United States
Department of
Agriculture

Soil
Conservation
Service

Soil Mechanics Training Series

Basic Soil Properties

Module 5 - Compaction

Part E - Evaluation of Compaction Data and Specifications

Study Guide

ENG-SOIL MECHANICS TRAINING SERIES--

BASIC SOIL PROPERTIES

MODULE 5 - COMPACTION

PART E

EVALUATION OF COMPACTION DATA AND SPECIFICATIONS

STUDY GUIDE

National Employee Development Staff
Soil Conservation Service
United States Department of Agriculture
December 1988

PREFACE

The design and development of this training series are the results of concerted efforts by practicing engineers in the SCS. The contributions of many technical and procedural reviewers have helped make this training series one that will provide basic knowledge and skills to employees in soil mechanics.

The training series is a self-study and self-paced training program.

The training series, or a part of it, may be used as refresher. Upon completion of the training series, participants should have reached the ASK Level 3, perform with supervision. Other modules for this training series will be released as they are developed.

CONTENTS

ENG - SOIL MECHANICS TRAINING SERIES--
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INTRODUCTION

This is Part E of Module 5 - Evaluation of Compaction Data and Specifications of the ENG-Soil Mechanics Training Series-Basic Soil Properties. Module 5 consists of five parts, Parts A to E. Each part has its own Study Guide and slide/tape presentation. The parts of the module are:

Part A - Introduction, Definitions, and Concepts
Part B - Compaction of Non-gravelly Soils
Part C - Compaction of Gravelly Soils
Part D - Compaction of Clean, Coarse-grained Soils
Part E - Evaluation of Compaction Data and Specifications

Soil Mechanics Level I contains Modules 1 through 3:

Module 1 - Unified Soil Classification System
Module 2 - AASHTO
Module 3 - USDA Textural Soil Classification

The modules in the ENG-Soil Mechanics Training Series--Basic Soil Properties are:

Module 4 - Volume-Weight Relations
Module 5 - Compaction
Module 6 - Effective Stress Principal
Module 7 - Qualitative Engineering Behavior by USCS Class
Module 8 - Estimated Soil Properties Table
Module 9 - Qualitative Embankment Design

INSTRUCTIONS

During the presentation you will be asked to STOP the machine and do activities in your Study Guide. These activities offer a variety of learning experiences and give you feedback on your ability to accomplish the related module objectives.

Part E has six objectives to be accomplished. If you have difficulty with a specific area, study, re-study, and, if necessary, get someone to help you. DO NOT continue until you can complete each objective.

You should complete Part E as follows:

1. Read the objectives.
2. Run the slide/audio cassette, stopping it when you need to work in the Study Guide.
3. Study and review all references.

If you have difficulty in a specific area, contact your State Engineering Staff, through your supervisor.

CONTENTS OF PACKAGE

1 slide tray
1 audio cassette
1 Study Guide

ACTIVITY 1 - OBJECTIVES

Part E of Module 5 covers evaluation of compaction test data and specifications. It also includes empirical methods for estimating typical compaction test results for the major fine-grained Unified Soil Classification System groups.

The objectives of Part E are:

1. List the main items for equipment calibration in a compaction test.
2. List the main items to check in compaction test procedures.
3. Define the zero air voids curve.
4. Using example data, calculate and plot a zero air voids curve.
5. Given an example plotted compaction test and a list of check procedures, critically evaluate the test and point out any major discrepancies or errors.
6. Given example design specifications for density and water content; evaluate their practicality.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 2 - CALIBRATION ERRORS IN PERFORMING COMPACTION TESTS

Performing compaction tests that are reliable and repeatable requires closely following standardized procedures using carefully calibrated equipment. Equipment factors that should be calibrated frequently and checked for proper operation include:

1. The volume of the mold used must be measured after at least every 1000 fillings of the mold. ASTM standards require that the mold to be used must have a volume that varies no more than 0.0004 cubic foot from 1/30 a cubic foot (for Method A and B tests). The volume tolerance on the larger mold used for method C tests is $\pm$ 0.0009 cubic foot. If the mold has been improperly manufactured or has worn so that it does not meet this volume criterion, it should not be used. ASTM standards detail acceptable methods for determining the volume of the mold accurately.

2. The rammer used must weigh within 0.02 pounds of the nominal weight required by the test standard. It should have a flat, circular face that is within 0.005 inches of 2.0 inches in diameter. The rammer device must fall freely through the nominal distance required by the standard within a tolerance of 1/16 inch.

3. The oven used for drying water content specimens must be thermostatically controlled capable of maintaining a temperature of 110 degrees Centigrade within a tolerance of 5 degrees.

4. Scales used for weighing the mold and soil should have a capacity of at least 20 kg with an accuracy of plus or minus 1 gram. Scales used for weighing water content samples should have a capacity of at least 1000 grams with an accuracy of at least plus or minus 0.01 grams.

Precisely calibrated equipment is required to maintain a standard energy delivery per volume of soil compacted. The examples and problems that follow illustrate how equipment factors may cause the energy delivered to be incorrect.

Example 1: Assume the mold employed has become worn from prolonged use. The mold has an actual volume of 0.03382 cubic foot (1/29.5683 cubic foot). Compare the energy delivered using this mold to that of a mold that is exactly 1/30 cubic foot. Note that this mold does not meet the requirement of a tolerance of 0.0004 cubic foot from 1/30 cubic foot.

$$\text{Energy} = \frac{5.5 \text{ lbs} \times 1 \text{ ft} \times 25 \times 3}{1/29.5683 \text{ ft}^3} = 12{,}196.9 \text{ ft-lbs/ft}^3$$

This compares to the standard energy of 12,375 ft-lbs/ft^3, a difference of 1.44 percent.

CONTINUE TO THE NEXT PAGE

ACTIVITY 2 - Continued

Example 2: Assume a hammer that is used in a standard ASTM D 698 compaction test has become worn. Its actual weight is 5.42 pounds. Compare the energy delivered using this hammer to that of a test using standard equipment. Note that the hammer does not meet the tolerance requirement of ± 0.02 pounds from 5.5 pounds.

$$\text{Energy} = \frac{5.42 \text{ lbs} \times 1 \text{ ft} \times 25 \times 3}{1/30 \text{ ft}^3} = 12{,}195.0 \text{ ft-lbs/ft}^3$$

This compares to the standard energy of 12,375 ft-lb/ft^3, a difference of 1.45 percent.

CONTINUE TO THE NEXT PAGE

ACTIVITY 2 - PROBLEMS

Problem 1:

Assume that both the mold in example 1 and the hammer in example 2 are used for a compaction test. Calculate the energy delivered in this test and compare it to the standard energy.

Problem 2:

Assume a mold that has a volume of exactly 1/30 cubic foot and a hammer that has a weight of 5.5 pounds is used in a standard compaction test. Calculate the energy delivered per cubic foot if the hammer is consistently picked up 1/2 inches further than the standard 12 inches before dropping it. Compare this energy to the standard energy.

AFTER COMPLETING THE ACTIVITY, CHECK YOUR ANSWERS ON THE FOLLOWING PAGE

ACTIVITY 2 - SOLUTIONS

Problem 1:

$$\text{Energy} = \frac{5.42 \text{ lbs} \times 1 \text{ ft} \times 25 \times 3}{1/29.5683 \text{ ft}^3} = 12{,}019.5 \text{ ft-lbs/ft}^3$$

This compares to standard energy of 12,375 ft-lbs/ft^3, a difference of 2.87 percent.

Problem 2:

$$\text{Energy} = \frac{5.5 \text{ lbs} \times (12.5/12) \text{ ft.} \times 25 \times 3}{1/30 \text{ ft}^3} = 12{,}890.6 \text{ ft-lbs/ft}^3$$

This compares to standard energy of 12,375 ft-lbs/ft^3, a difference of 4.17 percent.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 3 - PROCEDURAL ERRORS IN PERFORMING COMPACTION TESTS

Some types of procedural errors that can affect the accuracy and repeatability of compaction test results include:

1. The layers or lifts used to fill the mold must be equal height.

2. The mold must not be underfilled. No tolerance is allowed on underfilling. The maximum amount of overfill of the mold permissible is 1/4 inch.

3. The hammer must be moved so that the entire surface of each lift is uniformly covered with hammer blows.

4. The number of blows applied per lift must be carefully counted. No variation is permissible from the required number.

5. The water content sample must be obtained in acccordance with the instructions in the ASTM standard. At least 100 grams of soil should be used for the water content measurement. For soils that may drain internally during the compaction test, the entire specimen must be used for the water content measurement. Soils with minerals containing hydrated water must be dried at a reduced oven temperature of 60 degrees Centigrade. This prevents driving off the hydrated water and counting that as free soil moisture. An example of a mineral containing hydrated water is gypsum.

   The following example illustrates how important procedural errors may be.

   Example:

   Assume that a mold is overfilled by 7/16 inch. Calculate the energy actually delivered per cubic foot. Compare this to the standard energy. Assume the test uses the 4 inch mold. Note that this amount of overfill exceeds the acceptable overfill tolerance of 1/4 inch.

   The nominal diameter of the mold is 4 inches. The increased volume of the sample caused by overfilling is then:

$$\frac{3.14 \times (4/12)^2}{4} \times (7/16)/12 = 0.00318 \text{ ft}^3$$

The actual volume of the compacted soil is then equal to:

$$(0.0333333 + 0.0031816) = 0.036515 \text{ ft}^3$$

The energy per cubic foot is then:

$$\text{Energy} = \frac{5.5 \text{ lbs} \times 1 \text{ ft} \times 25 \times 3}{.036515 \text{ ft}^3} = 11{,}296.7 \text{ ft-lbs/ft}^3$$

This compares to standard energy of 12,375 ft-lbs/ft³, a difference of 8.71 percent.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 4 - SPECIFIC GRAVITY

To determine a soil's void ratio and saturated water content accurately, you must have a value for the soil's solid specific gravity. You may also need to know the value of the apparent specific gravity of gravel particles when using the rock correction equations.

Laboratory tests measure the specific gravity of soil solids, abbreviated G_s, and the apparent specific gravity of the gravel particles, abbreviated G_m. However, in some field situations, this data may not be available, and you may have to use an estimate.

Specific gravity values may be estimated using the following information when no other data is available.

The specific gravity of a soil depends primarily on the mineralogy of the soil grains. Most soils are a blend of several basic minerals such as quartz, feldspar, hornblende, biotite, calcite, etc. An estimate of the mineralogy of a soil is helpful in determining a reasonable value for the specific gravity of the grains.

Specific gravity values of some of the most important soil constituents are shown in the following table:

Mineral	Specific Gravity	Mineral	Specific Gravity
Gypsum	2.32	Dolomite	2.87
Montmorillonite	2.65-2.8	Biotite	3.0-3.1
Kaolinite	2.6	Hornblende	3.2-3.5
Illite	2.8	Limonite	3.8
Chlorite	2.6-3.0	Hematite, hydrous	4.3
Quartz	2.66	Magnetite	5.17
Talc	2.7	Hematite	5.2
Calcite	2.72	Muscovite	2.8-2.9

Many sands and gravels are composed primarily of quartz. A value of 2.66 is commonly assumed for G_s for these soils. Exceptions are sands and gravel particles that are shaly, limestone, or metamorphic in origin (such as granitic). The specific gravity of these sands and gravels would be higher.

Soil that has a high percentage of silt-size particles usually has a specific gravity value of about 2.68 because quartz is usually a major constituent and small additional amounts of clay minerals slightly increase the value.

Clay soil may have specific gravity values ranging from about 2.60 to 2.80. An average value of 2.7 is commonly assumed.

Soil that contains a large amount of micaceous flakes and soil that has significant amounts of hematite or magnetite may have quite high specific gravities, ranging from 2.75 to 3.3. Test data is usually necessary for accurate computations on these unusual soils.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 5 - ZERO AIR VOIDS CURVE

For any given value of dry unit weight, a soil has a unique value of saturated water content. The saturated water content is the water content of the soil when all of the voids are filled with water, and no air occurs in the pores of the soil. Soil that has high dry unit weight values has more closely crowded soil particles, and a lower volume of voids that can contain water.

The relationship between a soil's dry unit weight and saturated water content is as follows:

$$w_{sat}\ (\%) = \left[\frac{\text{Unit Weight of Water}}{\text{Dry Unit Weight of Soil}} - \frac{1.0}{\text{Specific Gravity}} \right] \times 100$$

Remember that in English units, the unit weight of water is equal to 62.4 pounds per cubic foot. In Metric units, water has a unit weight of 1.0 grams per cubic centimeter, or 1000 kilograms per cubic meter.

A plot of saturated water content versus dry unit weight is called the zero air voids curve or 100 percent saturation curve. It should be included on all plotted compaction tests for reasons detailed later in this Module. The procedure for obtaining data for the plot is as follows:

1. First, select a range of dry unit weights of interest. Usually, the range will be that covered by the plotted compaction test curve. Examples would be from 105.0 to 120.0 pcf, 85.0 to 105.0 pcf, etc.

2. Assume about four values of dry unit weight spaced evenly within this range. For the first example above, values of 105.0, 110.0, 115.0, and 120.0 pcf could be assumed.

3. For each assumed value of dry unit weight, calculate a value for saturated water content, using the equation shown above. You must either have test data or estimate the specific gravity of the soil solids in the soil on which the compaction test was performed.

4. Plot, on the compaction test plot, the data you have obtained, and connect the four data points with a smooth curve. The plotted curve is referred to as the zero air voids curve or the complete saturation curve.

5. Note that this curve is curved slightly and is not a straight line.

6. See Figure 5.2, page 15 for an illustration.

<u>Example</u>:

A compaction test is performed on a CH soil by Test Method ASTM D 698 Method A. The soil has a specific gravity value of 2.72. Compute and plot the zero air voids curve for the soil.

CONTINUE TO THE NEXT PAGE

ACTIVITY 5 - Continued

1. Assume a range of dry unit weights of 80.0-95.0 pounds per cubic foot.

2. Assume values to use for calculations of 80.0, 85.0, 90.0, and 95.0 pounds per cubic foot.

3. Calculate a value for water content at saturation at each dry unit weight assumed. The calculation for the first assumed value of dry unit is as follows:

$$W_{sat}\ (\%) = \left[\frac{\text{Unit Weight of Water}}{\text{Dry Unit Weight of Soil}} - \frac{1.0}{\text{Specific Gravity}}\right] \times 100$$

$$= \left[\frac{62.425}{80.0} - \frac{1.0}{2.72}\right] \times 100$$

$$= (0.7803 - 0.3676) \times 100$$

$$= 41.3\%$$

Using the same procedure, the following values are obtained:

Dry Unit Weight (pcf)	Saturated Water Content (%)
80	41.3
85	36.7
90	32.6
95	28.9

4. The plotted zero air voids curve is shown on figure 5.1, p. 13.

PROBLEM:

Plot a zero air voids curve for a range of dry unit weights between 105 and 120 pounds per cubic foot. The soil has a specific gravity of 2.65. Use the blank graph form attached to this Activity, on page 14. Remember to use the recommended scales for plotting compaction tests you learned in Part B of this module. The example shows suggested scales also.

WHEN YOU HAVE CHECKED THE SOLUTION ON PAGE 16, START THE TAPE

ACTIVITY 5 - PART E

LABORATORY NO ____________

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE
Figure 5.1 Example of Plotted 100 % Saturation (Zero Air Voids) Curve

FIELD SAMPLE NO	LOCATION		DEPTH
GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION ____________ LL ______ PI ______

MAX. PARTICLE SIZE INCLUDED IN TEST ____________"

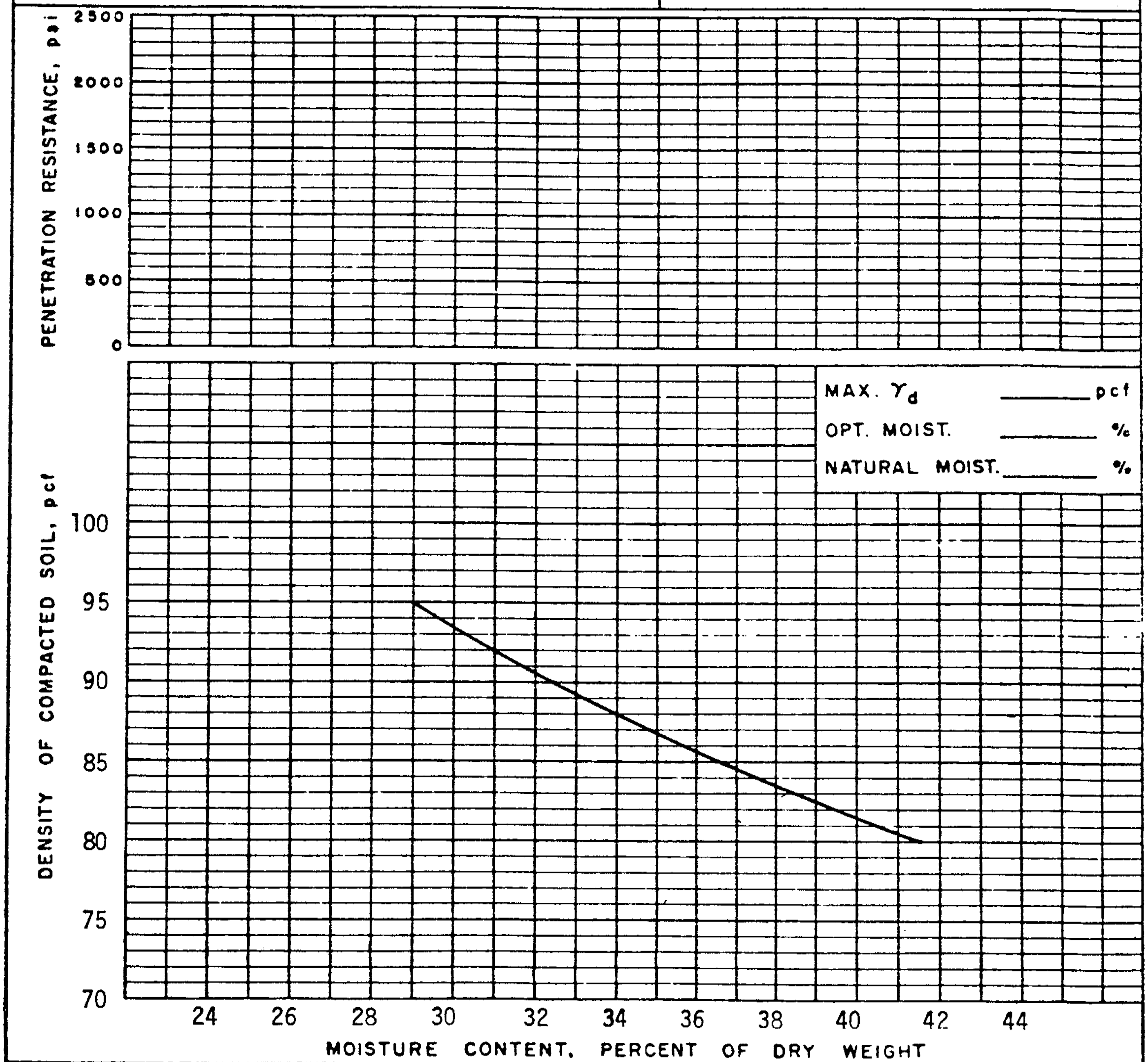
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.72 ; PLUS NO. 4 ________ }

CURVE NO. ________ OF ________

STD. (ASTM D-698) ☐; METHOD ________

MOD. (ASTM D-1557) ☐; METHOD ________

OTHER TEST ☐ (SEE REMARKS)



MAX. γ_d ________ pcf

OPT. MOIST. ________ %

NATURAL MOIST. ________ %

REMARKS

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ACTIVITY 5 - PART E

LABORATORY NO ______

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE: Problem

FIELD SAMPLE NO	LOCATION		DEPTH
GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION ______ LL ______ PI ______

MAX. PARTICLE SIZE INCLUDED IN TEST ______"

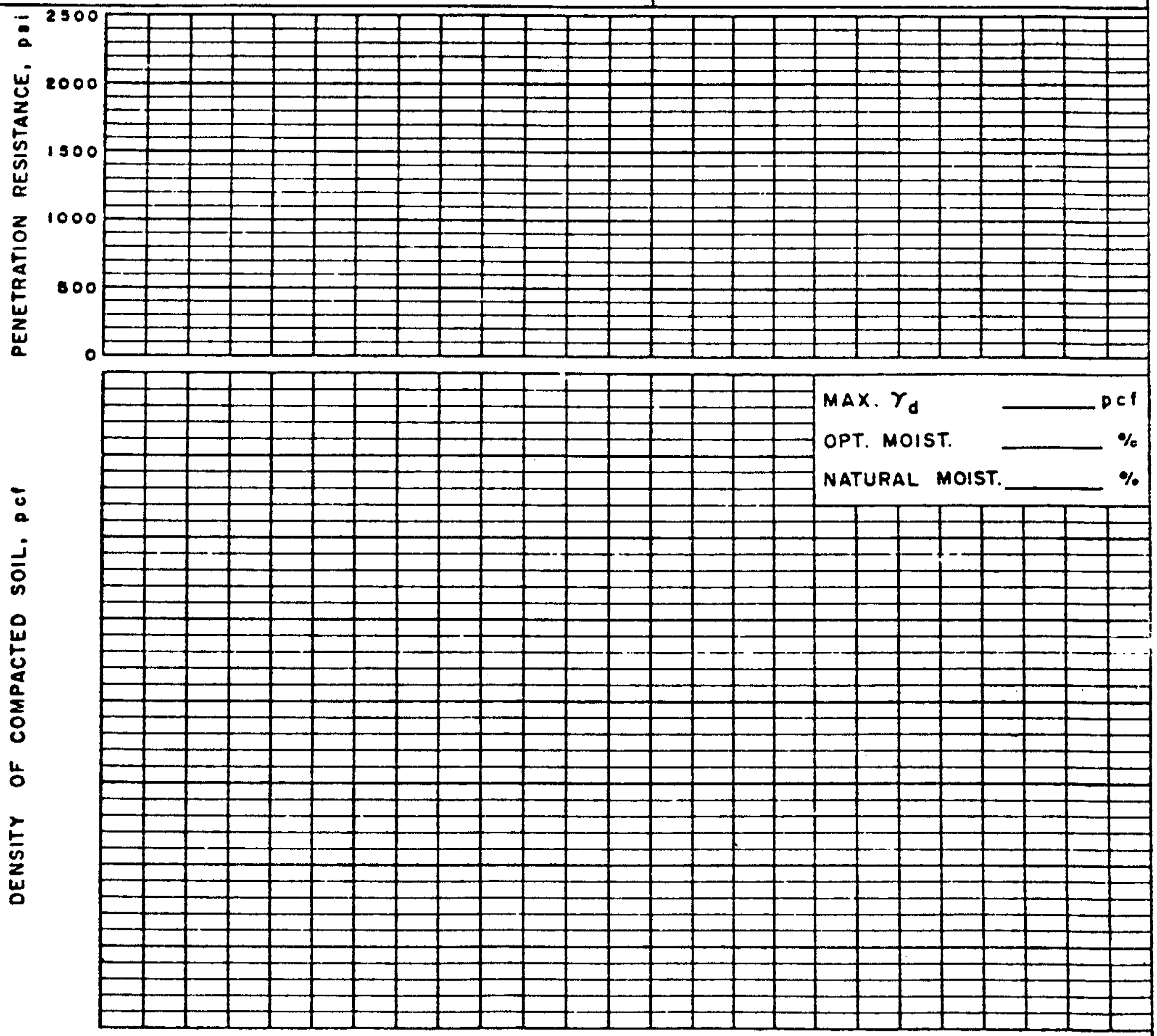
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 ______ / PLUS NO. 4 ______

CURVE NO. ______ OF ______

STD.(ASTM D-698) ☐; METHOD ______

MOD.(ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)



MAX. γ_d ______ pcf

OPT. MOIST. ______ %

NATURAL MOIST. ______ %

MOISTURE CONTENT, PERCENT OF DRY WEIGHT

REMARKS

Assume a specific gravity of 2.65 and plot a zero air voids curve. Use a range of dry unit weights of 105.0-120.0 pc:

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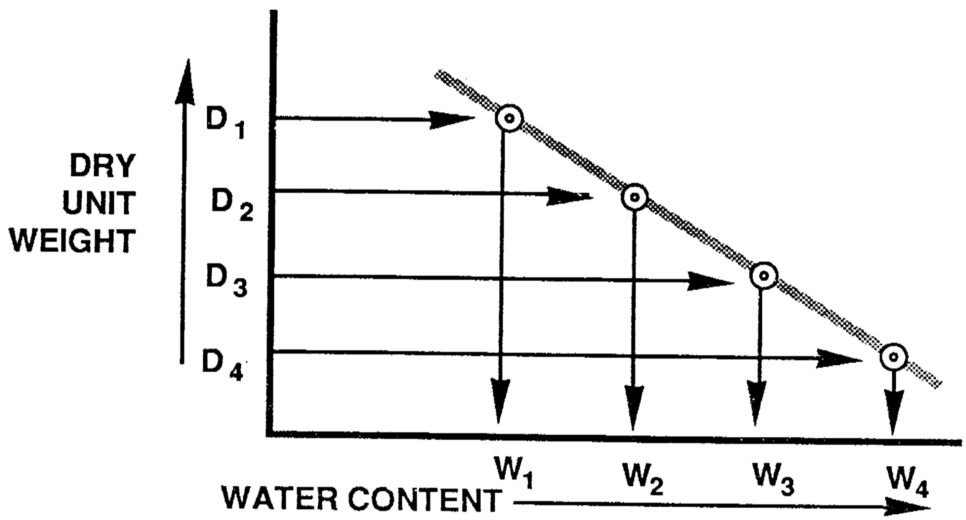

ASSUMED DENSITY	SATURATED WATER CONTENT
D_1	W_1
D_2	W_2
D_3	W_3
D_4	W_4

Figure 5.2--Construction of Zero Air Voids or 100% Saturation Curve.

AFTER COMPLETING THE ACTIVITY, CHECK YOUR ANSWERS ON THE FOLLOWING PAGE

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ACTIVITY 5 - PART E

LABORATORY NO ________

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE: Problem Solution

FIELD SAMPLE NO | LOCATION | DEPTH

GEOLOGIC ORIGIN | TESTED AT | APPROVED BY | DATE

CLASSIFICATION ________ LL ______ PI ______

MAX. PARTICLE SIZE INCLUDED IN TEST ________ "

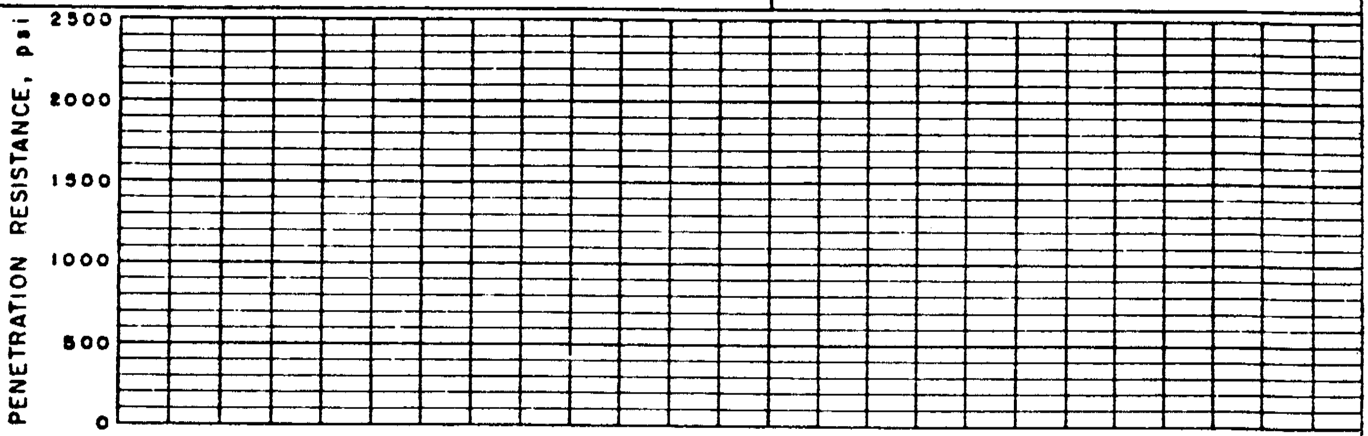
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.65 ; PLUS NO. 4 ________

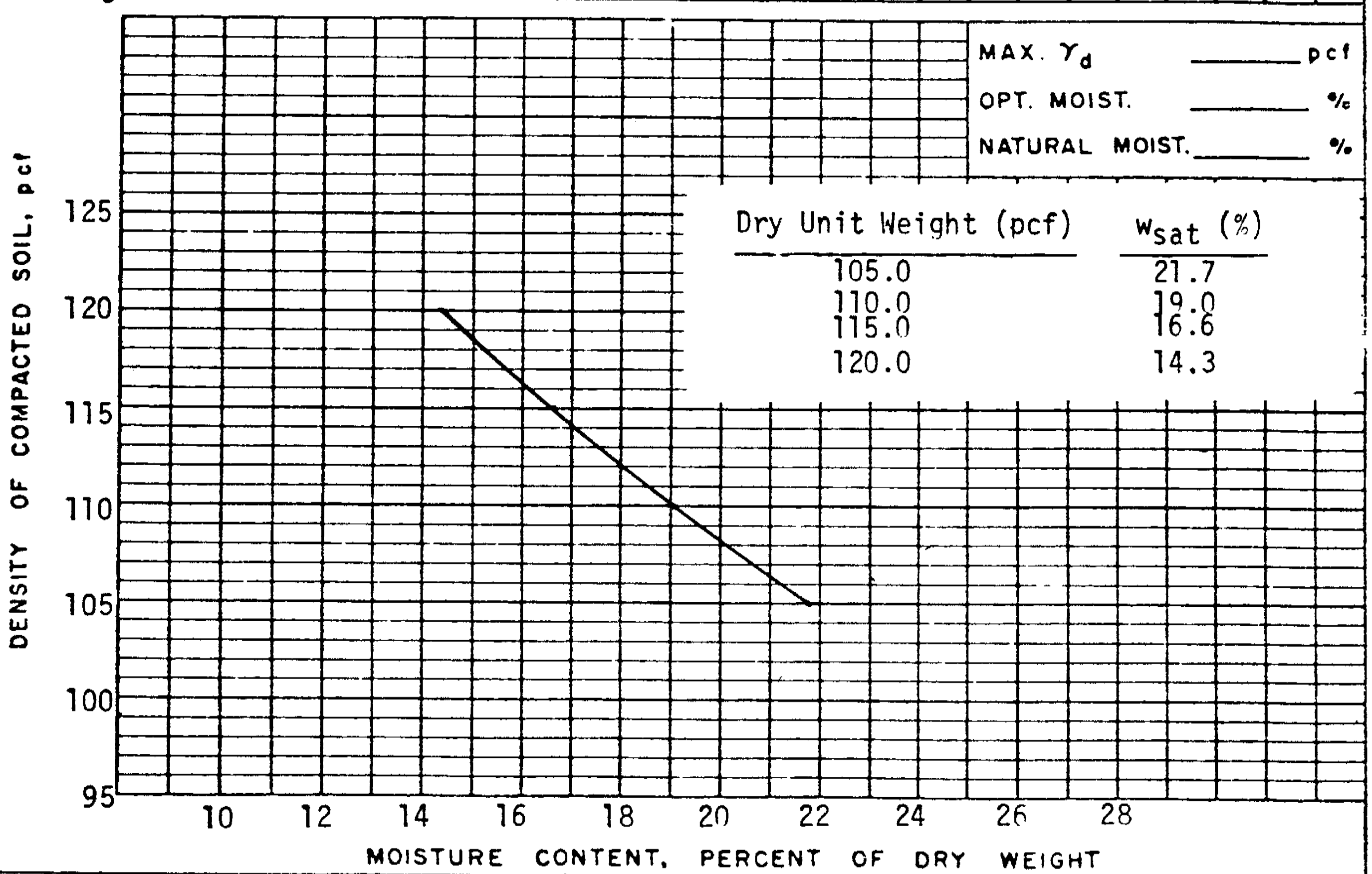
CURVE NO. ________ OF ________

STD. (ASTM D-698) ☐; METHOD ________

MOD. (ASTM D-1557) ☐; METHOD ________

OTHER TEST ☐ (SEE REMARKS)





MAX. γ_d ________ pcf

OPT. MOIST. ________ %

NATURAL MOIST. ________ %

Dry Unit Weight (pcf)	w_{sat} (%)
105.0	21.7
110.0	19.0
115.0	16.6
120.0	14.3

REMARKS

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ACTIVITY 6 - USE OF ZERO AIR VOIDS CURVE

The zero air voids curve has several uses in evaluating plotted compaction test data. It is essential in evaluating a compaction curve, and, it should always be plotted together with the compaction test data.

The following discussions apply primarily to compaction tests performed by ASTM Test Method D 698 Method A. Some of the "rules-of-thumb" shown are less applicable for ASTM Test Method D 1557, or the Modified method, and for methods which incorporate gravel in the test specimens.

From observations of hundreds of "standard", or D 698, Method A compaction tests where test procedures were carefully followed and careful calibration of equipment was maintained, the following generalizations were found:

1. Optimum water content often occurs at a water content about equal to 80 percent of saturated water content. For some soils, optimum water content may be as high as 90 percent of saturation, and for others may be as low as 75 percent of saturation, but any test where the optimum water content is outside this range should be examined further. This condition may occur if the specific gravity of the soil solids is substantially different than assumed for the plot of the zero air voids curve, or if test procedures or calculations are incorrect. See Figure 6.1, p. 18.

2. The compaction curve is often about parallel to the zero air voids curve at water contents above optimum water content. Water contents on this part of the compaction curve are often at about 90 percent of saturation. See Figure 6.2, p. 18.

3. A compaction curve can never intersect or plot to the right of the zero air voids curve. If it were to do so, this would mean that measured water contents in the compaction test were greater than saturation, which is impossible. See Figure 6.3, p. 19.

Refer to attached figures for illustrations of each of these rules-of-thumb. Figure 6.4, p. 20 is a plotted compaction test where the optimum water content is at 63 percent of saturation. The specific gravity of the sample must be in error, or other errors in test computations or equipment calibration could be responsible.

Figure 6.5, p. 21 is a compaction curve where the compaction curve on the wet side of optimum is not parallel to the zero air voids curve, and values are at less than 80 percent saturation on the wet side.

Figure 6.6, p. 22 illustrates a test where the compaction curve and the zero air voids curve intersect. Errors in the specific gravity value or in other test methodology are possible causes. This rule-of-thumb can never be violated, because this is an impossible situation.

CONTINUE TO PAGE 23

CHECK PERCENT SATURATION AT $\gamma_{d\ max}$ & W_{opt}

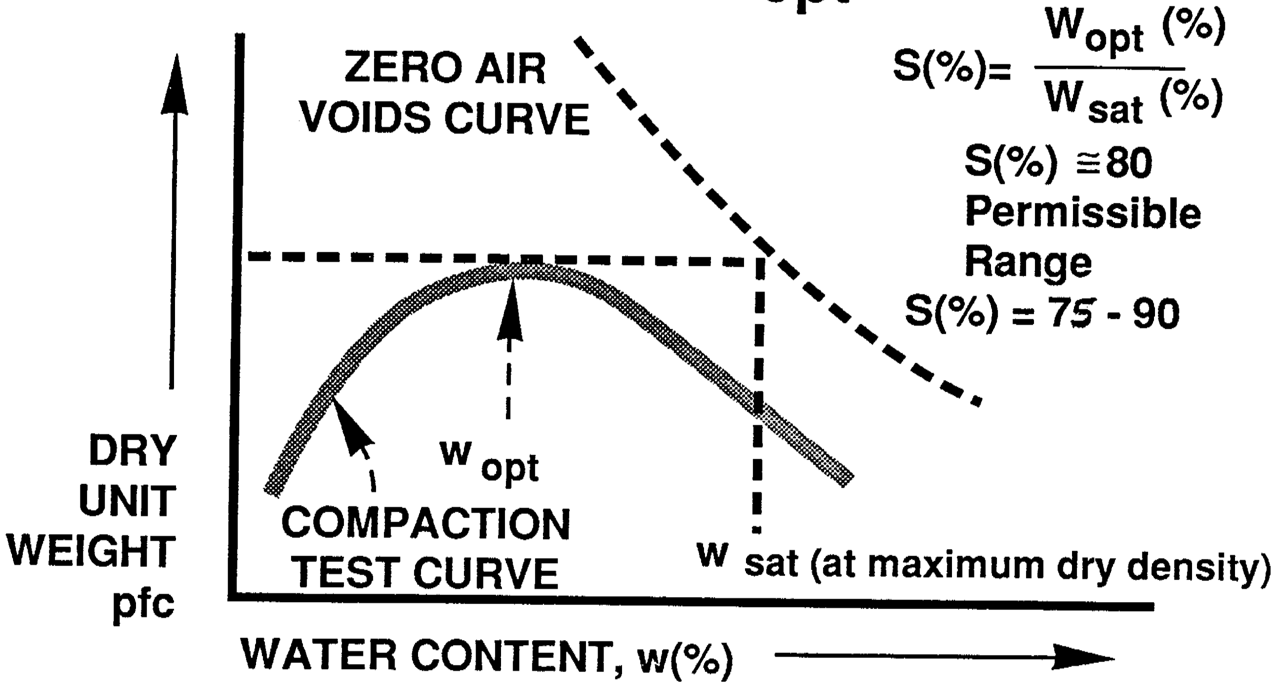

Fig. 6.1

CHECK COMPACTION CURVE "WET" SIDE

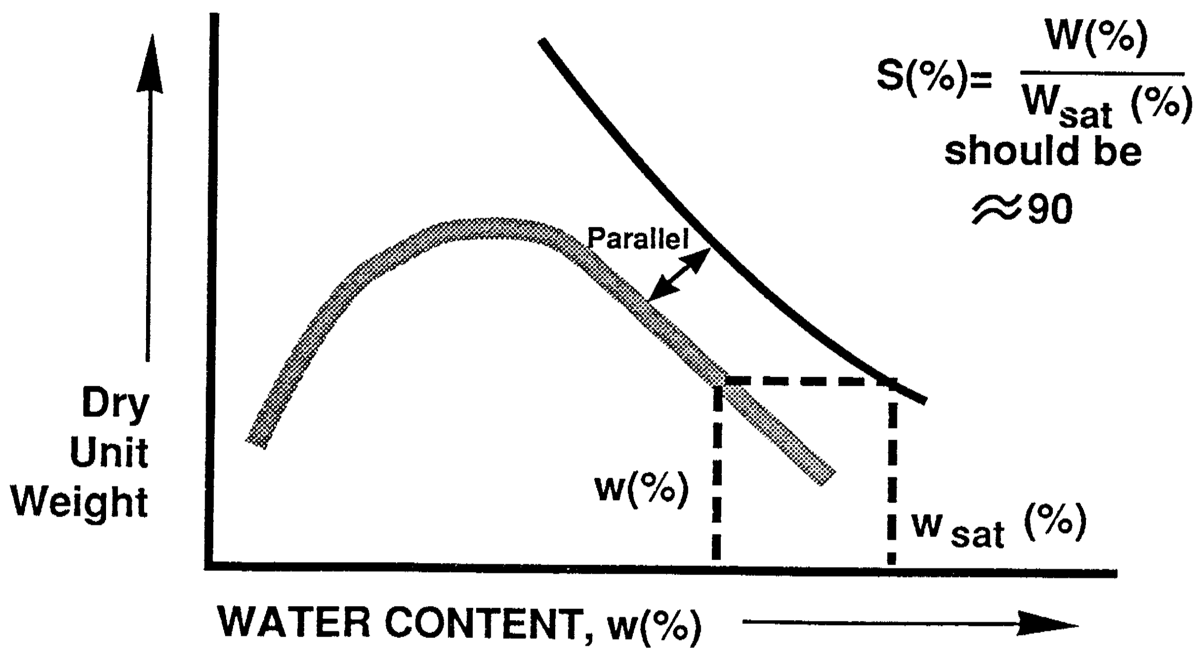

Fig. 6.2

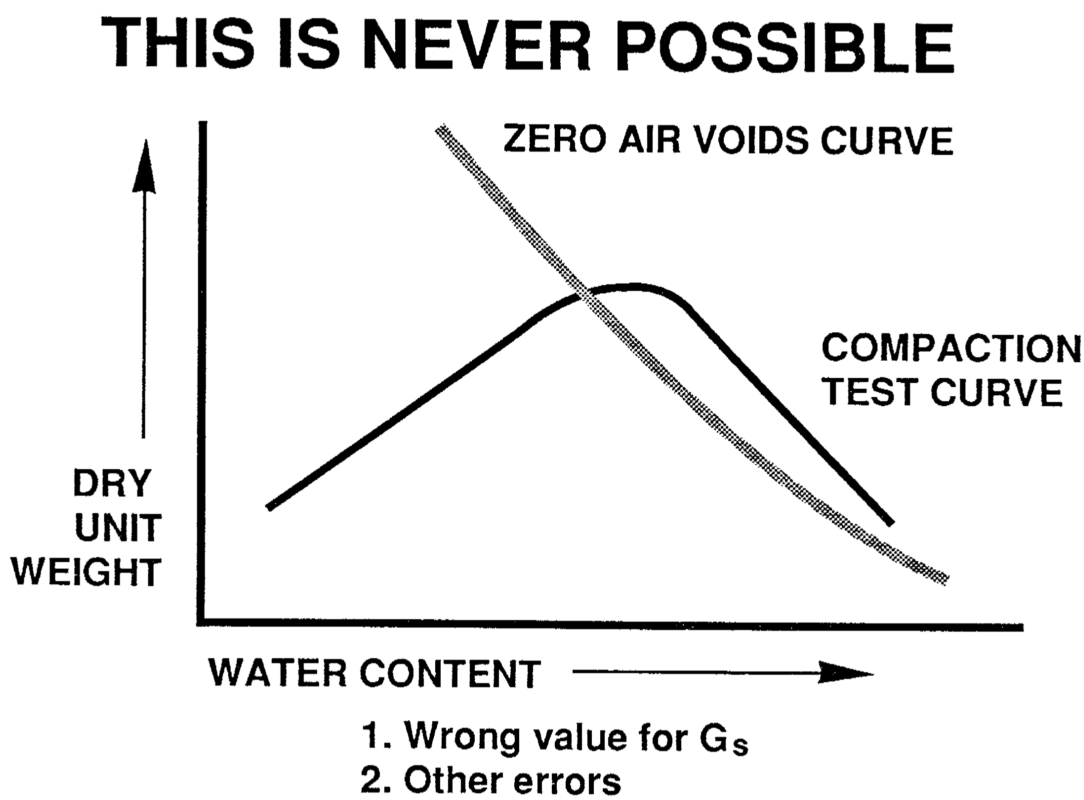

Figure 6.3--Ilustration of Compaction Curve Intersecting Zero Air Voids Curve.

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ACTIVITY 6 - PART E

LABORATORY NO ______

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE
Figure 6.4 Illustration of Optimum Moisture Less than 75 % saturated

FIELD SAMPLE NO	LOCATION	DEPTH

GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION ______ LL ______ PI ______

MAX. PARTICLE SIZE INCLUDED IN TEST ______ "

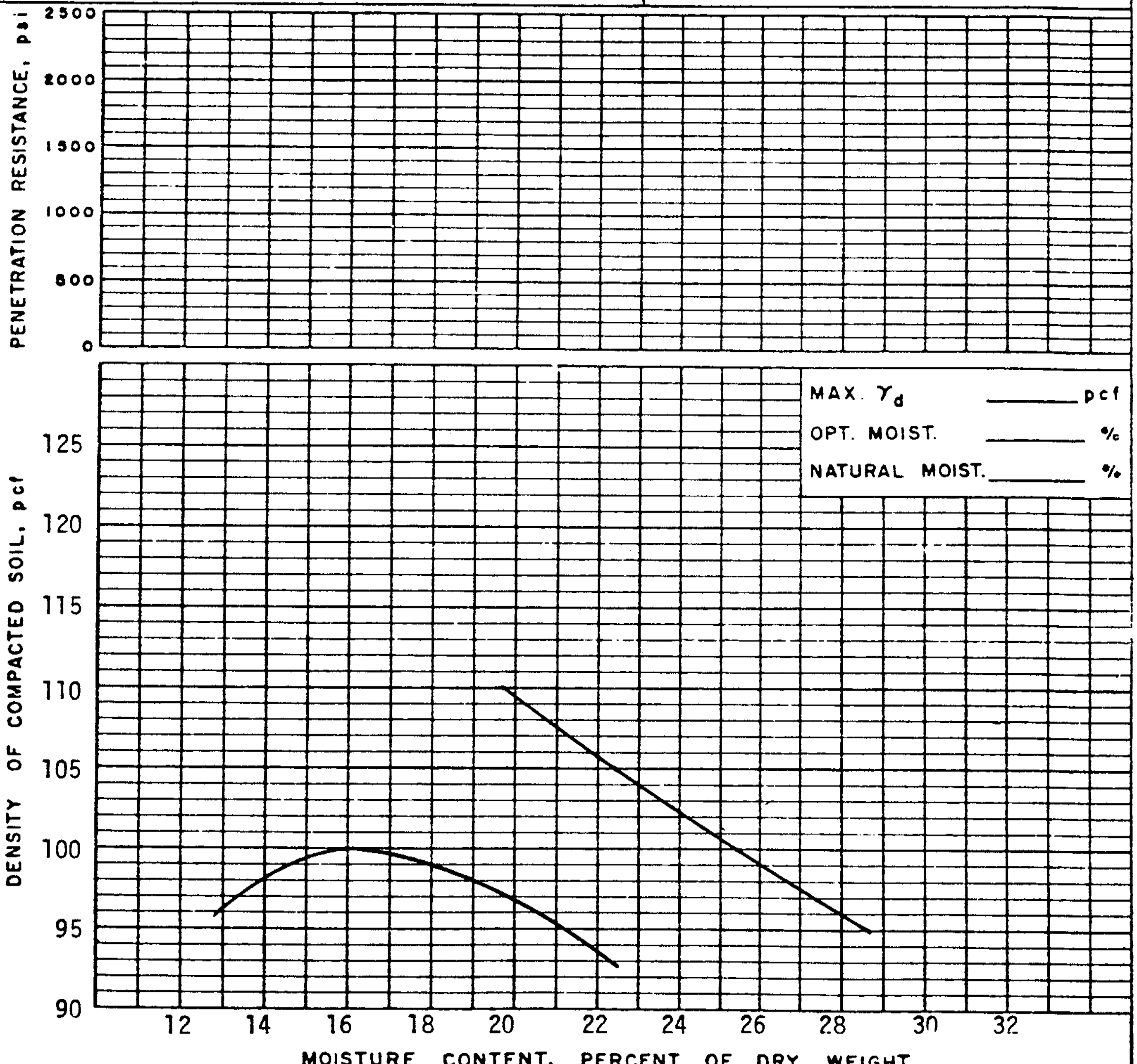
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 ______ ; PLUS NO. 4 ______

CURVE NO. ______ OF ______

STD. (ASTM D-698) ☐; METHOD ______

MOD. (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)



REMARKS

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ACTIVITY 6 - PART E

LABORATORY NO ______

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE

Figure 6.5 Illustration of Wet side of Compaction Curve Not Parallel to Zero Air Voids Curve

FIELD SAMPLE NO	LOCATION		DEPTH
GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION ______ LL ______ PI ______

MAX. PARTICLE SIZE INCLUDED IN TEST ______ "

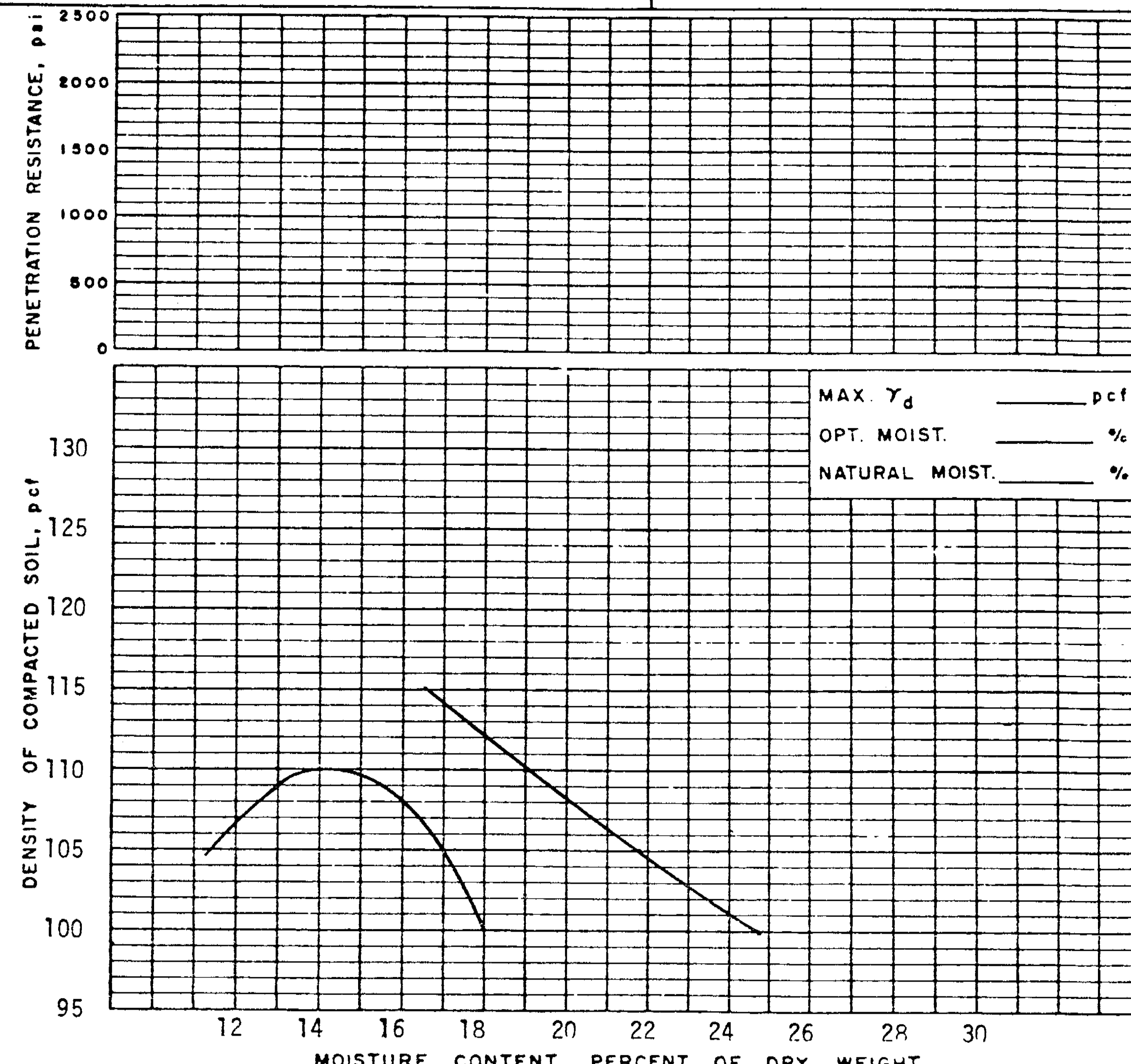
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 ______ / PLUS NO. 4 ______

CURVE NO. ______ OF ______

STD. (ASTM D-698) ☐; METHOD ______

MOD. (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)



REMARKS

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ACTIVITY 6 - PART E

LABORATORY NO ____________

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE: Figure 6.6 Illustration of Intersection of Compaction Curve with

FIELD SAMPLE NO	LOCATION Zero Air Voids Curve	DEPTH

GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION ____________ LL ______ PI ______

MAX. PARTICLE SIZE INCLUDED IN TEST ____________ "

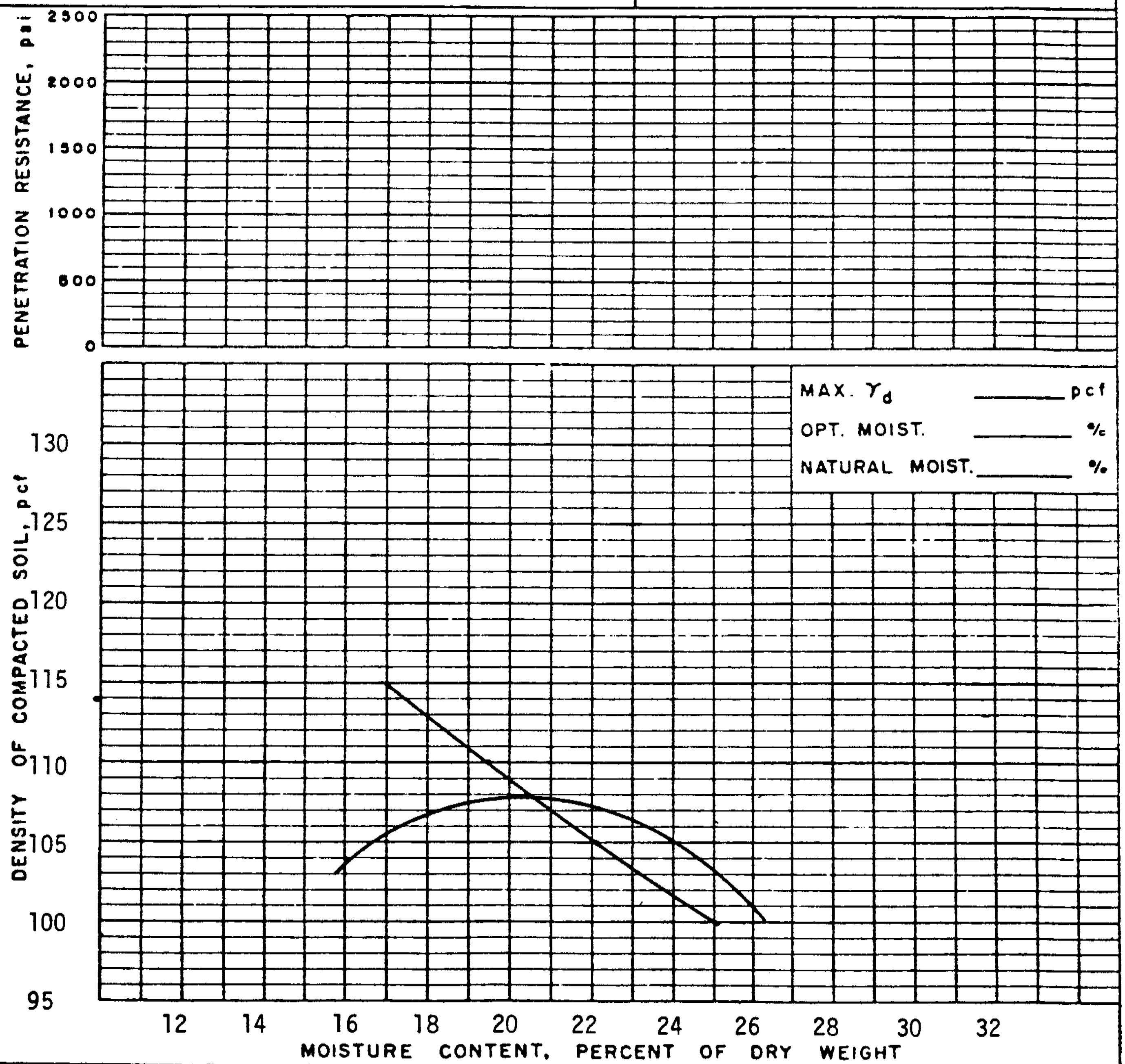
SPECIFIC GRAVITY (G_s) MINUS NO. 4 ____________ PLUS NO. 4 ____________

CURVE NO. ____________ OF ____________

STD. (ASTM D-698) ☐; METHOD ____________

MOD. (ASTM D-1557) ☐; METHOD ____________

OTHER TEST ☐ (SEE REMARKS)



REMARKS

ACTIVITY 6 - Continued

PROBLEM:

Using the plotted compaction test curve in Figure 6.7, p. 24 evaluate the plot using the information you have learned at this point.

Assume a value for specific gravity of 2.8 for the soil, a micaceous MH soil. Note discrepancies you learned in this Activity.

USE THE WORKSHEET ON PAGE 25 FOR CALCULATIONS

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ACTIVITY 6 - PART E

LABORATORY NO ______

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE: Figure 6.7 Problem

FIELD SAMPLE NO	LOCATION		DEPTH
GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION MH LL 61 PI 22

MAX. PARTICLE SIZE INCLUDED IN TEST #4"

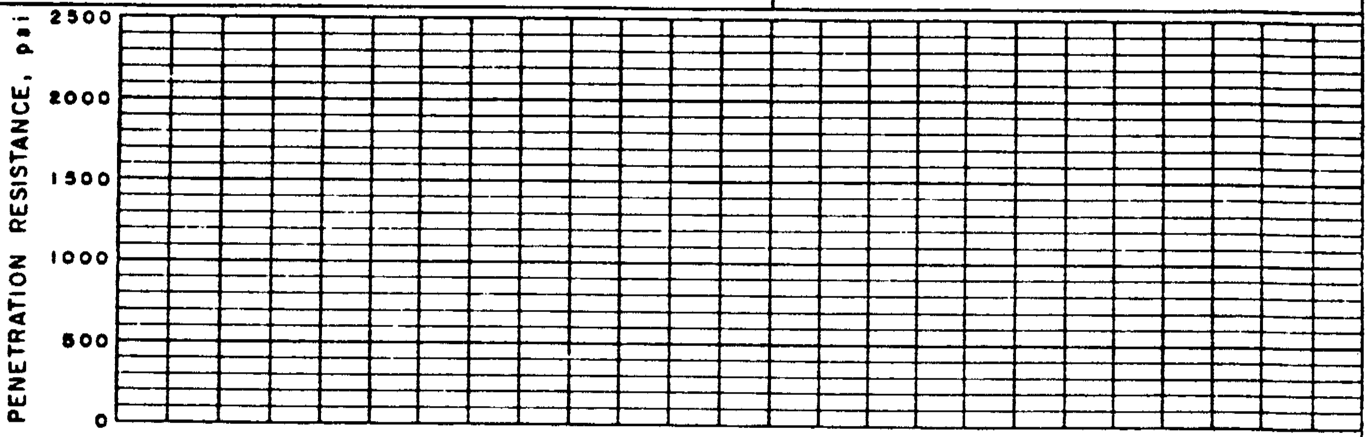
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.80; PLUS NO. 4 ______ }

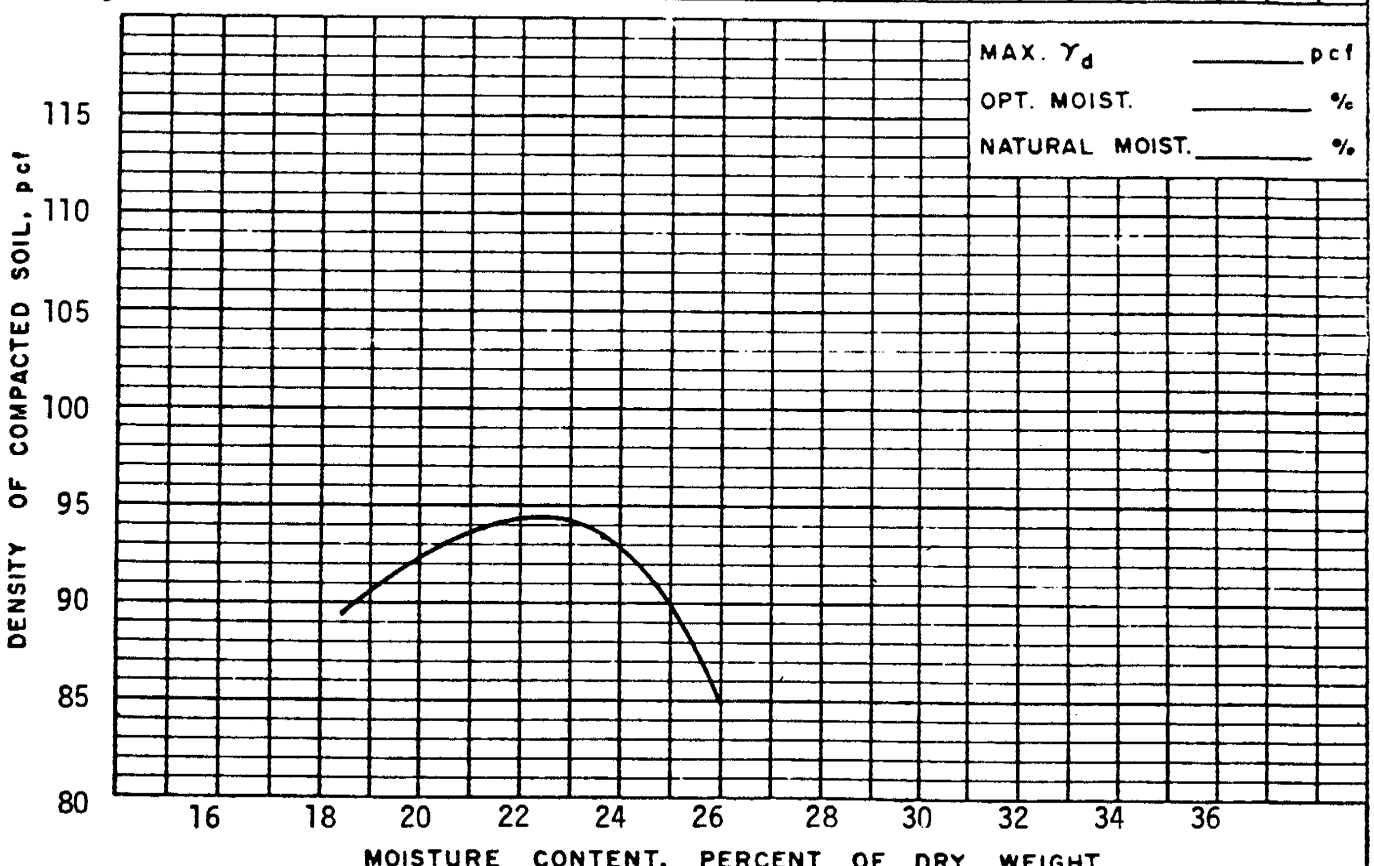
CURVE NO. 1 OF 1

STD. (ASTM D-698) ☒; METHOD D698A

MOD. (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)





REMARKS

Plot the zero air voids curve and evaluate the compaction test data.

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ACTIVITY 6 - PROBLEM WORKSHEET

WHEN YOU HAVE CHECKED THE SOLUTION ON THE FOLLOWING PAGE START THE TAPE

ACTIVITY 6 - PROBLEM SOLOUTION

Data for developing the zero air voids curve are summarized below:

Assumed Dry Unit Weight (pcf)	Saturated Water Content (%)
80	42.3
85	37.7
90	33.6
95	30.0

In examining the compaction curve, note that optimum water content is at about 74 percent saturation.[1] This is lower than normally expected. Note that the portion of the compaction curve at water contents higher than optimum is not parallel to the zero air voids curve. At higher water contents, the curve is not at percent saturation values of 90 percent or higher. For example, at the last point on the compaction curve, the water content is only about 69 percent of saturation.[2]

[1]

$$W_{sat}(\%) = \left[\frac{62.4}{94.5} - \frac{1}{2.80}\right] \times 100$$

$$= 30.3\%$$

$$S(\%) = \frac{22.5\%}{30.3\%}\,100$$

$$= 74.2\%$$

[2]

$$W_{sat}(\%) = \frac{62.4}{85.0} - \frac{1}{2.80} \times 100$$

$$= 37.7\%$$

$$S(\%) = \frac{26.0\%}{37.7\%}\,100$$

$$= 69.0\%$$

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 7 - EVALUATION OF COMPACTION DATA

ASTM test methods include several additional criteria which should be followed to obtain reliable and repeatable compaction test data. They may be summarized as follows:

1. The spread in water contents between successive points on a compaction curve should ideally be no more than 1-1/2 percent. Curves with spreads between points of about 2 percent are usually acceptable. This will mean, however, that if an operator selects an initial water content for the test substantially dry of optimum water content, a large number of specimens will be needed to develop a curve. This is ineffecient and requires a large sample to prevent re-using soil during the test. The determination of a suitable starting water content for the test requires substantial experience. Guidelines based on the feel of the soil are available. Figure 7.1 on page 28 shows a compaction test where 8 points were required to obtain a complete compaction curve because the initial water content selected for the test specimen series was too low.

2. Optimum water content should always be bracketed by a least four points. Two points on the curve should be below optimum and two points above optimum water content. As mentioned in the discussion of the test procedures, a minimum of four points are required to define a complete compaction curve. Figure 7.2 on page 29 shows a plotted compaction test where the optimum water content was selected at a point on the curve where only one point on the curve is below optimum water content. In the figure there are points that are more than the permissible 2 percent apart in water content, also.

3. The values of maximum dry unit weight and optimum water content should be reasonable, based on tests on similar soils. The following table shows typical values for maximum dry unit weight and optimum water content for major Unified Soil Classification System groups. The data are for ASTM Test Method D 698 Method A test.

Typical Values For ASTM D 698 Method A Tests

Soil Classification	Maximum Dry Unit Weight (pounds per cubic foot)	Optimum Water Content (%)
SC	105-125	11-19
SM	110-125	8-16
ML	95-120	12-22
CL	95-120	12-24
MH	70-95	22-40
CH	70-100	20-40
OL	80-100	21-33
OH	65-100	21-45

CONTINUE TO PAGE 30

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FILE CODE ENG-22

ACTIVITY 7 - PART E

LABORATORY NO ________

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE: Figure 7.1 Illustration of 8 point Compaction Test			
FIELD SAMPLE NO	LOCATION		DEPTH
GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION CH LL 65 PI 41

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

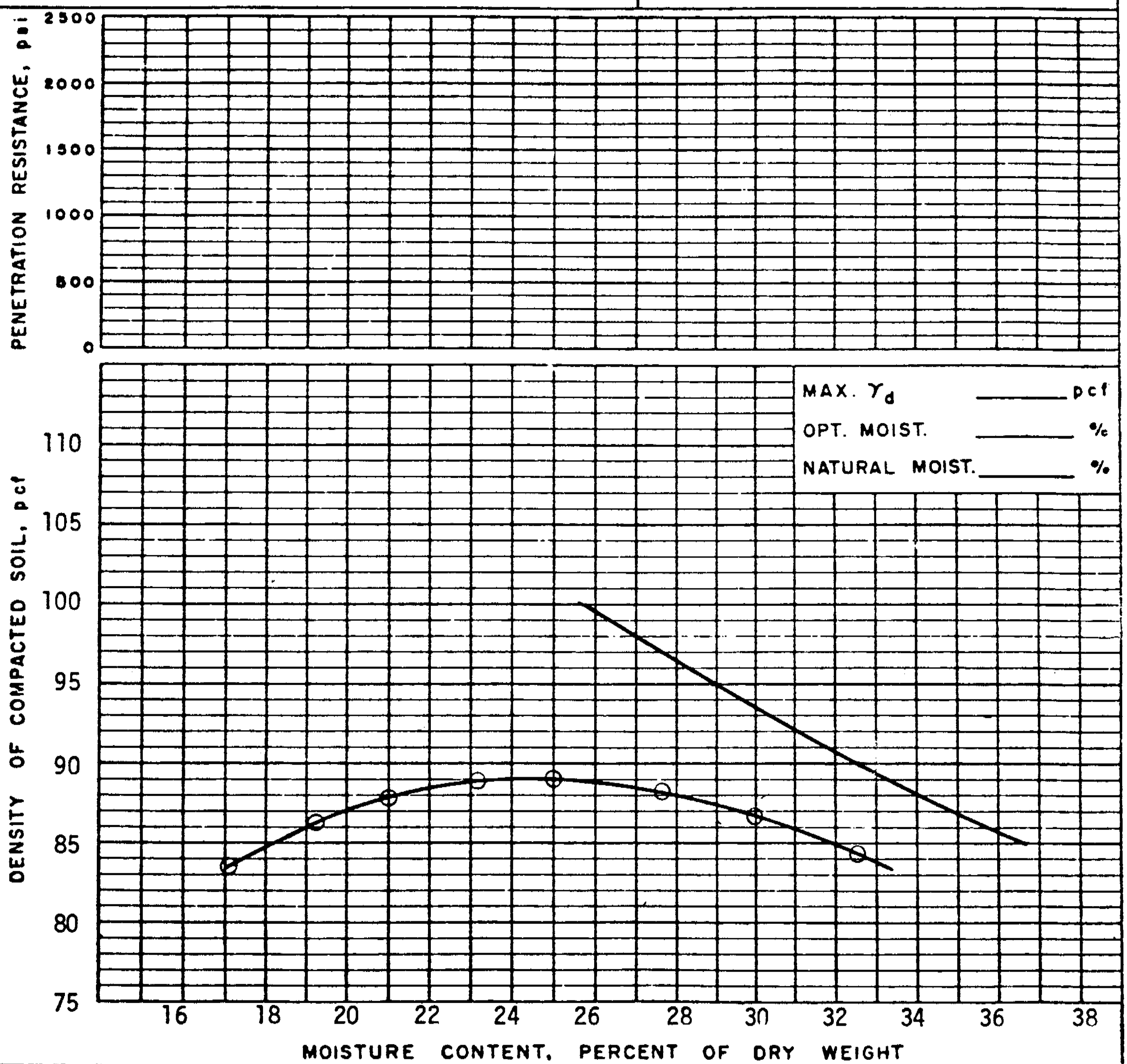
SPECIFIC GRAVITY (G_s) MINUS NO. 4 2.72 ; PLUS NO. 4 ________

CURVE NO. 1 OF 1

STD. (ASTM D-698) ☒; METHOD A

MOD. (ASTM D-1557) ☐; METHOD ________

OTHER TEST ☐ (SEE REMARKS)



REMARKS

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SCS-ENG-352 (REV. 3-70)
FILE CODE ENG-22

ACTIVITY 7 - PART E

LABORATORY NO ____

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE: Figure 7.2 Illustration of optimum water content not bracketed by 2

FIELD SAMPLE NO	LOCATION test data points	DEPTH

GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION CL LL 39 PI 20

CURVE NO. 1 OF 1

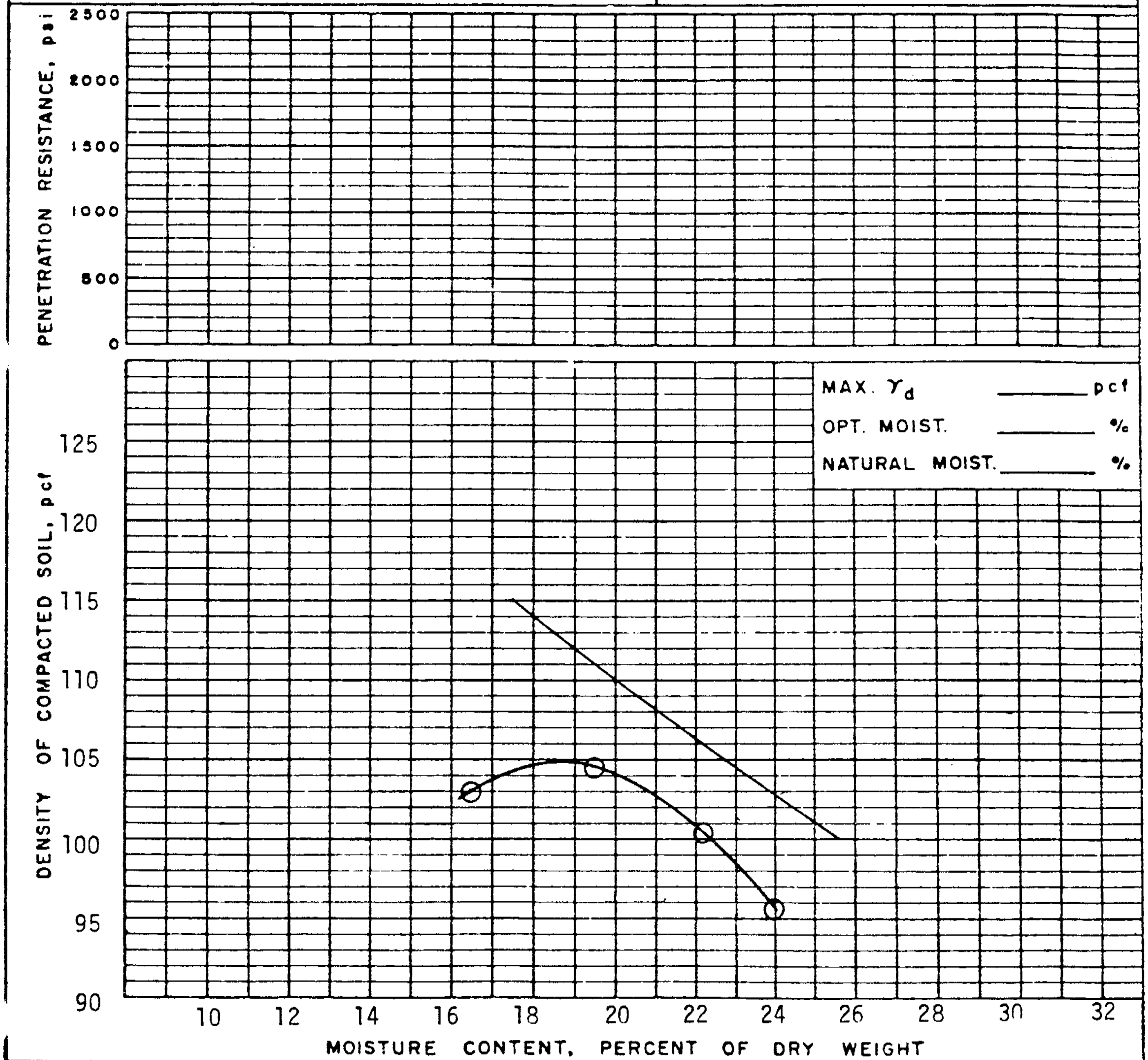
MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

STD. (ASTM D-698) ☒; METHOD A

SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.72 ; PLUS NO. 4 ____ }

MOD. (ASTM D-1557) ☐; METHOD ____

OTHER TEST ☐ (SEE REMARKS)



REMARKS

USDA SCS-HYATTSVILLE MD 1994

Problem:

Examine the plotted compaction test on Figure 7.3, page 31. Point out any major discrepancies in the plotted results. Use information you learned in Activity 6 and this Activity.

AFTER COMPLETING THE ACTIVITY, CHECK YOUR ANSWERS ON PAGE 32

ACTIVITY 7 - PART E

LABORATORY NO ______

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE: Figure 7.3 Problem

FIELD SAMPLE NO	LOCATION		DEPTH
GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION CL LL 32 PI 16

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

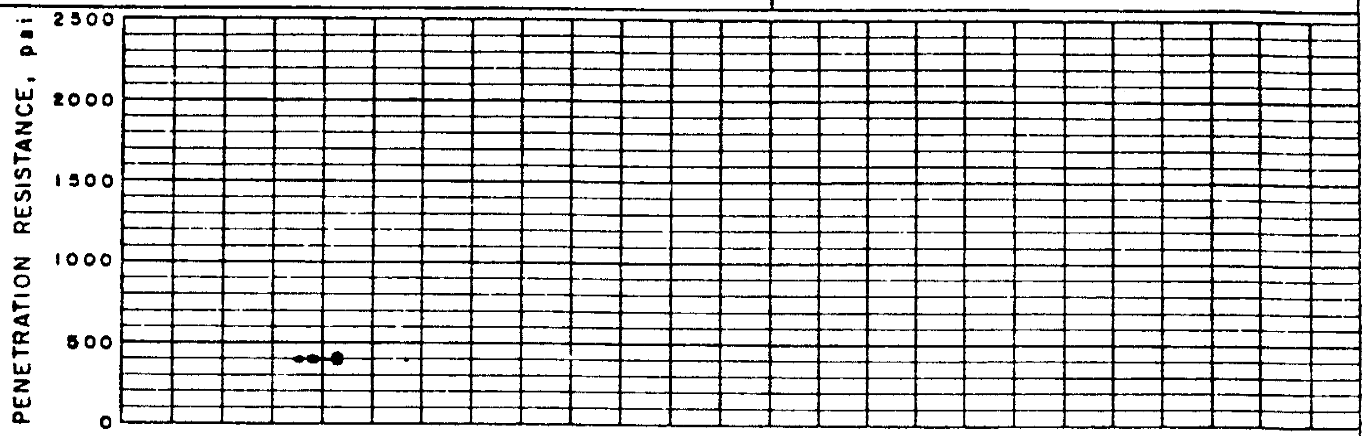
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.77 ; PLUS NO. 4 ______ }

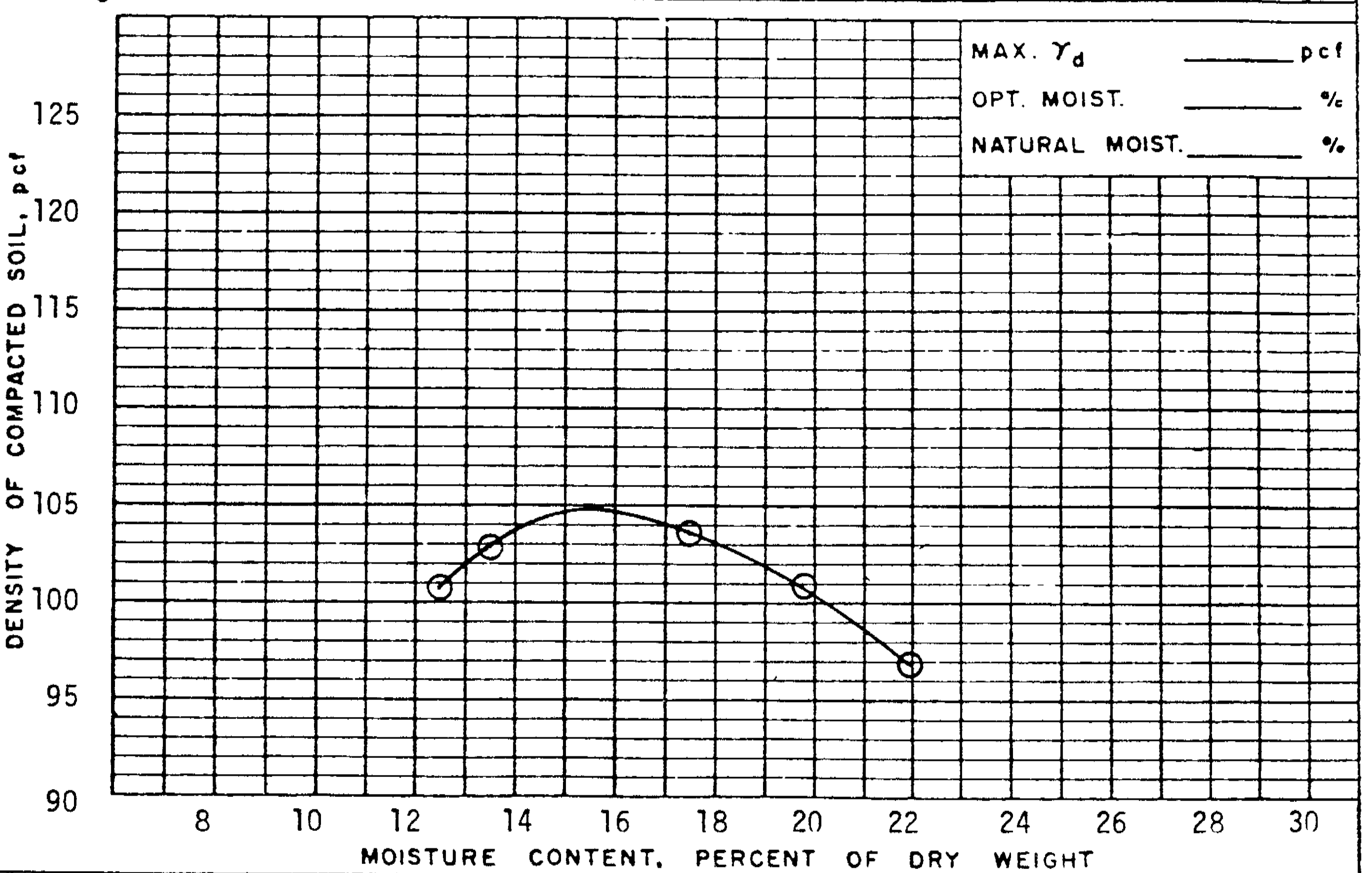
CURVE NO. 1 OF 1

STD. (ASTM D-698) ☒; METHOD A

MOD. (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)





REMARKS Note the discrepancies and/or errors in the test results.

(Plot the zero air voids curve to aid in your evaluation)

ACTIVITY 7 - SOLUTION

1. The 2d and 3d and 4th and 5th points are more than 2 percent apart in water content. ASTM requires successive points to be no more than about 1-1/2 percent apart in water content.

2. Optimum water content is bracketed by at least two points, which is acceptable. However, the large spread in water content between points 2 and 3 occurs within the range where optimum water is selected. The spread in water contents between successive points must be acceptable in this area of the curve.

3. Optimum water content (15.5%) is at about 66 percent saturation at the value of 105.0 pcf for maximum dry unit weight.[1] The normal range for optimum water content percent saturation is 75 to 90 percent. The specific gravity of the soil solids, G_s, should be re-checked, or other equipment or operator errors should be investigated.

4. The wet side of the compaction curve is not at saturation percentages of about 90 percent. Water contents on the wet side of the compaction curve are at percent saturation values of about 78 percent.[2] This is an additional cause for investigation into sources for the disprepancies in the test results.

5. If you think the value used for specific gravity may be incorrect, examine the effect of changes in the value. For instance, with a value of G_s of 2.60, the optimum water content is still 74% saturation and wet side curve points are still at only 85% saturation.

[1]

$$W_{sat}(\%) = \frac{62.4}{105.0} - \frac{1}{2.77} \times 100$$

$$= 23.3\%$$

$$S(\%) = \frac{15.5\%}{23.3\%} 100$$

$$= 66.4\%$$

[2] At wettest point

$$W_{sat}(\%) = \frac{62.4}{97.0} - \frac{1}{2.77} \times 100$$

$$= 28.2\%$$

$$S(\%) = \frac{22.0\%}{28.2\%} 100$$

$$= 77.9\%$$

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 8 - EMPIRICAL ESTIMATES OF COMPACTION DATA

Empirical correlations may be used to estimate values of maximum dry unit weight and optimum water content. Correlations are based on statistical analyses of several hundreds of compaction tests. The available correlations are developed for fine-grained soil that has a low sand content. The correlations should be used only for fine-grained soil that has liquid limit values of 30 or higher and plasticity indices of 7 or greater.

Correlations may be useful in determining a typical value for a compaction test on a similar soil. If compaction test results differ from values predicted by these correlations, additional investigation into possible cause is warranted.

This correlation is from a publication of the U.S. Navy entitled DM-7, Soil Mechanics. It is from an earlier version of the manual and is not included in current versions. Correlations performed by Soil Conservation Service engineers have verified the accuracy of the estimates.

Maximum Dry Unit Weight = 130.3 - (0.82 x LL) + (0.30 x PI)
Optimum Water Content = 6.77 + (0.43 x LL) - (0.21 x PI)

where,
- Maximum Dry Unit Weight is in pounds per cubic foot
- LL is the liquid limit, in percent
- PI is the plasticity index, in percent
- Optimum Water Content is in percent

The Soil Conservation Service's Soil Mechanics Laboratory at Fort Worth, Texas developed the following correlation for estimation of Modified (ASTM D 1557 Method A) compaction tests. The equations are based on a statistical analysis of over 300 compaction tests.

Maximum Dry Unit Weight (pcf) = 138.2 - (0.80 x LL) + (0.63 x PI)
Optimum Water Content (%) = 5.10 + (0.33 x LL) - (0.27 x PI)

CONTINUE TO THE NEXT PAGE

The units used in these equations are the same as those used in the above correlations.

PROBLEM:

A CH soil that has 12 percent sand and 88 percent fines has a liquid limit of 82 and a PI of 50. Estimate the maximum dry unit weight and optimum water content of this soil for both ASTM D 698 Method A and ASTM D 1557 Method A compaction tests.

AFTER COMPLETING THE ACTIVITY, CHECK YOUR ANSWERS ON PAGE 36

ACTIVITY 8 - PROBLEM SOLUTION

Given: The soil contains 12 percent sand, has a LL=82 and a PI=50.

Solution

1. The empirical equations in Activity 8 are applicable to the soil because it meets the criteria of being a fine-grained soil without a high sand content and a LL greater than 30 and a PI greater than 7.

Using the Navdocks equations for ASTM D 698 Method A tests:

Maximum dry unit weight = 130.3 - 0.82 x LL + 0.3 x PI
= 130.3 - 0.82 x 82 + 0.3 x 50
= 78.0 pcf

Optimum water content = 6.77 + 0.43 x LL - 0.21 x PI
= 6.77 + 0.43 x 82 - 0.21 x 50
= 31.5%

Using the Fort Worth Soil Mechanics Laboratory equations for ASTM D 1557 Method A tests:

Maximum dry unit weight = 138.2 - 0.8 x LL + 0.63 x PI
= 138.2 - 0.8 x 82 + 0.63 x 50
= 104.0

Optimum water content = 5.1 + 0.33 x LL - 0.27 x PI
= 5.1 + 0.33 x 82 - 0.27 x 50
= 18.5%

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 9 - SUMMARY OF EVALUATION STEPS

In evaluating a plotted compaction test, the following summary of steps should be helpful. The steps do not necessarily need to be followed in the sequence shown, but most of the steps shown should be considered in an evaluation.

1. Are the scales used for plotting water content and dry unit weight suitable for accurate interpolation on the completed curve. If too large a scale is used, the needed accuracy is not possible. If too small a scale is used, the curve may be exaggerated.

2. Is the spread between successive values of water content less than two percent?

3. Is the optimum water content on the curve bracketed by at least two points below optimum and two points above optimum?

4. Is optimum water content at between 75 and 90 percent of saturated water content, for a standard energy test?

5. Is the compaction curve about parallel to the zero air voids curve at water contents wet of optimum? Are water contents on the compaction curve wet of optimum about equal to 90 percent of saturation?

6. Is the shape of the compaction curve typical of similar soils? Is the shape of the curve parabolic?

7. Are the values for maximum dry unit weight and optimum water content typical of the soil classification? For fine-grained soil that has liquid limit values greater than 30 and plasticity indices greater than 7, correlation equations may be useful in this judgement.

Items that may be responsible for errors/discrepancies in test data that should be checked include operator error, equipment calibration, and specific gravity values.

CONTINUE TO THE NEXT PAGE

PROBLEM

The plotted compaction test shown on Figure 9.1, p. 39 was performed on a CL soil with 18 percent sand and a LL of 42 and a PI of 21. The soil has a specific gravity of the soil solids, G_s, of 2.72. Evaluate the plotted test using the check procedure provided and list any major discrepancies. Would you advise further checking of calculations, specific gravity values, or other factors?

AFTER COMPLETING THE ACTIVITY, CHECK YOUR ANSWERS ON PAGE 40

ACTIVITY 9 - PART E

LABORATORY NO ________

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE: Figure 9.1 Problem Evaluate the Plotted Test Data

FIELD SAMPLE NO	LOCATION		DEPTH
GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION CL LL 42 PI 21

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

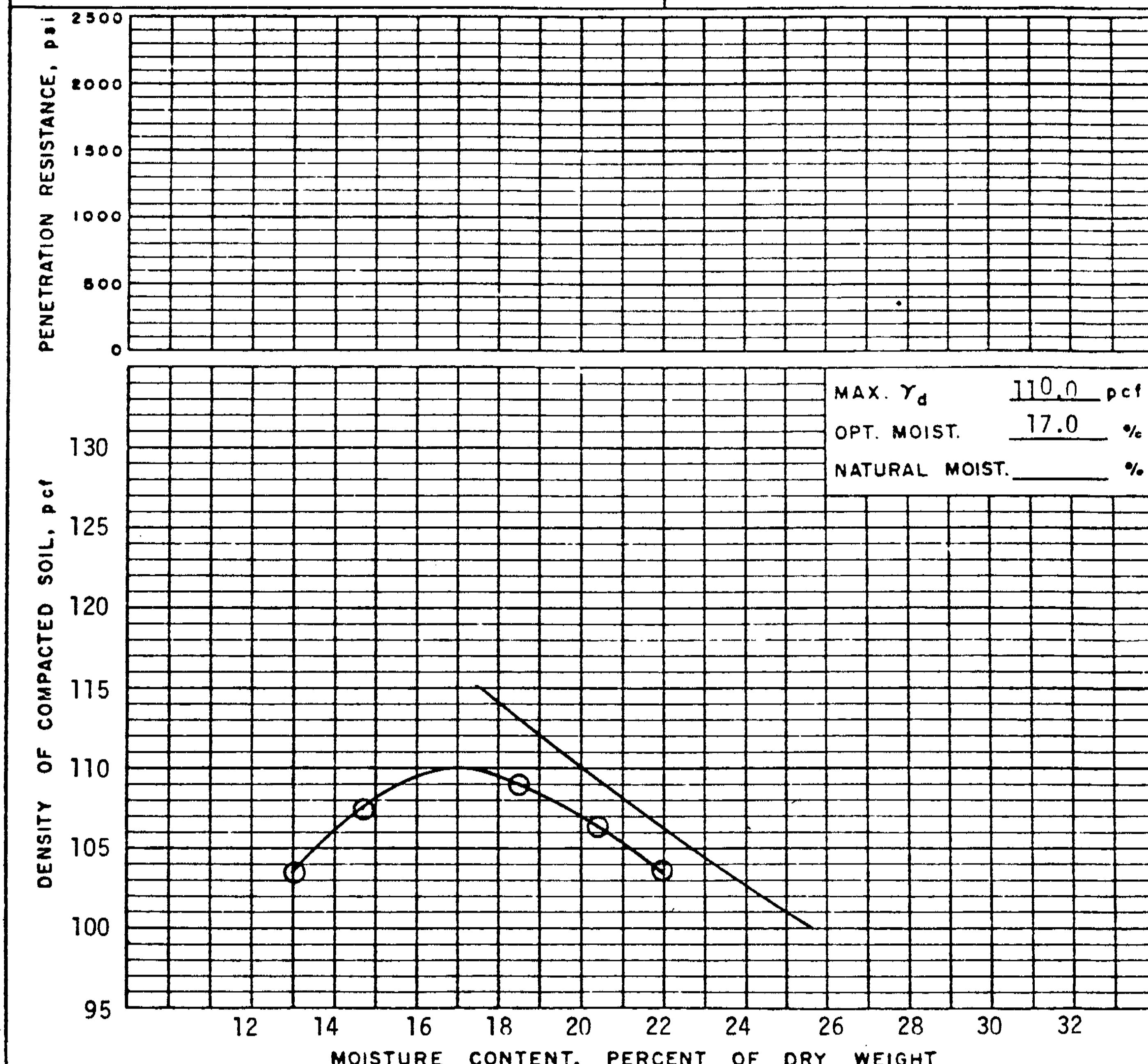
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.72; PLUS NO. 4 ________

CURVE NO. 1 OF 1

STD. (ASTM D-698) ☒; METHOD A

MOD (ASTM D-1557) ☐; METHOD ________

OTHER TEST ☐ (SEE REMARKS)



REMARKS

ACTIVITY 9 - SOLUTION

1. The scales used for plotting are appropriate.

2. The spread in water contents between the second and third points on the test is excessive, about 4 percent.

3. Optimum water content is bracketed by two points, which is acceptable, but the spread in points 2 and 3 mentioned in step 2 would make determination of optimum water content inaccurate.

4. Optimum water content is at about 85 percent saturation.[1] This is within the normal range.

5. The compaction curve is about parallel to the zero air voids curve at water contents above optimum water content, which is acceptable. However, water contents are at about 94 percent saturation along this portion of the curve, which is slightly above that normally experienced.[2]

6. The curve is slightly steeper than one would normally expect for a CL soil that has a plasticity index of 22.

7. The maximum dry unit weight is much higher than predicted by the Navdock correlation equation. The correlation estimate is 102.2 pcf, whereas the test value is 111.0 pcf. The optimum water content for the test is 17.0 percent, whereas the correlation estimate given by the Navdock equation is 20.4 percent. The sample did not contain an excessive amount of sand particles.

8. The most serious apparent flaw in the test results is the spread in the water contents between points 2 and 3. The other discrepancies noted warrant an investigation into the possible sources of these discrepancies.

Include a check of the soil's specific gravity value, and equipment and operator errors.

[1]

$$W_{sat}(\%) = \left[\frac{62.4}{115.0} - \frac{1}{2.72}\right] x\ 100$$

$$= 19.96\%$$

$$S(\%) = \frac{17.0\%}{19.96\%} 100$$

$$= 85\%$$

[2] At wettest point

$$W_{sat}(\%) = \left[\frac{62.4}{103.5} - \frac{1}{2.77}\right] x\ 100$$

$$= 23.53\%$$

$$S(\%) = \frac{22.0\%}{23.53} 100$$

$$= 93.5\%$$

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 10 - COMPACTION SPECIFICATIONS

In Activity 6, Part B, of this Module, you learned that the designer for an earth fill project will select an arbitrary percentage of a soil's maximum dry unit weight and a range of placement water content in relation to the soil's compaction test curve for a preliminary design. After performing engineering property tests, final design and construction specifications are prepared.

The following discussion gives factors that you should consider to insure that the final compaction specifications are realistic and attainable. You should realize that if unduly restrictive specifications are written, many problems may arise in the enforcement of the construction contract and bids for the placement of the earth fill may be excessively expensive.

1. In specifying a range of acceptable water contents, you must consider the in-situ water content of the borrow source from which the fill will be constructed. If the borrow soils are at much lower water contents than the minimum acceptable water content for that soil, then considerable expense could be entailed in addition of adequate amounts of water to the fill. If borrow soils are at water content much higher than the specified range of acceptable placement water content, then the soils may need to be dried considerably.

   In considering the specified upper limit of placement water content, remember that most soils are difficult to compact at water contents greater than 90 percent of saturation. Even if no limit were placed on an upper acceptable placement water content, the practicality of compacting the soil to its required dry unit weight at 90 percent of saturation in effect creates a practical upper limit on placement water content.

These considerations are illustrated with two examples as follows:

Example 1

The borrow soil for a proposed fill project exists at an in-situ water content of 9.3 percent. The soil has a maximum dry unit weight of 105.0 pcf and an optimu water content of 18.0 percent, as measured in an ASTM D 698 Method A compaction test. If the construction specifications call for the soil to be placed at 95 percent of maximum dry unit weight at water contents ranging from two percent dry of optimum to 3 percent wet of optimum, what are the apparent problems facing a contractor?

Solution

The minimum acceptable placement water content of the soil is 16.0 percent (2% dry of optimum). The in-situ water content is 9.3 percent. This means that 7.3 percent by dry weight of water must be added to the soil to meet specifications. For soil weighing 100 pounds per cubic foot (the required minimum dry unit weight), this amounts to 7.3 pounds per cubic foot, or 197 pounds per cubic yard or about 23.5 gallons of water per cubic yard of

CONTINUE TO THE NEXT PAGE

compacted soil must be added. The problems facing a contractor are: (1) Based on the maximum dry unit weight and optimum water content, the soil is probably moderately plastic. It will be difficult to mix in this much water because of the low permeability of the soil, either in the borrow or on the fill. (2) The large quantities of water required may entail extra costs in transporting and distributing the water.

Example 2:

The borrow soil for a proposed fill project has an inplace water content of 28.5 percent. The fill specifications require the soil to be placed at 95 percent of the soil's maximum dry unit weight at a water content equal to optimum water content or higher. The soil is a CL soil that has a maximum dry unit weight of 99.5 pounds per cubic foot and an optimum water content of 19.5 percent. The soil solid's specific gravity is 2.7. What are the apparent problems with complying with the contract specifications?

Solution:

At a minimum required dry unit weight of 95 percent of 99.5 pounds per cubic foot, or 94.5 pcf, the saturated water content is 29.0 percent. If the borrow soils are at 28.5 percent water content, this means the soil would need to be compacted at a water content that is 98 percent saturated to achieve the minimum required density. Compacting most soils at over 90 percent saturation is difficult. This means that the borrow soils will need to be dried either in the borrow by drainage or dried on the fill by processing to achieve the required density. Based on the probable classification of the soil, inferred from its compaction test values, the soil is a moderately plastic clay that will be difficult to dry either in the borrow or on the fill. Extra effort will be required that will add to the cost of the fill placement. The only alternative to drying out the soil would be to accept a lower value of placement dry unit weight, which would permit placement at a higher water content. Determining whether this is an acceptable alternative would require evaluation of the soil's engineering properties at the lower dry unit weight.

2. Is the range of water contents specified reasonable? If too narrow a range is specified, considerable manipulation of the soils on the fill may be needed to attain this narrow range. On many sites, it is desirable to have a range of water contents specified of at least 4 percent. You should be aware that even though you may not specify any upper water content, for any required density, a realistic upper limit on water content is determined by the 90 percent saturation guideline mentioned previously. This problem is illustrated with the following example.

Example 3:

Soil for a proposed fill has a maximum ASTM D 698 Method A dry density of 116.0 pcf and an optimum water content of 13.0 percent. The specifications for the fill require that the soil to be placed at a minimum dry unit weight of 113.7 pcf, which is 98 percent of its maximum dry unit weight. The water content range specified is one percent dry of optimum up to 4 percent wet of optimum. The G_s value of the soil is 2.66. Is this a reasonable specification?

CONTINUE TO THE NEXT PAGE

Solution

The saturated water content at the minimum required dry unit weight of 113.7 is 17.3 percent. If we assume that the soil may be compacted to 90 percent saturation satisfactorily, the practical upper limit of water content is 15.6 percent. The range of water contents, although specified as 12.0 to 17.0 percent, is in reality only from 12.0 percent to about 15.5 percent. This narrow a range of water contents will require the contractor to closely control densities and water contents to achieve the required product, but this can probably be done. In conclusion, this is probably a reasonable specification.

Problem

The soil for a proposed fill project has a compaction test curve as shown on figure 10.1,p. 44. The specifications for the fill require the soil to be placed at 95 percent of maximum dry unit weight at a minimum water content of 2 percent wet of optimum. No upper limit is placed on water content. (A) Is this a reasonable specification? (B) If the borrow soils had an in-situ water content averaging 26.3 percent at the time of construction, what problem(s), if any, should you anticipate? (C) If the borrow soils were to be at an average in-situ water content of 15.2 percent at the time of construction, what problem(s), if any, would you anticipate? Note that an ASTM D 1557, or modified energy test is used as the control test.

USE PAGE 45 AS A WORKSHEET FOR THE PROBLEM

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FILE CODE ENG-22

ACTIVITY 10 - PART E

LABORATORY NO ______

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE: Figure 10.1 Problem

FIELD SAMPLE NO	LOCATION	DEPTH

GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION CH LL 68 PI 38

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

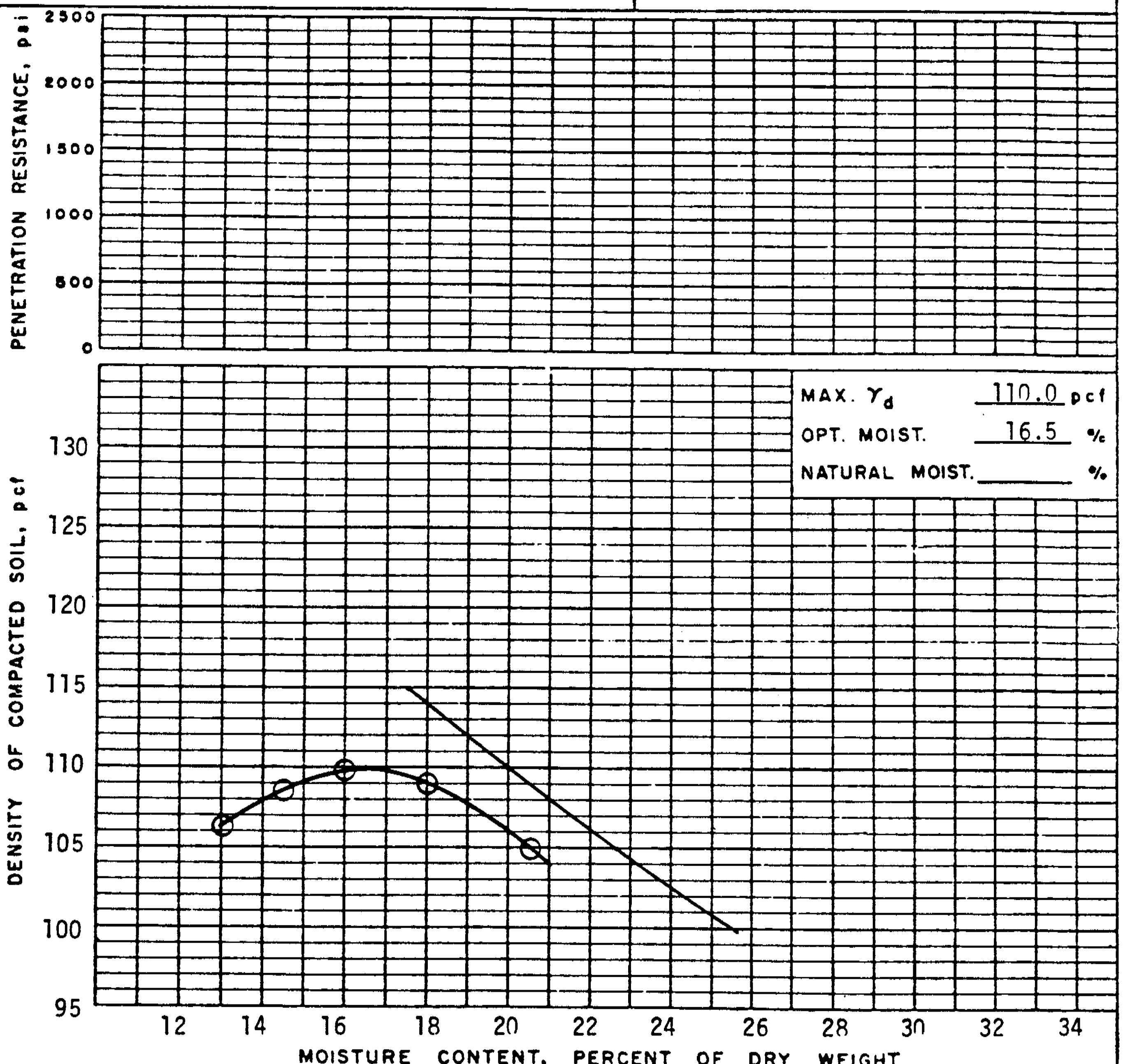
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.70 ; PLUS NO. 4 ______ }

CURVE NO. 1 OF 1

STD. (ASTM D-698) ☐; METHOD ______

MOD. (ASTM D-1557) ☒; METHOD A

OTHER TEST ☐ (SEE REMARKS)



MAX. γ_d 110.0 pcf

OPT. MOIST. 16.5 %

NATURAL MOIST. ______ %

REMARKS

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ACTIVITY 10 - WORKSHEET FOR PROBLEM

AFTER COMPLETING THE ACTIVITY, CHECK YOUR ANSWERS ON PAGE 46

ACTIVITY 10 - SOLUTION

Given: Maximum dry unit weight = 110.0 pcf. Optimum water content equals 16.5 percent. G_s = 2.70. Placement specifications are 95 percent of maximum dry unit weight at water contents of 2 percent wet of optimum or higher.

A. Is this a reasonable specification?

1. 95 percent of maximum dry unit weight = 0.95 x 110.0 pcf
   = 104.5 pcf

2. Calculate saturated water content at this density:

$$w_{sat}\ (\%) = \left[\frac{62.4}{104.5} - \frac{1}{2.70}\right] \times 100$$

= 22.7% (You could also read this value directly from the plotted zero air voids curve on page 44)

3. The upper feasible placement water content is at 90 percent of saturation.

   0.9 x 22.7% = 20.4%

4. The minimum required water content is 2 percent above optimum. Optimum water content is 16.5 percent, so the minimum required placement water content is 18.5 percent.

5. The practical range of water contents is then between the minimum allowable water content of 18.5 percent and the maximum water content at which the required density can be realistically obtained of 20.4 percent. This is probably too narrow a range of water contents to expect a contractor to operate efficiently. One can concluded that the specifications should be adjusted if design of the project permits it.

B. In-situ water content averages 26.3 percent problem.

The in-situ water content is about 6 percent higher than the maximum feasible placement water content calculated in A., of 20.4 percent. This means soils must be intensively processed on the fill to dry them before the specified density can be achieved. Considering the CH classification of the sample, this will be difficult to accomplish. The design should be re-evaluated to determine if acceptable engineering properties could be attained at a lower placement density, so that higher placement water contents could be used. If this not possible, some provisions should be made to construct this site in a drier period of the year, or provisions should be made to provide some drainage of the borrow area before construction to lower the in-situ water contents.

CONTINUE TO THE NEXT PAGE

C. In-situ water content averages 15.2 percent problem.

The minimum specified water content is 18.5 percent. With an in-situ water content of 15.2 percent, water must be added to the soil on the fill or in the borrow area. With the proper equipment and processing, this should not be too difficult and should pose no special problems. The problem mentioned previously of having too narrow a range of water contents practical for construction is still serious, however.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 11 - FINAL PROBLEMS

To test your completion of the objectives of Part E, complete the following questions.

Label the following 9 statements as true or false (T/F).

1. A plotted compaction test should always include a curve showing dry unit weight versus saturated water content. _____

2. The specific gravity of clay soils is usually lower than the specific gravity of sandy soils. _____

3. Maximum dry unit weight values for tests using Modified (D1557) energies will usually be lower than maximum dry unit weight values for tests using Standard (D698) energies, for the same soil. _____

4. An acceptable spread for successive water contents on a compaction curve is 3 percent. _____

5. A compaction test using Standard energy on a CH soil will always have a sharp peak in the dry unit weight vs. water content curve. _____

6. A test with an optimum water content equal to 63 percent of saturated water content probably contains errors in either the specific gravity used or procedures. _____

7. A compaction curve can intersect the zero air voids curve. _____

8. Another term used for the zero air voids curve is the complete saturation curve. _____

9. It is possible for a soil to have a specific gravity value greater than 3.0. _____

10. Evaluate the plotted compaction test on figure 11.1. List each evaluation step and whether the data is acceptable or unacceptable for each evaluation you make. Use the check procedures given in Activity 9.

11. Soil like that shown on Figure 11.2, p. 52 is being used in a fill project. Specifications require the soil to be placed at a minimum dry unit weight equal to 110 percent of its maximum dry unit weight according to ASTM D 698 Method A. Specified water contents for the soil are from 3 percent dry of optimum as a minimum to 1 percent wet of optimum as a maximum. Are these specifications reasonable?

USE PAGES 51 AND 53 FOR WORKSHEETS
AFTER COMPLETING THE ACTIVITY, CHECK THE ANSWERS ON THE PAGE 54

SCS-ENG-352 (REV. 3-70)
FILE CODE ENG-22

ACTIVITY 11 - PART E

LABORATORY NO ______

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE: Figure 11.1 Problem. Evaluate the Plotted Data. List each step.

FIELD SAMPLE NO	LOCATION		DEPTH
GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION CL LL 32 PI 14

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

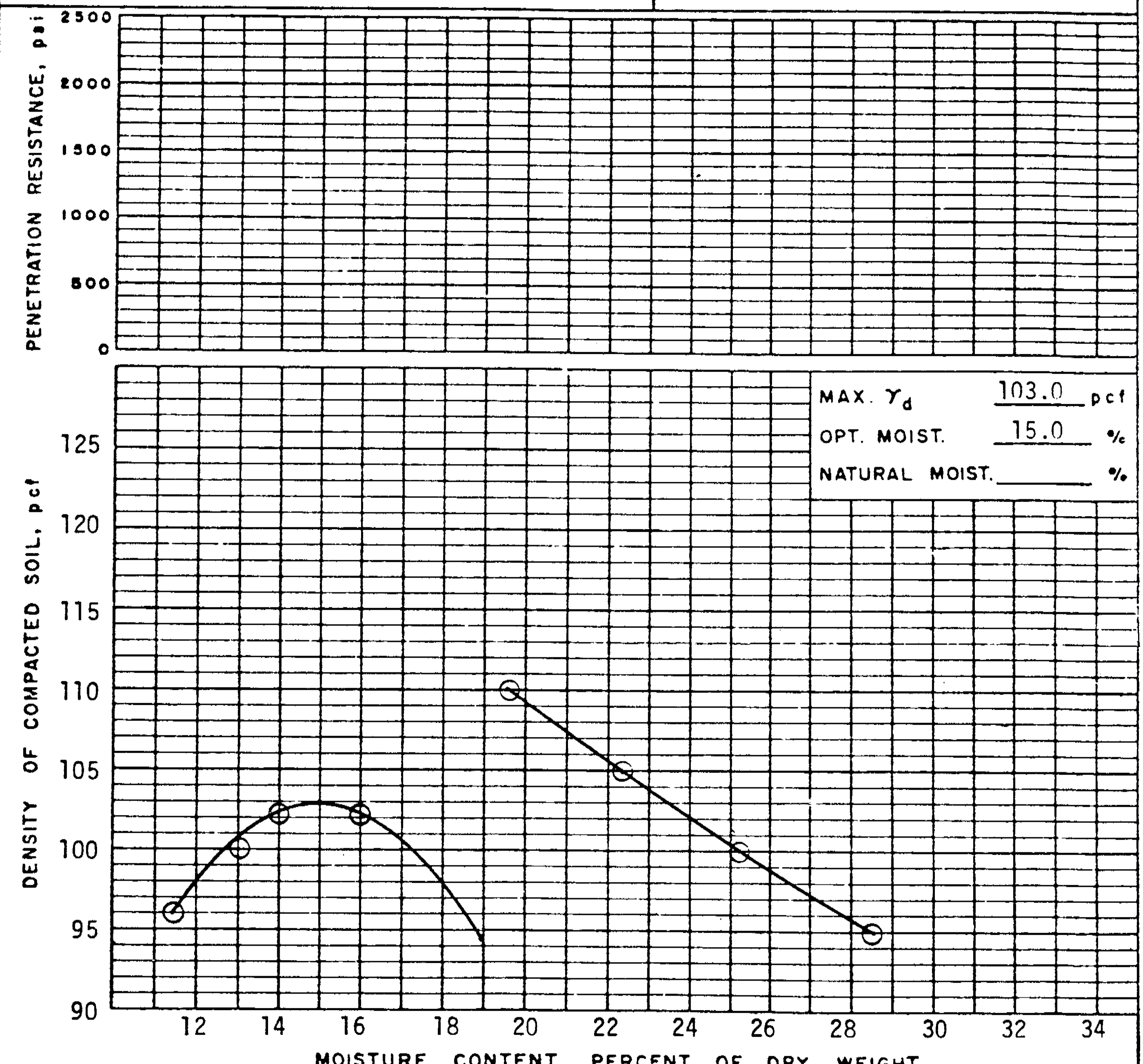
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.69 ; PLUS NO. 4 ______

CURVE NO. 1 OF 1

STD. (ASTM D-698) ☒; METHOD A

MOD. (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)



REMARKS

USDA SCS-HYATTSVILLE MD 1966

ACTIVITY 11, Problem 10 - Worksheet

SCS-ENG-352 (REV. 3-70)
FILE CODE ENG-22

LABORATORY NO ________

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

PROJECT and STATE Figure 11.2 Problem 11

FIELD SAMPLE NO	LOCATION		DEPTH
GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION CH LL 68 PI 38

MAX. PARTICLE SIZE INCLUDED IN TEST #4

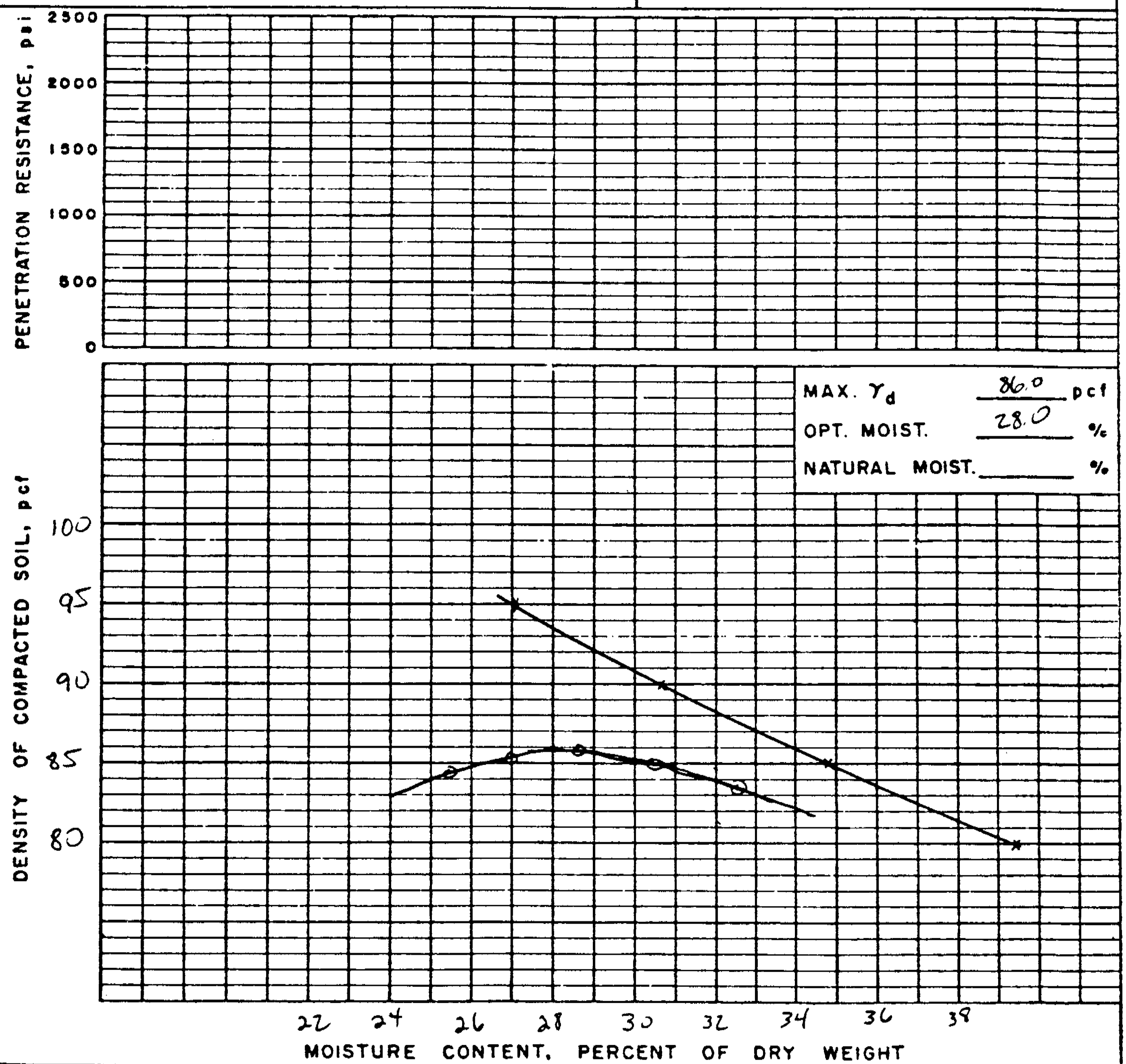
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.59 ; PLUS NO. 4 ________

CURVE NO. 1 OF 1

STD. (ASTM D-698) ☑; METHOD A

MOD. (ASTM D-1557) ☐; METHOD ________

OTHER TEST ☐ (SEE REMARKS)



REMARKS

USDA-SCS-HYATTSVILLE MD 1966

ACTIVITY 11 - Worksheet

CHECK THE ANSWERS ON PAGE 54 AFTER COMPLETING THE ACTIVITY

ACTIVITY 11 - PROBLEM SOLUTIONS

True/false questions:

1.	T	6.	T
2.	F	7.	F
3.	F	8.	T
4.	F	9.	T
5.	F		

Problem 10. Evaluation of plotted compaction test:

1. The scales used for plotting are appropriate.

2. The spread in water contents between successive points is acceptable.

3. Optimum water content is not bracketed by two points on the test. At least one additional trial should have been performed at a water content of about 18 percent.

4. Calculating saturated water content at the maximum dry unit weight,

$$w_{sat}\ (\%) = \left[\frac{62.4}{103.0} - \frac{1}{2.69}\right] \times 100$$

$= 23.4\%$ (This value may also be read directly from the plotted zero air voids curve.)

Using the value for saturated water content as calculated above, then optimum water content is seen to be at a percent saturation value of:

$$\begin{aligned} S(\%) &= [w_{opt}\ (\%)/w_{sat}\ (\%)] \times 100 \\ &= [15.0/23.4] \times 100 \\ &= 64\% \end{aligned}$$

This is outside the normal range of 75 to 90 percent. Sources for this discrepancy should be investigated, including whether the specific gravity value used is correct. It is unlikely that specific gravity errors account for all of this discrepancy.

5. The compaction curve is not parallel to the zero air voids curve at water contents above optimum water content. Water contents on the plotted compaction curve are at about 68 percent of saturation. This may be determined by calculating one point on the wet side of the curve as follows, using a value of dry unit weight of 99.0 pcf:

$$w_{sat}\ (\%) = \left[\frac{62.4}{99.0} - \frac{1}{2.69}\right] \times 100$$

$= 25.9\%$ (You could also read this value from the plotted zero air voids curve.)

CONTINUE TO THE NEXT PAGE

ACTIVITY 11 - Continued

Calculate a percent saturation as follows using the water content on the curve at a dry unit weight of 99.0 pcf of 17.6 percent:

$$S(\%) = [w(\%)/w_{sat}(\%)] \times 100$$
$$= [17.6/25.9] \times 100$$
$$= 68\%$$

This is much less than the value of 90 percent normally expected for water contents on the wet side of a compaction curve.

6. The curve has a parabolic shape which is acceptable. The curve may be slightly steeper than one would normally expect for a CL soil.

7. The values for maximum dry unit weight and optimum water content are not typical of a CL soil with the Atterberg limits shown. Using the Navdock's equations, the estimated value for dry unit weight is 108.3 pcf and the estimated value for optimum water content is 17.6 percent. This compares to the test values of 103.0 pcf and 15.0 percent. Ordinarily, if a test value for dry unit weight is lower than the estimate, the value for optimum water content would be higher. This indicates a major discrepancy in the test result which should be resolved before using the test results.

Problem 11. Solution

1. The specified dry unit weight is 110 percent of maximum dry unit weight.

   110% x 86.0 pcf = 94.6 pcf

2. The saturated water content at a dry unit weight of 94.6 pcf is calculated as follows:

$$w_{sat}\ (\%) = \left[\frac{62.4}{94.6} - \frac{1}{2.59} \right] \times 100$$

$$= 27.4\%$$ (The zero air voids curve could also be used to obtain this value)

3. The maximum feasible placement water content is about 90 percent saturation. 90% x 27.4% = 24.6%. Compacting soils will be difficult at water contents higher than this.

4. The minimum permissible water content is 3 percent below optimum water content. Using the test result, optimum water content is 28.0 percent, so the minimum permissible water content is 28.0% - 3.0% = 25.0%.

5. This means that the minimum required water content is slightly greater than the maximum feasible water content that can be used and still obtain the required dry unit weight. The specification is unreasonable.

STOP THE TAPE WHEN YOU HAVE FINISHED

APPENDIX

SCS Logo

ENG-SOIL MECHANICS TRAINING SERIES--
BASIC SOIL PROPERTIES
MODULE 5 - COMPACTION
PART E
EVALUATION OF COMPACTION DATA AND SPECIFICATIONS
1 Study Guide

-

Part E covers evaluation of compaction test data, gives empirical methods for estimating typical compaction test results for the major Unified Soil Classification groups, and
2 gives guidelines on design considerations.

-

At the completion of Part E you will be able to complete the following objectives:

1. List the main items to check for equipment calibration
3 in a compaction test.

-

2. List the main items to check in compaction test
4 procedures.

-

3. Define the zero air voids curve.
5

-

4. Using example data, calculate and plot a zero air voids
6 curve.

-

5. Given an example plotted compaction test and a list of check procedures, critically evaluate the test and point
7 out any major discrepancies or errors.

-

6. Given example design specifications for density and
8 water content, evaluate their practicality.

-

9 Activity 1, Part E of your Study Guide lists these objectives for reference. Stop the tape and review the Activity.

-

The factors affecting the quality of compaction tests include both equipment factors and operator factors.

Factors in the calibration of compaction test apparatus include the following items. These items should be calibrated frequently for good quality test results.

1. Volume of mold.
2. Weight of hammer and height of drop.
3. Friction in hammer sleeve.
4. Oven temperature used for water content measurements.
5. Weighing devices accuracy. 10

-

Activity 2 contains a summary of these equipment calibrations and has examples and problems. Stop the tape player and
11 complete the Activity.

-

Possible sources of operator error include the following items. Operators should be especially watchful against these errors.

1. Careful filling of mold within required tolerances. If the mold is overfilled, the unit energy will be low. If the mold is underfilled, the volume of the specimen will be inaccurate. 12

-

2. The proper number of blows per lift must be maintained. Each lift should be about equal in thickness. Each lift should be equally covered with hammer blows. 13

-

3. A representative water content sample must be obtained from the entire specimen. The proper oven temperature must be used for the soil being tested. Soil containing minerals that have hydrated water should be dried at 60 degrees Centigrade. Samples should be dried to a constant weight. 14

-

More detailed specifications are contained in the ASTM test methods. Each operator should be intimately familiar with
15 these standard test methods.

-

ACTIVITY 3

Activity 3 contains a summary of important procedural evaluations. Stop the tape player and carefully study the
16 information before resuming.

-

Evaluating the plotted test data is important in disclosing any questionable test results. One of the most important tools for this purpose is the zero air voids or complete saturation curve. The development, significance, and use of
17 this curve will now be examined.

-

w_{sat} (%) = ((gamma water/dry unit wt) -(1/specific gravity))*100

You should recall from Module 4 - Volume-Weight Relation that, for a given value for dry unit weight, a saturated water content may be calculated. At the saturated water content, all of the void spaces in the soil mass are full of water. The saturated water content is usually calculated
18 from this equation:

-

ACTIVITY 4
SPECIFIC GRAVITY

Specific gravity values of the soil solids are measured with a laboratory test or may be estimated with experience. Typical values for specific gravity for different kinds of soil are given in Activity 4 of your Study Guide. Stop the
19 tape and study this information before continuing.

-

A plotted compaction test encompasses a range of dry unit weight values. If we assume several values for dry unit weight over this range and calculate a value for saturated water content at each assumed dry unit weight, then a plot of saturated water content versus dry unit weight may be developed. This plot of saturated water content versus dry unit weight is often called the zero air voids curve, or 100%
20 saturation curve.

-

ACTIVITY 5

Activity 5, Part E, of your Study Guide gives an example of this procedure and a problem to test your understanding of the procedure. Stop and complete this Activity before
21 continuing.

-

The zero air voids curve is useful in several ways in critiquing a compaction test. Some of these include:

1. A compaction test curve cannot intercept the zero air voids curve. Because a soil cannot exist at a water content greater than theoretical saturation, a compaction plot intersecting or plotting to the right of the zero air voids curve indicates that an error has been made. The error can be in the determination of the soil solids' specific gravity, or it may be in calculations, operator
22 errors such as mis-weighings, or others.

-

2. Optimum water content for standard energy tests for many soils occurs at about 80 percent of theoretical saturation. Standard energy compaction tests where optimum water content is less than 75 percent or greater than 90 percent saturation water content should be
23 double-checked for sources of error.

-

3. The "wet-side" of a compaction curve (that portion of the dry unit weight versus water content curve wetter than optimum water content) usually parallels the zero air voids curve. For many soils, using standard energy this
24 is at water contents of about 90 percent saturation.

-

ACTIVITY 6 Activity 6, Part E, of your Study Guide has examples and problems on the use of the zero air voids curve in critiquing compaction test results. Stop and complete that Activity
25 before continuing.

-

Additional items that should be checked in evaluating a compaction test include:

1. Was the correct method of compaction test used. That is, if the sample contained gravel, was the proper test
26 method selected?

-

2. The spread between successive water contents in the test should not be more than about 2 percent water content. If two successive points are more than about 2 percent water content apart, this is probably too large an
27 interpolation for accurate results.

-

28 3. The optimum water content on the plotted curve should fall between plotted points so that at least two points occur at less than optimum water content and two plotted points are greater than optimum water content.

-

ACTIVITY 7

29 Activity 7 in your Study Guide summarizes these points. Stop the tape and complete the Activity.

-

30 Another important step in the evaluation of plotted data is to determine whether the completed test results are reasonable based on previous experience with soils of similar geologic origin, with similar gradation and Atterberg limit data.

-

31 Correlations are useful to form a basis for this judgement. One correlation developed for fine-grained soil that has Liquid Limit values greater than 30 and Plasticity Index values greater than about 7 is taken from a U.S. Navy Design Manual on Soil Mechanics: The correlations are for ASTM D 698, Method A tests.

-

Maximum Dry Unit Weight (pcf) = 130.3-0.82*LL + 0.63*PI

32 This equation relates maximum dry unit weight to liquid limit and plasticity index:

-

Optimum Water Content = 6.77+0.43*LL - 0.21*PI

33 This equation relates optimum water content to liquid limit and plasticity index.

-

Maximum Dry Unit Weight (pcf) = 138.2-0.8*LL+0.63*PI

Correlations for estimating modified (ASTM D 1557, Method A) compaction test results for plastic clay soils were developed by the Soil Mechanics Laboratory in Fort Worth, Texas, and are given by the following equations:

34 This equation estimates maximum dry density.

-

Optimum Water Content (%)=5.1+0.33*LL-0.27*PI

35

This equation estimates optimum water content.

-

ACTIVITY 8

Activity 8, Part E, of your Study Guide gives details on these correlation procedures and has example problems to illustrate their use. You should stop the tape and complete
36 the Activity.

-

ACTIVITY 9

Activity 9, Part E, of your Study Guide summarizes the steps to follow in critically evaluating a plotted compaction test. Examples and problems are also given. Stop the tape and
37 complete that Activity.

-

Evaluation of minimum and maximum index density test results is difficult. There are many sources of error in the performance of the test, and careful calibration of equipment and trained personnel are required for accurate test results.

You should at least evaluate whether the proper size mold was used, depending on the maximum particle size in the sample tested, whether the maximum index density test was performed wet or dry, and whether the test results appear reasonable based on empirical correlations that you learned in Part D
38 of this Module, and based on previous test results.

-

The last portion of Part E will cover specifications and quality control of earth fill. Designers must be aware of construction procedures so that specifications are reasonable, obtainable, practical, enforceable, and
39 economical.

-

The specifications for density and water contents for an earth fill should be based on engineering property tests or
40 estimated engineering behavior based on experience.

Some of the items a designer should consider when writing specifications for an earth fill project include:

1. Has a range of water contents been given that permits
some latitude in the contractor's operations. If very
high densities and high water contents are specified,
there may be only a narrow range of water contents over
41 which the contractor can operate.

2. Has the in-situ water content of the borrow soils been
adequately considered. If specifications call for
substantially higher or lower water contents than exist
in the borrow areas, then extra effort and expense are
42 usually required.

ACTIVITY 10 Activity 10 illustrates several typical situations with which
43 you should be familiar. Stop and complete that Activity.

Design and construction personnel must consider many items in the area of density specifications and quality control of earth fills. Much more detail on quality control during construction is planned for Module 11 of this series.

A few items to consider are:

1. If an in-place density measurement is performed on a
completed earth fill, has a compaction test been
44 performed on the same soil?

2. If the earth fill has gravels, have oversize corrections
been made for compaction test results to reflect the
gravel content of the completed earth fill? Are bulk
specific gravity values for the oversize particles
45 correct?

Let's review the objectives of Part E. Objective 1 was to
list the main items to check for equipment calibration in a
46 compaction test.

Objective 2 was to list the main items to check in compaction
47 test procedures.

-

Objective 3 was to define the zero air voids curve.

48

-

Objective 4 was to use example data, calculate and plot a zero air voids curve.

49

-

Objective 5 was to use an example plotted compaction test and a list of check procedures to critically evaluate the
50 test and point out any major discrepancies or errors.

-

Objective 6 was to evaluate the practicality of given example
51 design specifications for density and water content.

-

To test your completion of these objectives, stop the tape
52 and complete Activity 11 in your Study Guide.

-

This completes Module 5 on compaction. If you completed this portion of the module without performing the compaction test in Part B, Activity 8, be sure to complete that activity as
53 soon as possible.

-

ENG-SOIL MECHANICS TRAINING SERIES

(BASIC SOIL PROPERTIES)

MODULE 5 - COMPACTION

CERTIFICATE OF COMPLETION

This certifies that ______________________________ completed Module 5-Compaction of the ENG-Soil Mechanics Training Series (Basic Soil Properties) ____________________ (Date) and is credited 42 hours of training.

Signed ______________________ Supervisor/Trainer

Signed ______________________ Participant

Completion of Module 5-Compaction of the ENG-Soil Mechanics Training Series (Basic Soil Properties) is acknowledged and documented in the above named employees training record.

Signed ______________________ State Training Officer

______________________ (Date)

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