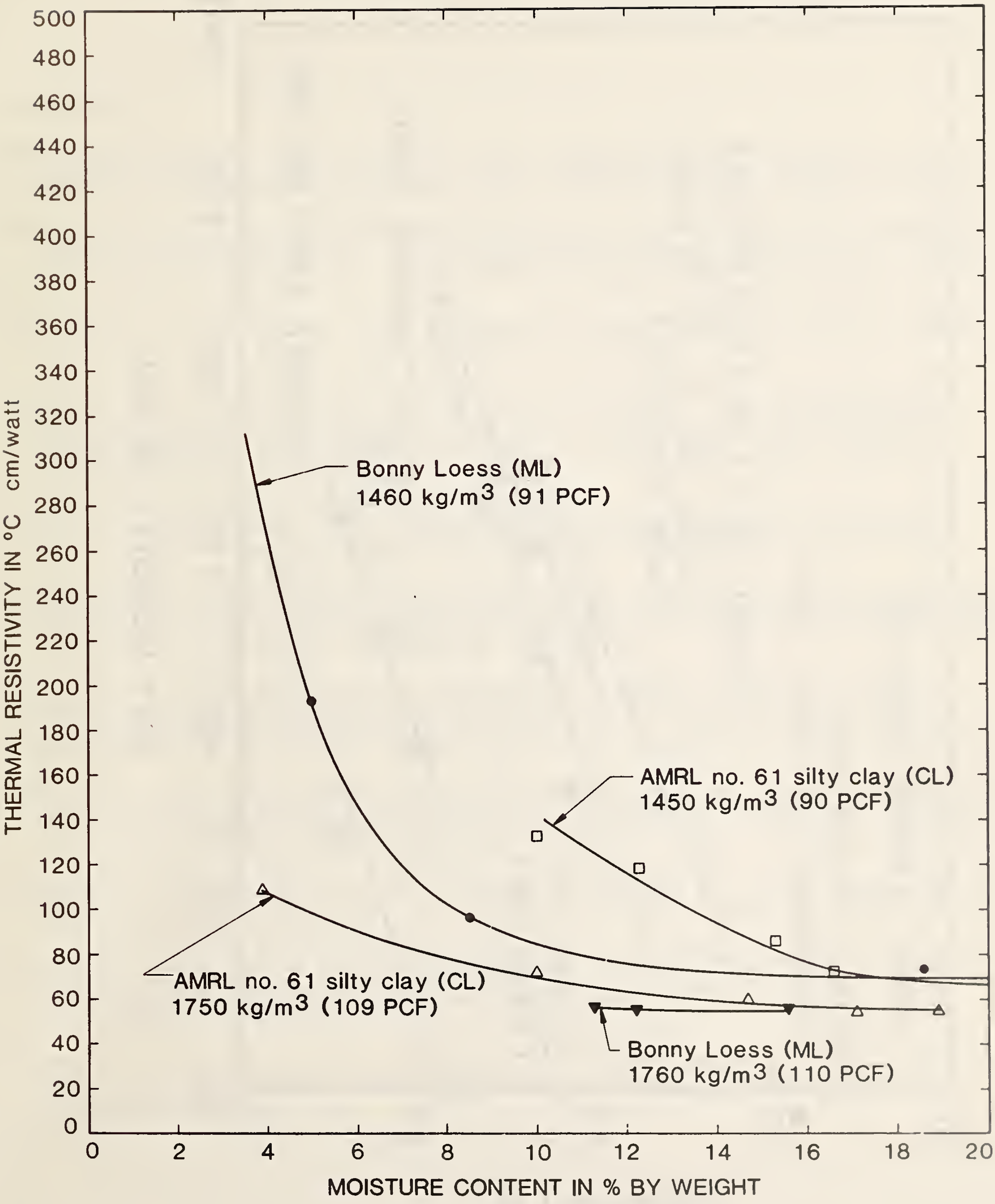


Figure 16. Envelope of thermal behavior of fine-grained soils

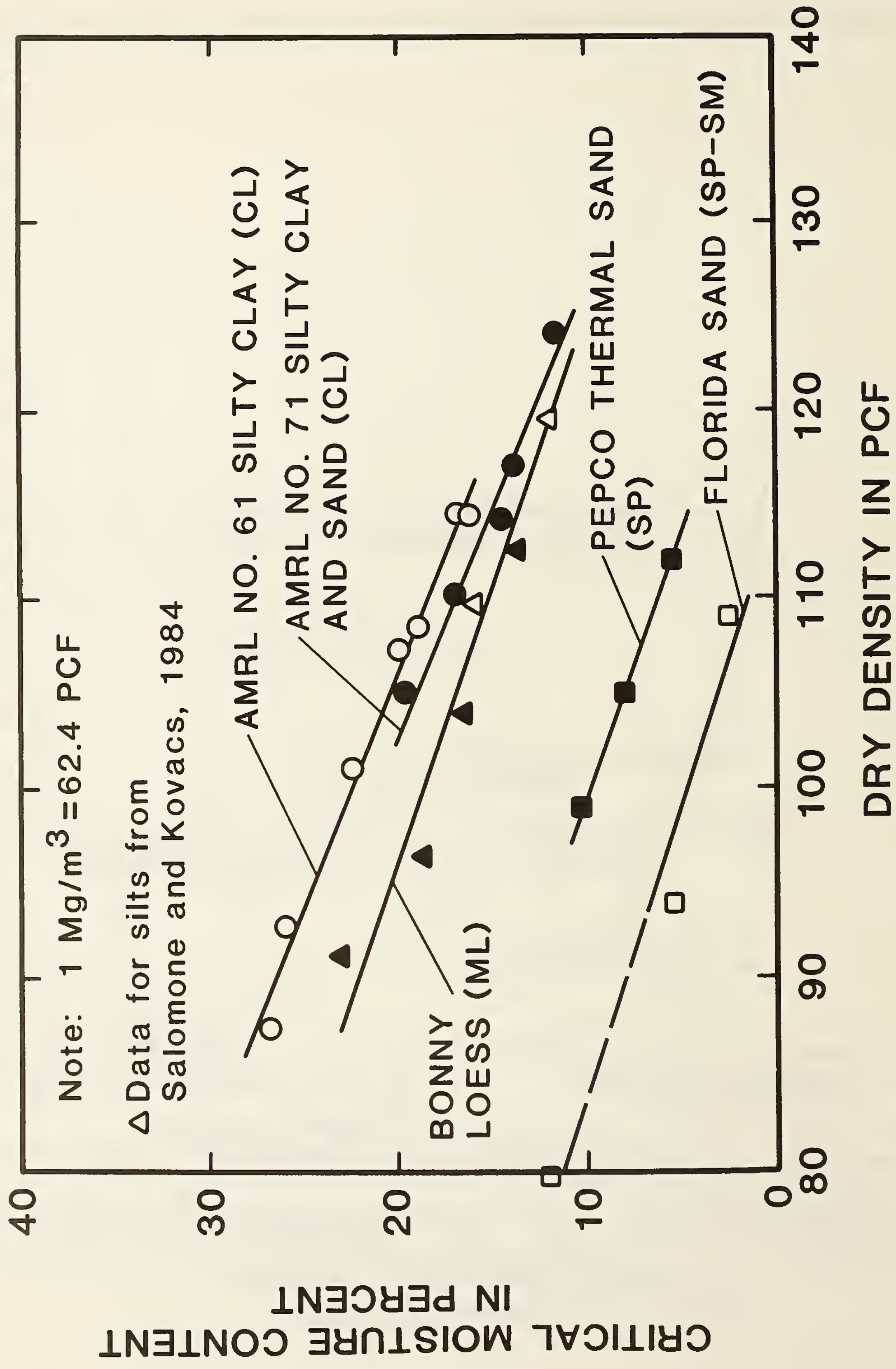


Figure 17. Influence of dry density on critical moisture content

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NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET *(See instructions)*	1. PUBLICATION OR REPORT NO. NBSIR 84-2935	2. Performing Organ. Report No.	3. Publication Date

4. TITLE AND SUBTITLE

THE INFLUENCE OF SOIL TYPE AND GRADATION ON THE THERMAL RESISTIVITY OF SOILS

5. AUTHOR(S)

Lawrence A. Salomone, Felix Y. Yokel and Herbert Wechsler

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

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8. Type of Report & Period Covered

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10. SUPPLEMENTARY NOTES

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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 four (4) different soils were used to study the influence of soil type and gradation on the thermal resistivity of soils. The four soils covered a wide range of gradations and included: two sands (SP and SP-SM), a silty clay (CL), and a silt (ML).

Results are presented which indicate that as the sand content increases in a silty clay (CL), the minimum thermal resistivity and the critical moisture content decrease for the range of compactive efforts studied. Increasing the medium and coarse sand fraction in a granular soil significantly increases the heat conductive properties of the soils. Also, in the stable region of each of the major soil groups (i.e. granular and fine-grained soils), the influence of soil type and density on the thermal resistivity of soils is negligible and a constant value of thermal resistivity is observed. The constant value of thermal resistivity is approximately 30 to 40°C·cm/watt and 50 to 70°C·cm/watt for granular soils and fine-grained soils, respectively.

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

compaction; compaction tests; gradation; heat flow; laboratory tests; soil moisture; soil tests; soil type; tests; thermal conductivity; thermal resistivity

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14. NO. OF PRINTED PAGES

38

15. Price

$8.50