United States
Department of
Agriculture

**Soil
Conservation
Service**

Soil Mechanics Training Series

Basic Soil Properties

Module 5 - Compaction

Part A - Introduction, Definitions, and Concepts

Study Guide

ENG-SOIL MECHANICS TRAINING SERIES--

BASIC SOIL PROPERTIES

MODULE 5 - COMPACTION

PART A

INTRODUCTION, DEFINITIONS, AND CONCEPTS

STUDY GUIDE

National Employee Development Staff
Soil Conservation Service
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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 reviews have helped make this training series one that will provide basic knowledge and skills to employees in soil mechanics.

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

Completion of Module 4, Volume-Weight Relations, is a prerequisite for this Module. If you have not completed Module 4, you should do so before attempting completion of this module.

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

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INTRODUCTION

This is Part A of Module 5 - Compaction - of the ENG-Soil Mechanics Training Series-Basic Soil Properties. The module 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 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.

In the Study Guide, instructions are given at the bottom of each page to assist you in each Activity. Carefully note and follow the instructions.

Part A has four 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 A 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.

You will need a pocket-type calculator for calculations in several parts of this module.

CONTENTS OF PACKAGE

2 slide trays
1 audio cassette
1 Study Guide

ACTIVITY 1 - OBJECTIVES

At the completion of Part A you will be able to:

1. Define the terms, symbols, and equations used with compaction of soil.

2. State from memory how the engineering properties of the major Unified Soil Classification System groups are affected by compaction. State generally whether each effect is beneficial or harmful.

3. List the three primary factors that affect the compaction characteristics of a soil.

4. Describe the general compaction characteristics and most appropriate construction equipment for each major Unified Soil Classification System group.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 2 - DEFINITIONS AND TERMINOLOGY

Important terms and their definitions that apply to the subject of compaction are listed below. Additional terminology and definitions that you will need are in Soil Mechanics Module 1 - Unified Soil Classification System, and Soil Mechanics Module 4 - Volume-Weight Relationships.

Compaction - The densification of a soil by means of mechanical manipulation.

Consolidation - The gradual reduction in void space of a soil mass resulting from an increase in compressive stress. The volume change results from air and/or water being expelled from the soil voids due to the stress increase.

Compaction is a dynamic process, whereas consolidation is a static process. Compaction usually results in substantial rearrangement of soil particles, which does not occur to any great degree in the application of a static load. In consolidation, the expulsion of air and water from the soil pore spaces is the primary action; minimal particle rearrangement takes place. Consolidation will be covered in more detail in other Modules.

A few other terms are used in this module with which you should be familiar:

Compactive effort - An expression of the amount of energy expended to compact a soil mass. It is usually expressed as foot-pounds per cubic foot or meter-kilograms per cubic meter.

Density - The mass per unit volume of a substance. Because weight is equal to mass times the gravity constant, weight may vary with gravity over the earth's surface. Strictly speaking, the terms weight and mass are not interchangeable, but for practical purposes, the two are about the same. Consequently, you may see both dry unit weight and dry density used to express the amount of dry soil solids per unit volume.

CONTINUE TO THE NEXT PAGE

ACTIVITY 2 - QUESTIONS

In each of the following situations, state whether the phenomenon occurring is one of compaction or consolidation, and why you think so.

1. A building is constructed on a thick deposit of clay soil. Subsequently, the groundwater table is lowered by excessive groundwater withdrawal. As a result, the building settles and cracks.

2. Soil is transported to a site in dump trucks and spread in a rectangular strip to a thickness of about 4 feet. Bulldozers are used to spread the soil, but no other equipment is used. A building is constructed on the pad, and several years later, the building is observed to have cracks in one corner.

3. A farm pond would not hold water after construction. The pond was drained and a small flock of sheep was penned in the bottom of the pond area for several weeks. The sheep were then removed and the pond allowed to refill with water. It subsequently held water satisfactorily.

4. A house was constructed on a loose sand deposit. Subsequently, a major highway was constructed close to the house. The house was observed to settle excessively and suffer considerable structural distress. The vibrations of the traffic were considerable because of the high incidence of heavy truck traffic on the road.

WRITE YOUR ANSWERS ON THE WORKSHEET ON THE FOLLOWING PAGE

ACTIVITY 2 - ANSWER SHEET

1.

2.

3.

4.

WHEN YOU HAVE COMPLETED THE ACTIVITY, REVIEW THE ANSWERS PROVIDED ON THE FOLLOWING PAGE

ACTIVITY 2 - ANSWERS

1. The phenomenon occurring is consolidation. The settlement occurred as a result of an external load application and an increase in intergranular stress, as the groundwater table was lowered. The settlement was not due to the mechanical manipulation of the soil mass.

2. Consolidation of the loosely dumped fill was the cause of the distress to the building. The static weight of the building was the primary force, and not any mechanical manipulation of the soil.

3. The penned animals effectively compacted the soil in the bottom of the pond by the mechanical manipulation of the soil by their hooves. The soil in the bottom of the pond was compacted and the permeability was reduced.

4. The loose sand under the house was densified by the vibration of the sand caused by the adjacent traffic. This mechanical application of energy to the soil induced excessive settlement of the foundation and subsequent damage to the structure.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 3 - TYPES OF LOAD APPLICATION IN COMPACTION

Compaction is the application of mechanical forces to a soil mass. The ways in which these forces may be applied are grouped as follows:

1. Static load application, live weight.
2. Kneading action.
3. Vibratory action.
4. Impact load application.
5. Combinations of two or more of the above.

Examples of static load live weight application are heavily loaded trucks or scrapers moving slowly over a fill, smooth wheeled steel drum rollers, heavily loaded pneumatic (rubber-tired) rollers that have closely spaced rollers, and heavy crawler tractors.

Examples of kneading action compactors are tamping rollers, hand tamping, motorized, hand-held compactors, wobbly-wheeled rollers, and pneumatic-tired equipment that has widely spaced rollers.

Vibratory compaction equipment types include steel-wheeled rollers that have a vibrating mechanism, small vibratory plate compactors, and the vibratory action of crawler tractors (bulldozers) treads. Other types of equipment use vibratory rods inserted into a soil deposit.

Impact loads may be applied with motorized, hand-held compactors (pogo-stick type action), with hand tampers, and by dropping heavy weights from a considerable height onto a soil deposit.

Most machines employ a combination of these actions to compact soil. A crawler tractor imparts static live load and at the same time vibrates the underlying soil considerably. A tamping roller uses static live load application and kneading action to compact soil.

CONTINUE TO PAGE 9

ACTIVITY 3 - PROBLEMS

Describe the action(s) of each of the following equipment or procedures in compacting a soil. Describe as one, or a combination of, the four types of force applications discussed.

1. The effect of the foot traffic of animals on a deposit of a soil.

   ____

2. A set of explosive charges placed around the perimeter of a soil deposit and simultaneously exploded.

   ____

3. The traffic of a farm tractor over a fill. ____________________

   ____.

4. The action of a fence post tamper. _________________________

   ____.

SEE THE FOLLOWING PAGE FOR DISCUSSION OF THE PROBLEMS

ACTIVITY 3 - ANSWERS

1. The foot traffic of animals is primarily a kneading type of compaction. Some static compaction also results.

2. The explosions create a vibratory action that would be effective in compacting coarse-grained soil.

3. The farm tractor's tires would compact by static load primarily, but some kneading action would also take place.

4. A fence post tamper would compact primarily by impact, but some kneading action would also occur.

Remember that nearly any mechanical device uses one or more of the types of compactive effort to compact soil. Few devices apply only one type of compactive effort.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 4 - VOLUME-WEIGHT RELATIONS REVIEW

This Activity reviews the concepts of Module 4, Volume-Weight Relations, that are essential to the completion of this Module.

The important definitions and terms needed in this module include:

Moist Unit Weight - The weight of moist soil per unit volume. Calculated from the equation:

$$\text{Moist unit weight} = \frac{\text{total weight}}{\text{total volume}}$$

It may be expressed in pounds per cubic feet, pcf, or as kilograms per cubic meter, kg/m^3.

Dry Unit Weight - The weight of soil solids per unit of total volume of a soil mass. It is usually obtained by weighing the soil mass after drying in an oven set to 110 degrees Centigrade for 12 hours or until a constant weight is obtained. Calculated from the equation:

$$\text{Dry unit weight} = \frac{\text{weight of solids}}{\text{total volume}}$$

Note: The weight of solids may also be calculated knowing the total moist weight and the water content.

$$W_S = \frac{W}{1+\frac{w\%}{100}}$$

Dry unit weight may be expressed in pounds per cubic feet, pcf, or in kilograms per cubic meter, kg/m3.

Remember that density is often used interchangeably with the term unit weight, and that the differences are minor, changing only with the effect of gravity over the surface of the earth. Where gravity is substantially different, as on the surface of the moon, the difference is substantial and cannot be ignored.

Water Content - The ratio of the weight of water in a soil sample to the weight of soil solids in the sample is expressed as a percentage. It is usually obtained by weighing a moist sample, then drying in an oven, then weighing the dry sample and calculating the water content by the equation:

$$\text{Water content (\%)} = \frac{(\text{wet weight - dry weight})}{\text{dry weight}} * 100$$

Specific Gravity of Soil Solids, abbreviated Gs - The ratio of the weight in air of a given volume of soil solids at a stated temperature to the weight in air of an equal volume of distilled water at a stated temperature. It is

CONTINUE TO NEXT PAGE

obtained from a laboratory test, or may be estimated on the basis of soil classification as follows:

sands/gravels - 2.65 to 2.67
silts - 2.66 to 2.69
clays - 2.66 to 2.80

More detailed information on specific gravity is given in another activity in Part E of this module.

Percent Saturation - The ratio of the water content of a sample to the theoretical saturated water content of the sample is expressed as a percentage. Calculated from the equation:

$$\%S = \frac{\text{water content (\%)}}{\text{saturated water content(\%)}} * 100$$

Saturated Water Content - The water content is measured when a soil sample's voids are completely filled with water. No air is in the sample.

In English units, it is calculated from the equation below:

$$W_{sat}(\%) = \left[\frac{62.4}{\text{Dry Unit Weight(pcf)}} - \frac{1}{G_s} \right] \times 100$$

In metric units, the equation is as shown:

$$W_{sat}(\%) = \left[\frac{1.0}{\text{Dry Unit Weight(g/cm}^3\text{)}} - \frac{1}{G_s} \right] \times 100$$

CONTINUE TO THE NEXT PAGE

ACTIVITY 4 - PROBLEMS

To test your understanding of these definitions from Module 4, work the following problems.

1. A sample container is measured and its volume is .01768 cubic feet. The sample in the container is weighed in a moist state and weighs 2.12 pounds. After drying, the sample weighs 1.69 pounds. The soil solids' specific gravity is 2.69.

   Determine the moist unit weight, water content, dry unit weight, and percent saturation of the sample.

WRITE YOUR ANSWERS ON THE WORKSHEET ON PAGE 15

ACTIVITY 4 - ANSWER SHEET

WHEN YOU HAVE COMPLETED THE ACTIVITY, REVIEW
THE ANSWERS PROVIDED ON THE FOLLOWING PAGE

ACTIVITY 4 - PROBLEM SOLUTIONS

$$\text{Moist unit weight} = \frac{\text{total weight}}{\text{total volume}}$$

$$= \frac{2.12 \text{ pounds}}{0.01768 \text{ cubic feet}}$$

$$= 119.9 \text{ pounds per cubic foot}$$

$$\text{Water content} = \frac{(\text{wet weight-dry weight})}{\text{dry weight}} \times 100$$

$$= \frac{(2.12-1.69)}{1.69} \times 100$$

$$= 25.4\%$$

$$\text{Dry unit weight} = \frac{\text{wet unit weight}}{1 + \frac{w\%}{100}}$$

$$= \frac{119.9 \text{ pcf}}{1 + \frac{25.44}{100}}$$

$$= \frac{119.9 \text{ pcf}}{1.2544}$$

$$= 95.6 \text{ pounds per cubic foot}$$

$$\text{Saturated water content} = \frac{62.4}{\text{Dry Unit Weight/pcf}} - \frac{1}{G_s} \times 100$$

$$= \frac{62.4}{95.6} - \frac{1}{2.69} \times 100$$

$$= 28.13\%$$

$$\text{Percent saturation} = \frac{w_n (\%)}{w_{sat}(\%)} \times 100$$

$$= \frac{25.44}{28.13\%} \times 100$$

$$= 90.4\%$$

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 5 - EFFECT OF COMPACTION AND COMPACTION WATER CONTENT ON ENGINEERING PROPERTIES OF SOILS

The increase in the density of a soil mass resulting from compaction causes significant changes in the engineering properties of the soil mass. Properties such as shear strength, consolidation, and permeability are affected. Other properties that are affected include flexibility and shrink-swell potential.

The water content at which a soil is compacted is also important in determining the engineering properties of the compacted soil.

Table 1 summarizes the important properties of soils that are affected by compaction, how compaction affects those properties, and what the influence of compaction water content is on the properties. The table also notes whether this effect is in general beneficial or detrimental for most uses.

This table assumes no particular kind of soil. Remember that in general the effects of densification and the importance of water content at compaction are most significant for fine-grained soil and coarse-grained soil with significant fines content.

You should understand that other factors also strongly affect the resultant engineering properties of a compacted soil mass. In other words, density alone does not determine many of these properties. For instance, the shear strength of a clean angular sand will be higher than that of a clean sand that has round particles, even though both are compacted to the same density. The way in which a soil is compacted may also influence its engineering properties. A clay soil which is compacted with kneading type compaction may have different shear strength behavior than one which is compacted to the same density using static load application. These factors may also affect the other properties discussed such as permeability and consolidation potential.

A designer must consider all of the probable effects of degree of compaction and water content at compaction on a soil. If a soil is compacted to a high degree at a low water content, the soil will have high shear strength and low compressibility. But, the soil will have reduced flexibility and increased swell pressure potential. Likewise, if the soil is compacted to a low degree of compactness at a high water content, it will have lower shear strength and higher compressibility, but it will be more flexible and less prone to have swell problems.

The balancing of adverse and favorable properties resulting from compaction and water content at compaction is often referred to as "trade-offs" in the design of the earth fill. Generally, the designer must decide which engineering property is most important for that earth fill and select the compaction and water content which will produce the greatest reward in that property. The adverse results of that decision will have to be handled by other design features.

START THE TAPE AFTER YOU HAVE STUDIED THE TABLE AND FIGURES ON PAGES 18-26

ACTIVITY 5

Table 1. Effect of densification and water content on engineering properties of soil

Engineering Property	Effect of Compaction	Beneficial/ Harmful	Effect of Higher Water Content	Beneficial/ Harmful
Shear Strength	Increases	Beneficial	Reduces	Harmful
Consolidation Potential	Reduces	Beneficial	Increases	Harmful
Permeability	Reduces	Beneficial	Reduces	Beneficial
Flexibility	Reduces	Harmful	Increases	Beneficial
Shrinkage Potential	Reduces	Beneficial	Increases	Harmful
Swell Potential	Increases	Harmful	Reduces	Beneficial

Figure 5.1

EFFECT OF COMPACTION ON ENGINEERING PROPERTIES

SHEAR STRENGTH

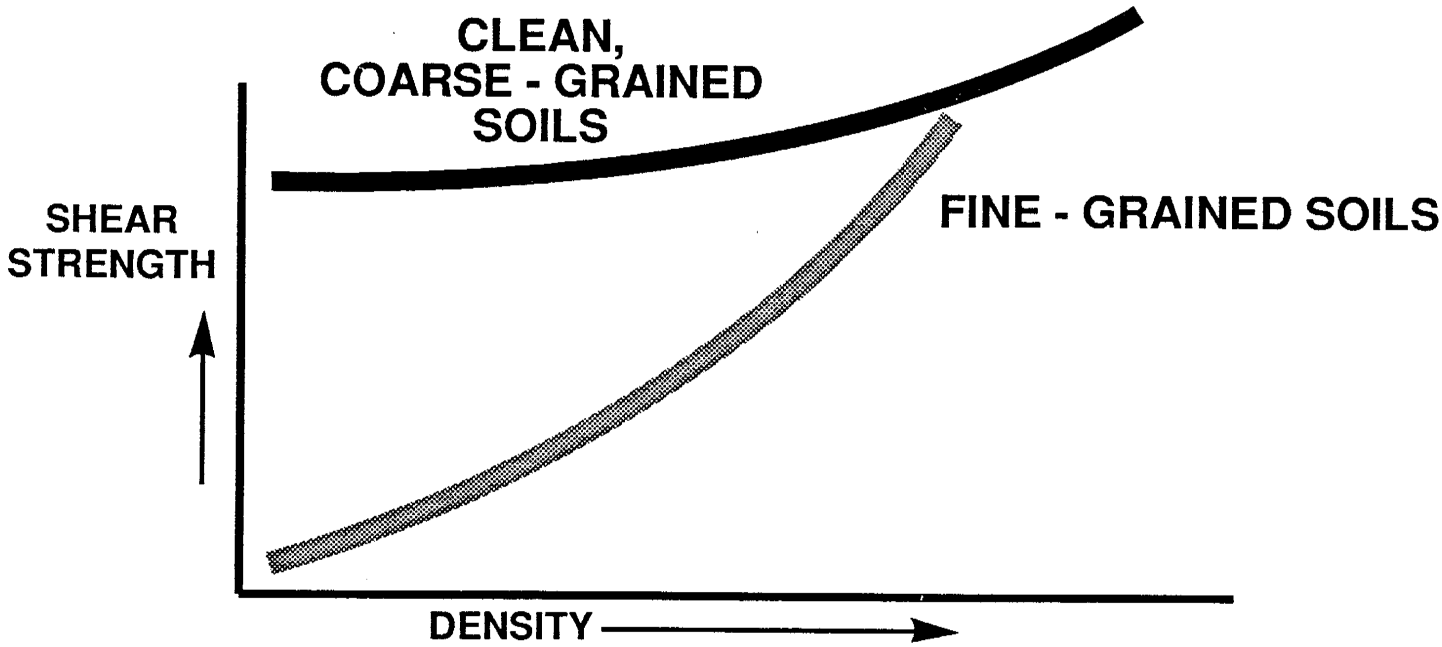


Figure 5.2

FACTORS OTHER THAN DENSITY AND WATER CONTENT AFFECT STRENGTH

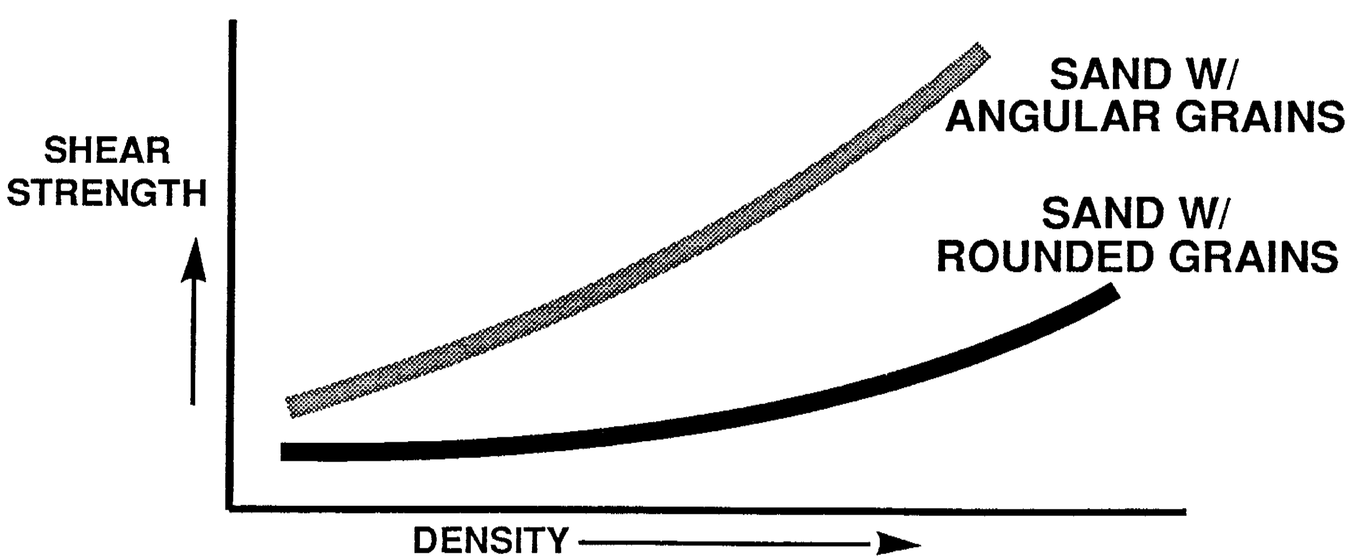


Figure 5.3

EFFECT OF COMPACTION ON ENGINEERING PROPERTIES

SHEAR STRENGTH

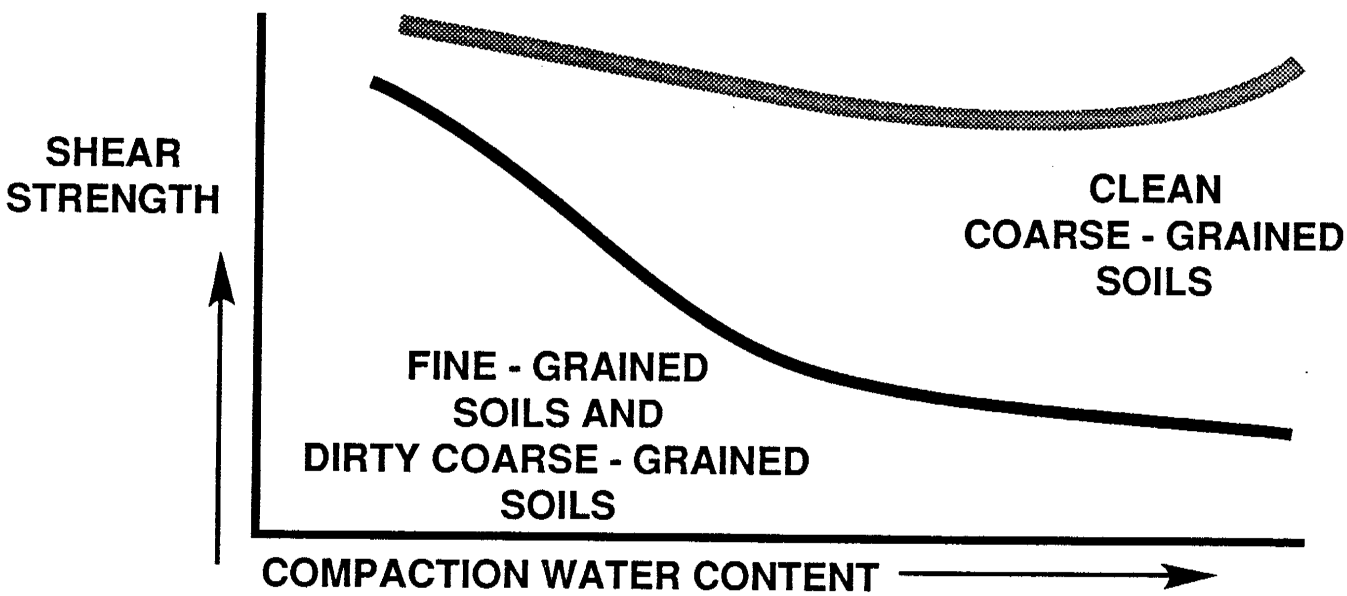


Figure 5.4

EFFECT OF COMPACTION ON ENGINEERING PROPERTIES
CONSOLIDATION POTENTIAL

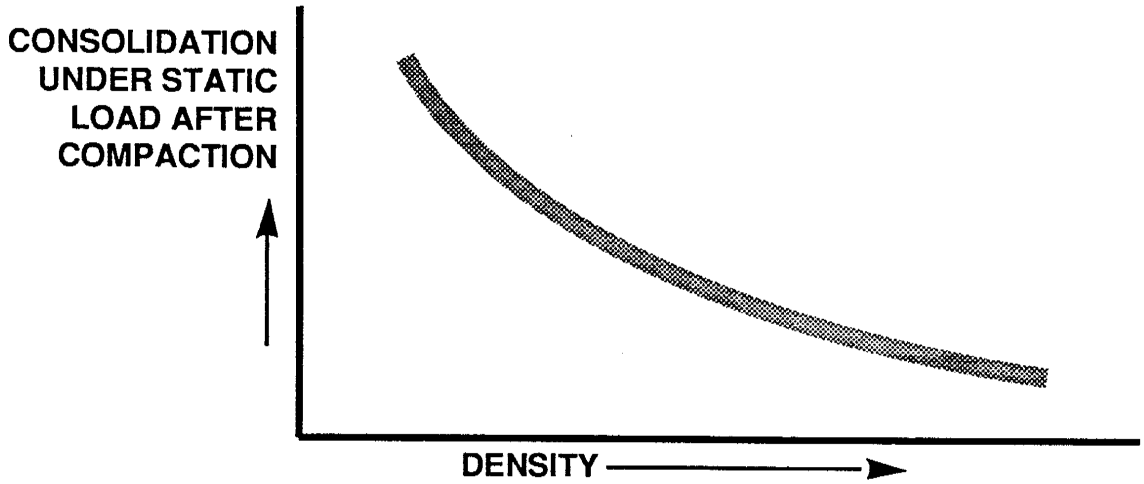


Figure 5.5

EFFECT OF COMPACTION WATER CONTENT ON ENGINEERING PROPERTIES
CONSOLIDATION POTENTIAL

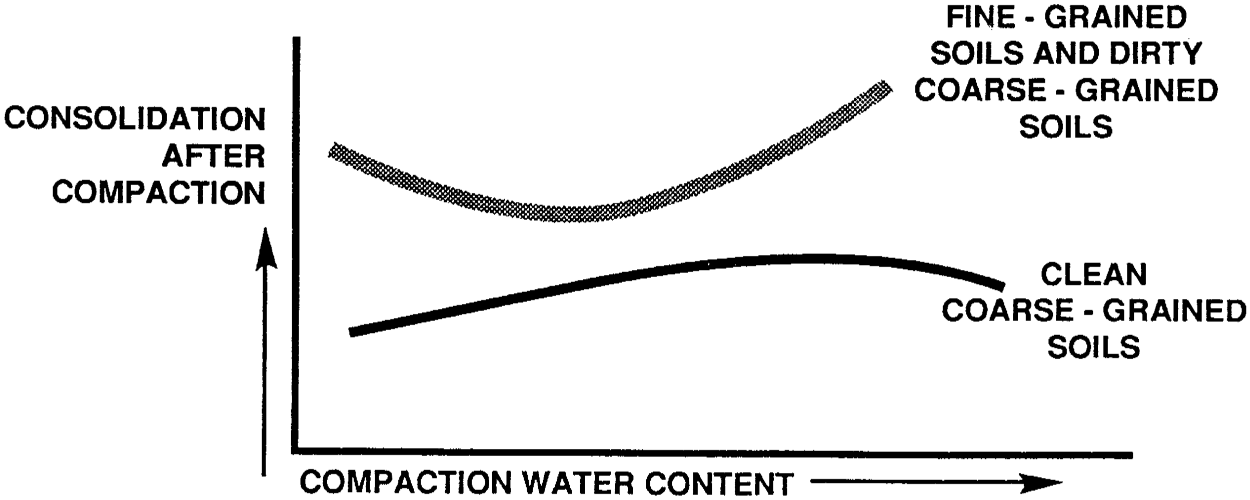


Figure 5.6

EFFECT OF COMPACTION ON ENGINEERING PROPERTIES

PERMEABILITY

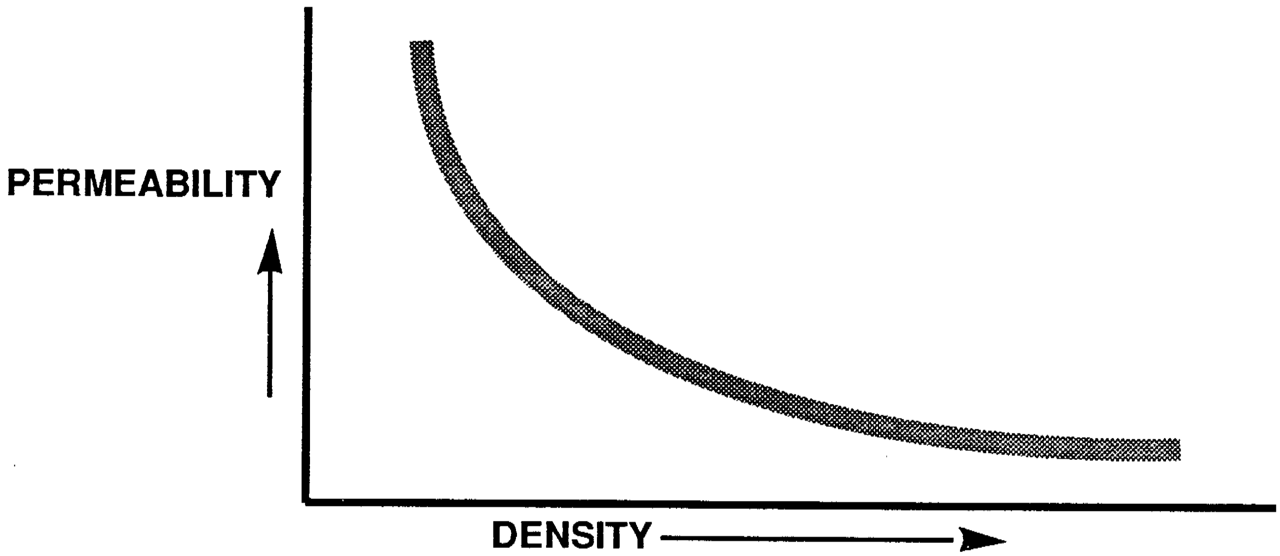


Figure 5.7

EFFECT OF COMPACTION WATER CONTENT ON ENGINEERING PROPERTIES

PERMEABILITY

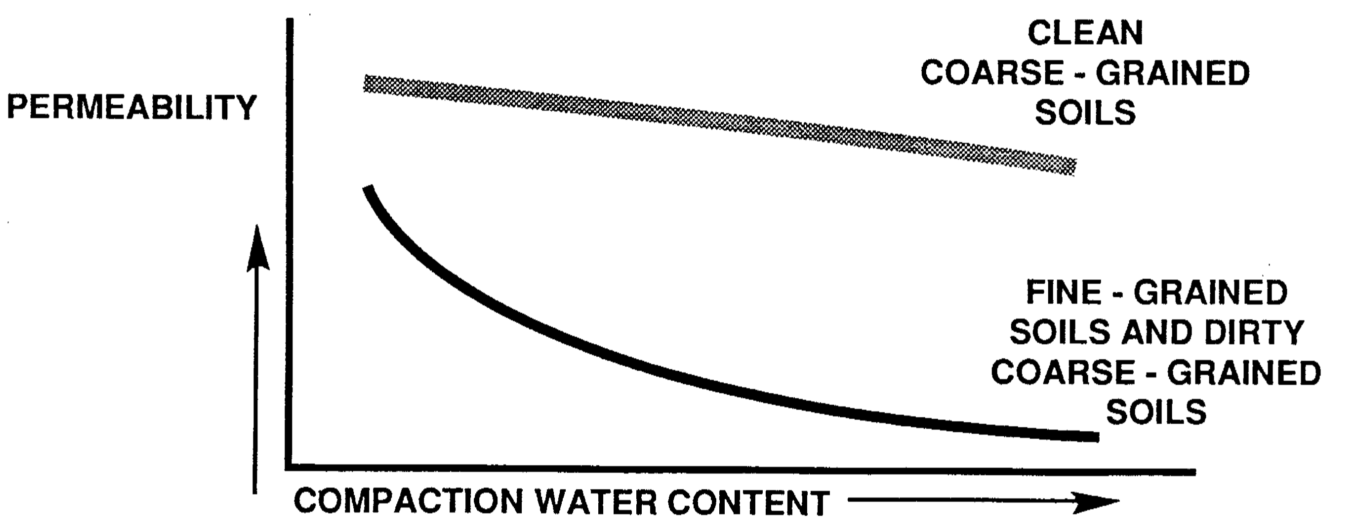


Figure 5.8

EFFECT OF COMPACTION WATER CONTENT ON ENGINEERING PROPERTIES

SHRINK - SWELL

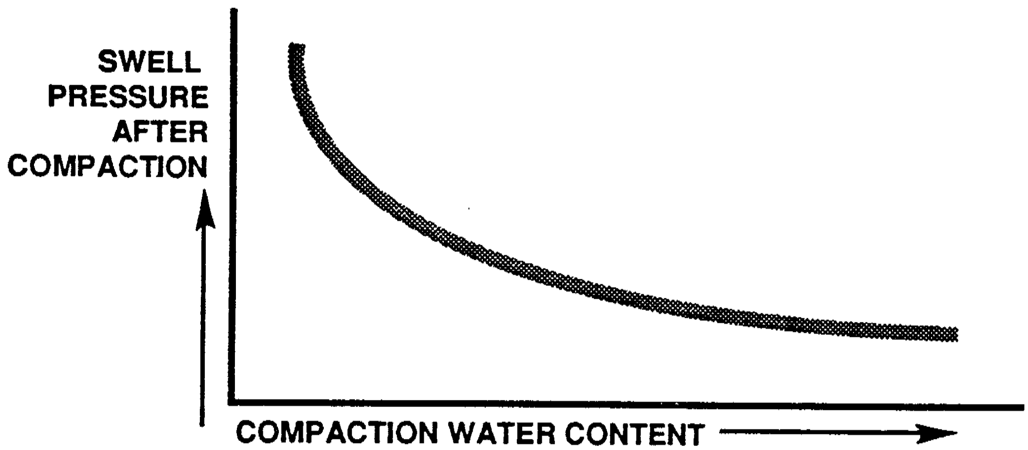


Figure 5.9

EFFECT OF COMPACTION WATER CONTENT ON ENGINEERING PROPERTIES

SHRINK - SWELL (CONT.)

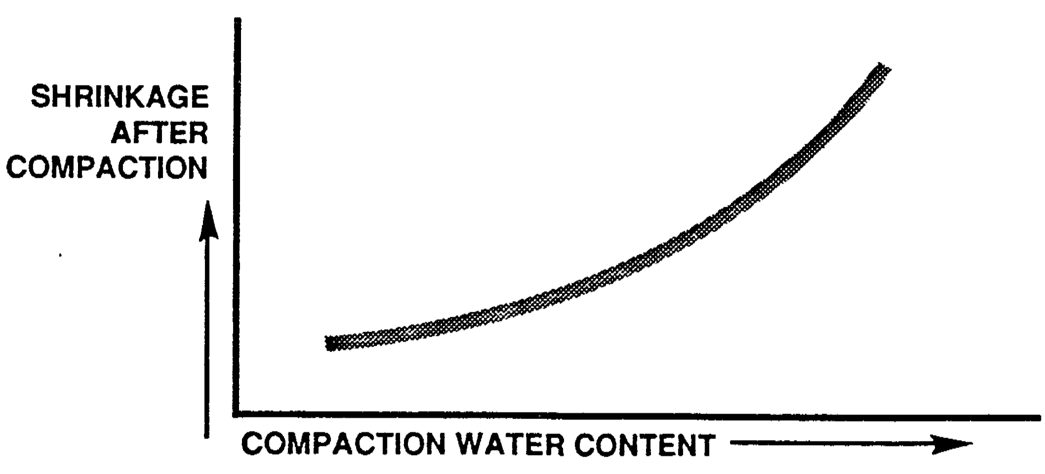


Figure 5.10

EFFECT OF COMPACTION ON ENGINEERING PROPERTIES
FLEXIBILITY

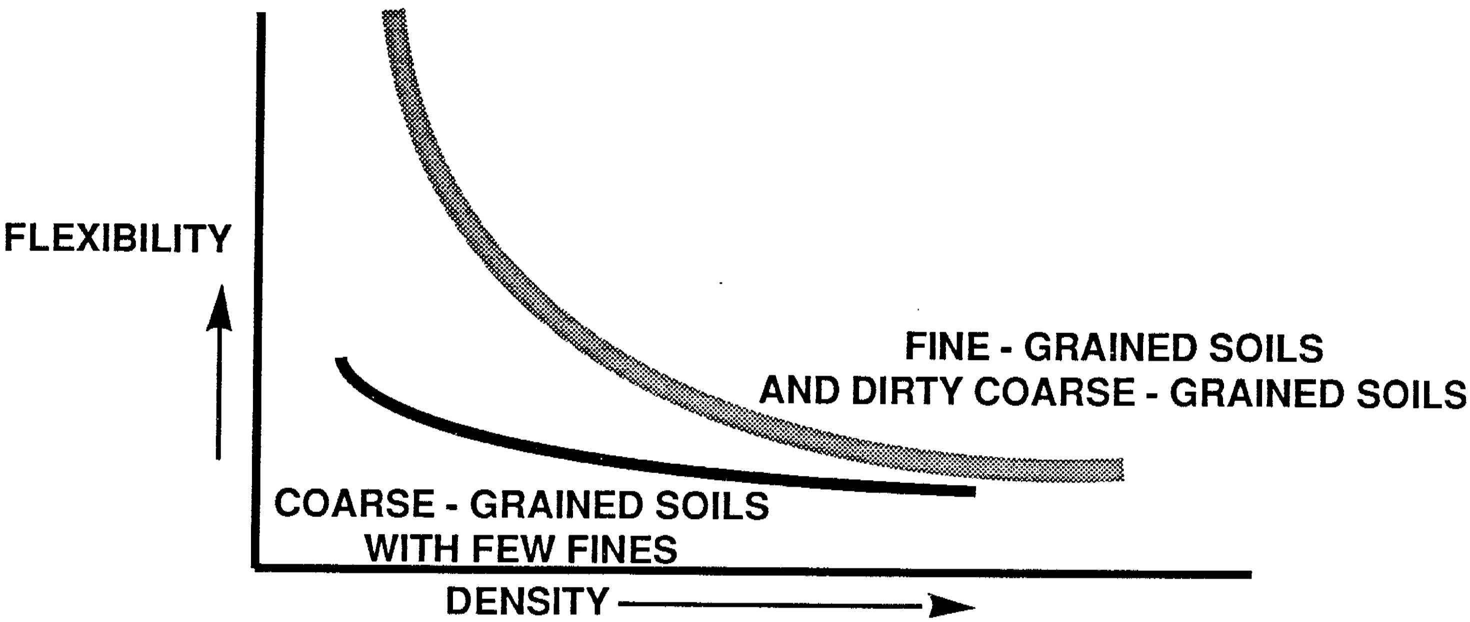
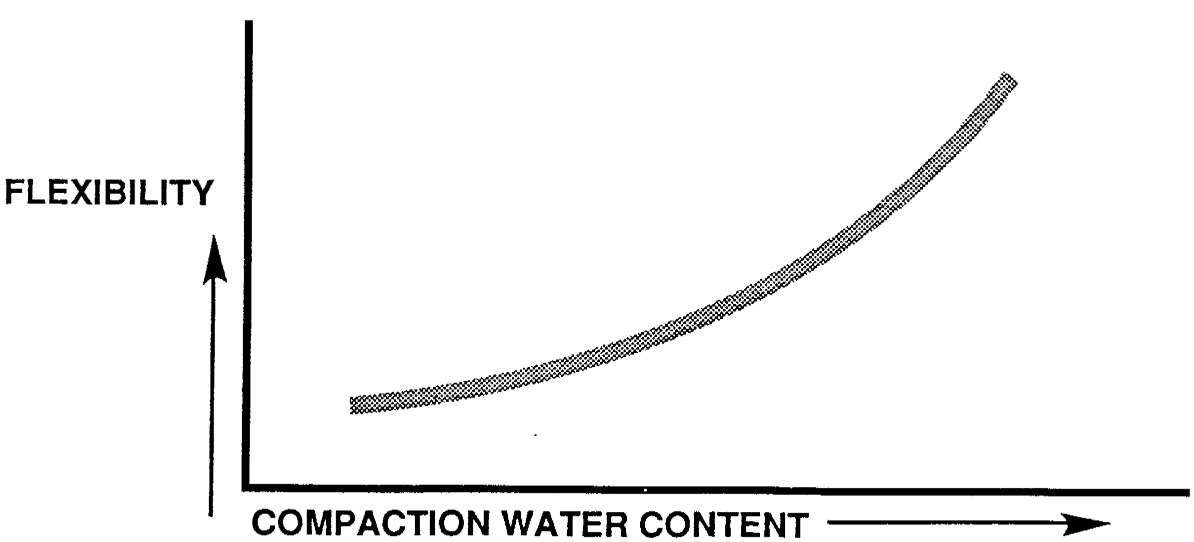


Figure 5.11

EFFECT OF COMPACTION WATER CONTENT ON ENGINEERING PROPERTIES
FLEXIBILITY



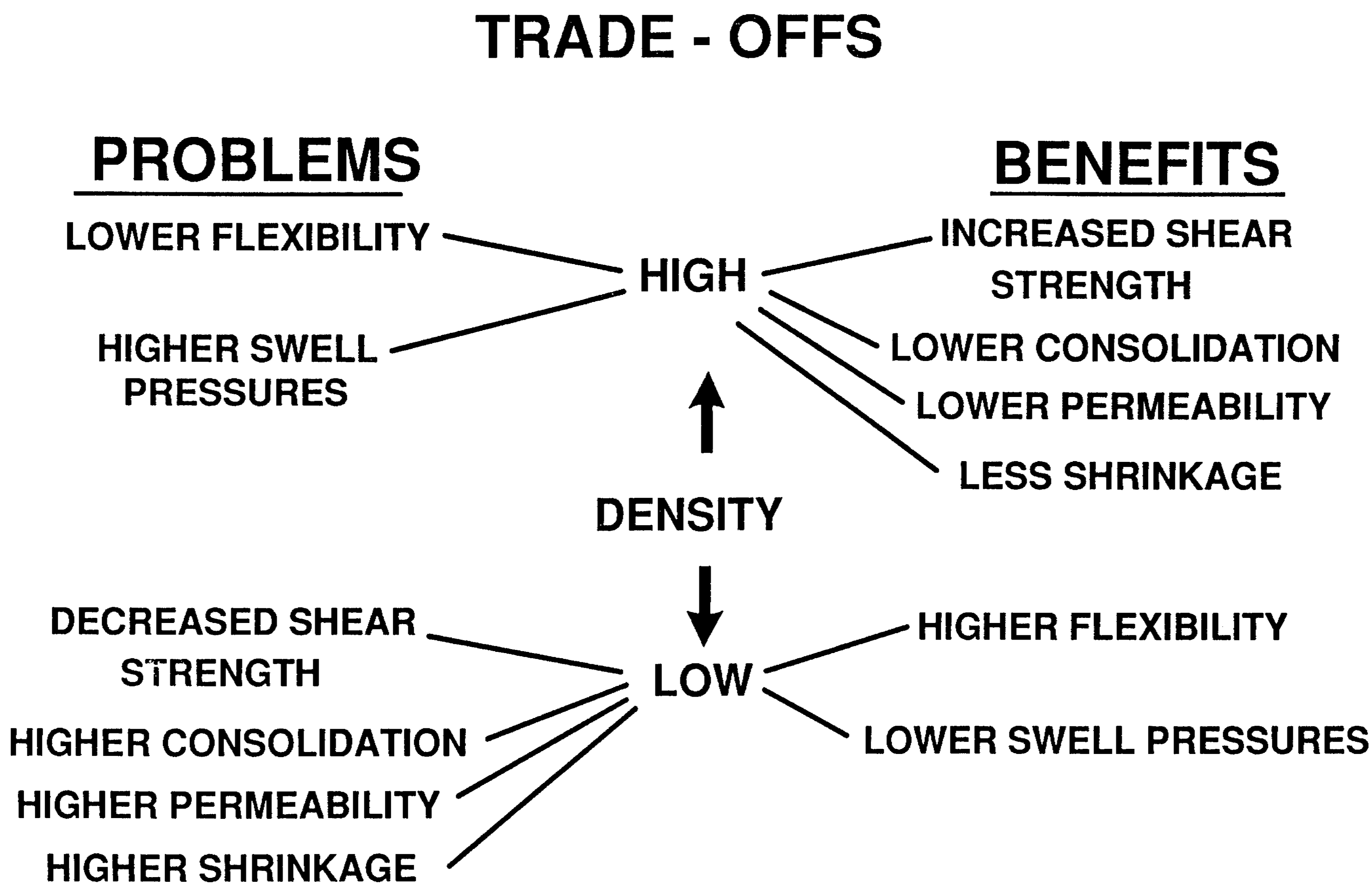

TRADE - OFFS
PROBLEMS
BENEFITS
LOWER FLEXIBILITY
HIGH
INCREASED SHEAR STRENGTH
HIGHER SWELL PRESSURES
LOWER CONSOLIDATION
LOWER PERMEABILITY
LESS SHRINKAGE
DENSITY
DECREASED SHEAR STRENGTH
LOW
HIGHER FLEXIBILITY
HIGHER CONSOLIDATION
LOWER SWELL PRESSURES
HIGHER PERMEABILITY
HIGHER SHRINKAGE

Figure 5.12

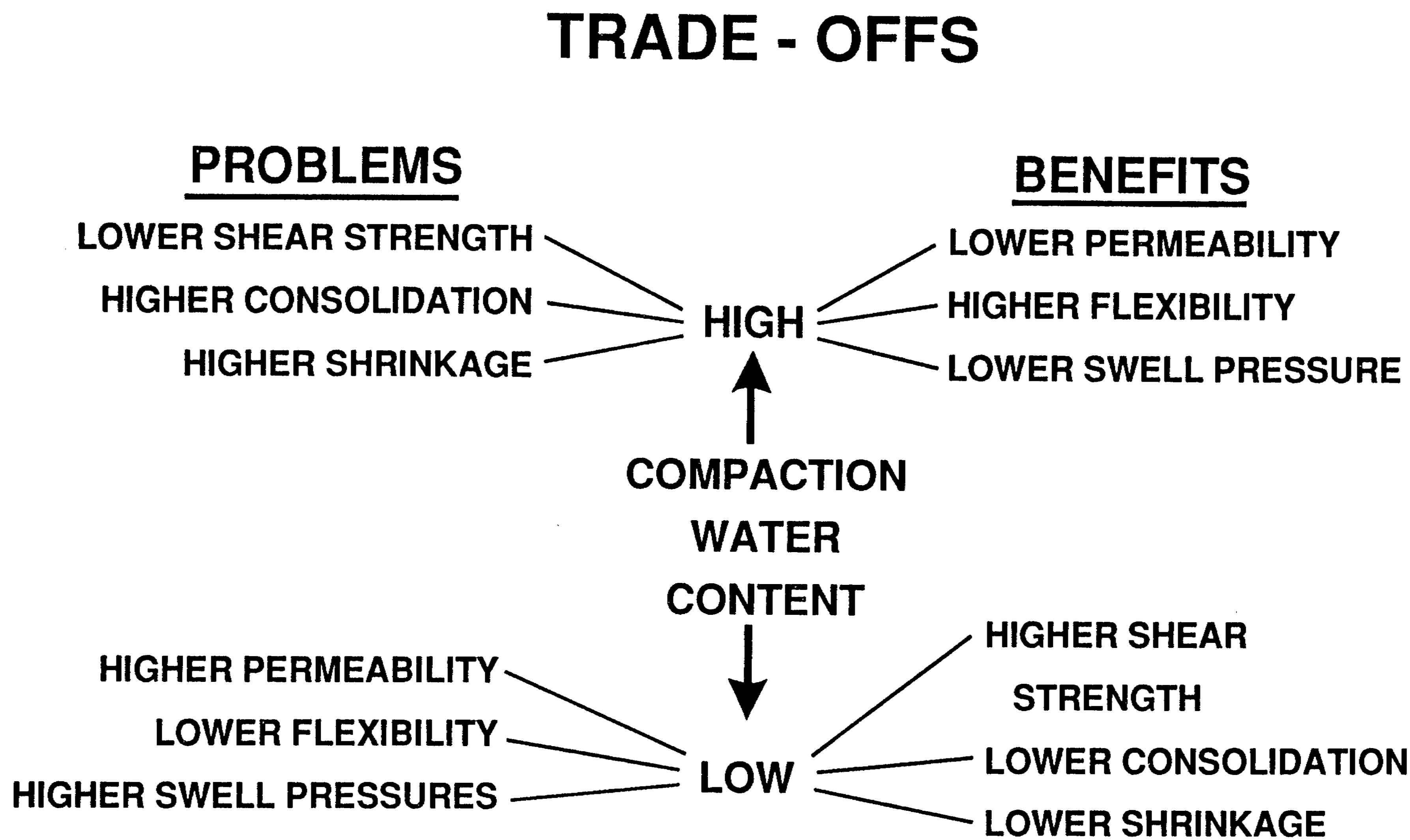

TRADE - OFFS
PROBLEMS
LOWER SHEAR STRENGTH
HIGHER CONSOLIDATION
HIGHER SHRINKAGE
BENEFITS
LOWER PERMEABILITY
HIGHER FLEXIBILITY
LOWER SWELL PRESSURE
HIGH
COMPACTION
WATER
CONTENT
LOW
HIGHER PERMEABILITY
LOWER FLEXIBILITY
HIGHER SWELL PRESSURES
HIGHER SHEAR
STRENGTH
LOWER CONSOLIDATION
LOWER SHRINKAGE

Figure 5.13

ACTIVITY 6 - FACTORS AFFECTING THE COMPACTION CHARACTERISTICS OF SOILS

Three factors determine the compaction characteristics of a soil. They are:

I. The soil characteristics.
II. The water content at which the soil is compacted.
III. The type and amount of energy applied in compaction.

In discussing each of the factors affecting compaction characteristic, it is convenient to group soils according to their Unified Soil Classification System groupings. In following discussions for each group of soils, the importance of soil characteristics and water content on compaction characteristics are covered in detail. More detail is given on the effect of energy in the next Activity.

Three soil characteristics may be listed which affect a soil's compaction. They are:

A. Grain-size.
B. Size and distribution of void spaces.
C. Electro-chemical properties.

In the following discussions of soil groups, the importance of these factors is covered in detail.

The first group of soils to be discussed are the relatively clean sands and gravels. Recal that these soils have 12 percent or fewer fines. The following classifications are included:

GP, GW, SP, SW, GP-GM, SP-SM, GP-GC, SP-SC, GW-GM, SW-SM, GW-GC, and SW-SC

For this group of soils, the electro-chemical properties are relatively unimportant. Electro-chemical properties apply primarily to silt and clay fines, and are discussed later. These soil classifications have so few fines that this soil property is of little importance. The main soil characteristics affecting compaction of these soil types are the grain-size and the size and distribution of the voids in the samples.

The grain-size of the soil and the size and distribution of the voids in these soils is important because of the presence of surface tension forces. These forces exist in moist coarse-grained soils due to the water films between the particles. These forces permit a sand castle to be constructed of clean sands with no cohesion between its particles. These forces are most powerful for finer sands which are poorly graded. They are almost non-existent in coarse gravels.

One way to overcome these forces which tend to resist compaction is to flood the soil being compacted. Commonly, when compacting fine, clean sands, the Soil Conservation Service requires thorough wetting of the soils during compaction to destroy the surface tension forces and reduce the tendency of the sands to bulk or increase in volume when placed. Flooding destroys the surface tension forces, just as a tide melts away a sand castle.

CONTINUE TO THE NEXT PAGE

ACTIVITY 6 - Continued

The most effective type of energy application for these soil types is vibratory. Vibration also is helpful in destroying surface tension forces, thus permitting compaction. Vibratory energy is much more effective for these soil types than static load application or kneading compaction. Types of equipment that apply vibratory energy are smooth-wheeled vibratory rollers and crawler tractor treads.

Generally, the smaller the void space in the soil, the more powerful are the surface tension forces. Therefore, the more difficult soils to compact are the fine, poorly graded sands, classifying as SP. In well-graded sands, the wide distribution of particle sizes results in much fewer voids, and the sand is inherently more dense than a poorly graded sand. Gravels have much larger voids generally than sands, and therefore the surface tension forces are much less. This is summarized in Figure 6.1, p. 30.

The next soil group to be discussed are the fine-grained soils. The following Unified Classifications are included:

CL, ML, CL-ML, CH, MH, OL, and OH

These soils consist of various percentages of silt and clay fines, together with lesser amounts of sands and gravels. The most important factor affecting compaction of these soils is the electro-chemical properties of the fine particles. Silt size particles are relatively inert, and the soil classifications which are predominated by silt are less affected, such as the ML and CL-ML classifications.

Soils with a high percentage of clay, where the clay particles have a high electrical charge are strongly affected by these electrically charged particles. Clays with a finer structure and higher electrical charge, such as montmorillonite, are the most affected. Clays with a more coarse lattice structure and less electrical charge, such as kaolinite, are less affected.

Clay particles have a high attraction to water, and to each other. They can only be compacted over a narrow range of water contents effectively. At very low water contents there is insufficient water for lubrication and to generate the attraction of the particles for one another. At very high water contents, the soils are difficult to compact, because expelling water from the voids is difficult. Due to the small size of the voids in clays, permeability is low, and expelling water is very slow.

Generally speaking, the higher the liquid limit, and the higher the plasticity index, the more difficult a fine-grained soil is to compact, and the more important water content is to effective compaction.

The most effective type of energy application for these soils is kneading action. Kneading is necessary to destroy the bonds of the particles and permit rearrangement necessary for densification. A tamping roller is the only type of equipment that effectively applies this type of energy. Some fine-grained soils with very low plasticity fines, such as the ML classification, may be effectively compacted with pnuematic rollers, but most fine-grained soils require tamping rollers.

CONTINUE TO THE NEXT PAGE

ACTIVITY 6 - Continued

The final soil group to be discussed are the dirty, coarse-grained soils. The following Unified Soil Classification System Groups are included:

GC, SC, GM, SM, GC-GM, SC-SM

Recall that these soil groups may contain anywhere from 13 to 49 percent fines. The amount of fines and the type of fines are probably the most important influence on the compaction of these soils. Although the size of the soil grains and the size and distribution of voids in the soil are important, the presence of the fines in the voids is a more important factor. Depending on whether the fines are non-plastic or plastic, water content may be very important in the ease of compaction. For low fines content with silty fines, however, suface tension forces may be highly significant, and flooding to permit compaction may be advisable.

START THE TAPE WHEN YOU HAVE FINISHED

SURFACE TENSION FORCES AND EASE OF COMPACTION

SURFACE TENSION	Soil		EASE OF COMPACTION
HIGH ↑	Fine Poorly Graded Sands	- SP	↑ DIFFICULT
	Fine Well Graded Sands	- SW	
	Fine Poorly Graded Gravels	- GP	
	Coarse Poorly Graded Sands	- SP	
	Fine Well Graded Gravels	- GW	
	Coarse Well Graded Sands	- SW	
LOW ↓	Coarse Well Graded Gravels	- GW	EASY ↓

ACTIVITY 7 - FACTORS AFFECTING COMPACTION - III ENERGY

One of the three factors affecting compaction of soil is the amount and type of energy applied to the soil mass. This energy is also called compactive effort. Factors that affect the amount of energy delivered to a soil mass in compaction are:

A. Thickness of soil layer being compacted, often referred to as lift thickness.

B. Size and type of equipment. Size may be expressed in total weight of the equipment or in terms of contact pressure of the equipment tires, feet, or treads on the fill surface.

C. Speed of operation of the equipment over the surface, and in the case of vibratory equipment, the frequency of vibration of the exciting mechanism on the equipment.

Slower speed of operation of equipment is beneficial on fine-grained, plastic soil. Faster speeds are acceptable on sands in thin lifts and other coarse-grained soil placed in thicker lifts.

D. Number of passes of equipment over the fill surface. Equipment with narrow contact surfaces such as bulldozers may have to traverse a fill several times just to get one coverage of the treads over the fill surface; other equipment such as smooth wheeled steel rollers exert uniform pressure over the entire machine area. Normally, each pass of equipment over a fill will produce additional compaction, but a point of diminishing returns is reached for most equipment after four to six passes.

Specifications should also contain provisions for scarifying between lifts. The aim of this is to obtain better bonding of the successive lifts in a fill.

Typical specifications for equipment control of compaction are:

Tamping roller - 4 passes with contact pressure of 450 psi, towed at a minimum speed of 4 mph with a maximum 6-inch loose lift thickness.

Pneumatic roller - 4 passes with a wheel load of at least 22,000 pounds and a tire pressure of 100 psi, towed at a speed of at least 4 mph with loose lift thickness of 12 inches.

Crawler tractor weighing at least 50 tons - 6 passes with a minimum tread contact pressure of 10 psi. Maximum loose lift thickness of 12 inches.

Smooth wheeled vibratory roller - 4 passes with a minimum weight of 50 tons and a vibration frequency of at least 2,000 cycles per second. The contact pressure shall be at least 10 pounds per square inch.

Soils may be compacted with a variety of types of equipment. If compaction is to be efficient, the appropriate equipment must be selected. The most important factor in determining the suitable type of equipment is the kind of

CONTINUE TO THE NEXT PAGE

soil to be compacted. Using machinery and operation techniques not appropriate for the soil to be compacted is inefficient and will also probably not result in a desirable fill product.

Similar soils are grouped below with a discussion of the most effective means of compacting each group, and the importance of water content upon compaction.

Relatively Clean Sands and Gravels (less than 15% fines)

The Unified Soil Classifications included in this group:
GP GW SP SW GP-GM SP-SM GW-GM SW-SM GP-GC SP-SC GW-GC SW-SC

These soils are compacted best with equipment that has vibratory action. Significant static load is also effective. Compaction is most efficiently accomplished at either low or high water content. Usually, two to three passes of equipment coverage is sufficient to produce a desirable product for SCS structures.

Poorly graded, finer sands are difficult to compact at intermediate water contents and should be compacted either dry or thoroughly wet. Water content is less critical for well-graded soils because their density is inherently higher. Use of high water content is inadvisable for soils that have higher fines contents.

Loose lift thickness of 12 to 15 inches can usually be compacted with good results.

These soils can also be compacted in-place, as well as after transporting to a fill area. In-place compaction is usually done for foundations of structures when excavating and re-compacting the deposit is less economical than treating the soil in place. Special equipment has been developed for this purpose. One type of equipment consists of rods that can be inserted into the deposit and then vibrated. Another method of treating these soils in place is the use of large weights that are dropped onto the surface of the deposit from a great height. The impact of the weight produces vibration and densification of the deposit. Blasting has also been used successfully for densifying these soils in the field.

CONTINUE TO THE NEXT PAGE

ACTIVITY 7 - Continued

<u>Fine-grained, plastic soils and dirty coarse-grained soils that have plastic fines</u>

The Unified Soil Classifications included in this group:

CH CL MH SC GC

These soils are best compacted with kneading type compactors, specifically tamping rollers. No other type of equipment will efficiently compact these soils. These soils must be spread in relatively thin layers, usually 9 to 12 inches in depth. Water content of the soils when compacted is critical in how efficiently compaction is accomplished. Usually, four to eight passes of the proper size roller will produce an acceptable fill for most SCS structures.

<u>Fine-grained, low plasticity soils and fine sands and gravels that have low plasticity fines</u>.

The Unified Soil Classification included in this group:

ML GM SM CL-ML GC-SM SC-SM

The best type of equipment for compaction of these soils may be a heavy, rubber-tired roller or a heavy wobbly-wheeled roller. A tamping roller may be the best suited equipment for soils of this group with a high percentage of fines, especially the ML and CL-ML groups. Water content must be ideal for most efficient compaction. Compaction is most effective when layer thicknesses are 6 to 9 inches. Usually four to eight passes of equipment is sufficient to produce an acceptable fill for SCS structures.

The tables on the following pages contain generalized information on the compaction characteristics of various soil groups. Some of the tables use the Unified System for grouping, and some tables use a more generalized grouping of soils. You should carefully study these tables before continuing with this Module.

START THE TAPE AFTER YOU HAVE STUDIED THE TABLES AND FIGURES ON PAGES 34-39

ACTIVITY 7
Summary of Compaction Characteristics of Unified Soil Classes

USCS CLASS	RELATIVE EASE OF COMPACTION	BEST SUITED EQUIPMENT	COMPACTED LIFT THICKNESS	IMPORTANCE OF WATER CONTENT CONTROL
GW	Very Easy	Vibratory Roller Crawler Tractor	10 -12 Inches	Either Dry Or Saturated
GP	Good To Excellent	Vibratory Roller Crawler Tractor	10 - 12 Inches	Either Dry Or Saturated
GM	Good With Close Control	Rubber-Tired Or Tamping Roller	6 - 8 Inches	Fairly Important
GC	Good	Tamping Or Rubber-Tired Roller	6 Inches	Very Important
SW	Excellent	Crawler Tractor Vibratory Roller	10 - 12 Inches	Either Dry Or Saturated
SP	Fair	Crawler Tractor Vibratory Roller	10 - 12 Inches	Either Dry Or Saturated
SM	Fair	Rubber-Tired Or Tamping Roller	6 - 8 Inches	Important
SC	Good	Tamping Or Rubber-Tired Roller	6 Inches	Very Important

Continued to next page

ACTIVITY 7 (continued)
Summary of Compaction Characteristics of Unified Soil Classes

USCS CLASS	RELATIVE EASE OF COMPACTION	BEST SUITED EQUIPMENT	COMPACTED LIFT THICKNESS	IMPORTANCE OF WATER CONTENT CONTROL
ML	Fair	Tamping Roller	6 Inches	Important
CL	Good To Fair	Tamping Roller	6 Inches	Very Important
OL	Fair	Tamping Roller	6 Inches	Important
MH	Poor	Tamping Roller	6 Inches	Very Important
CH	Very Poor	Tamping Roller	6 Inches	Critical
OH	Very Poor	Tamping Roller	6 Inches	Important
Pt	Not Suitable			

ACTIVITY 7
Summary of Compaction Characteristics of Unified Soil Classes

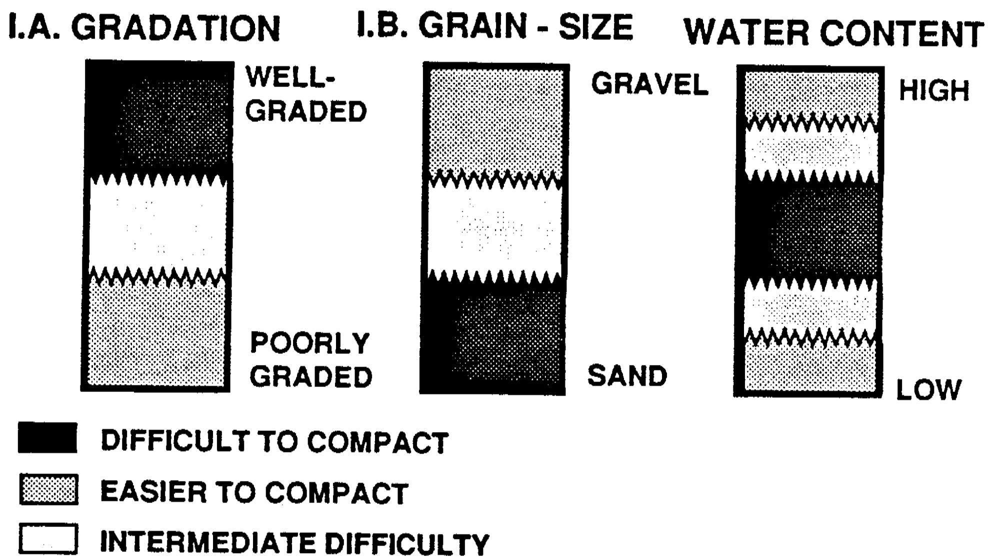
UNIFIED CLASS	PREFERRED TYPE OF EQUIPMENT	NUMBER OF PASSES	TYPICAL DRY UNIT WEIGHTS (PFC)	TYPICAL WATER CONTENTS (%)
GW	Crawler Tractor Vibratory Roller	3-4	125-135	9-12
GP	Crawler Tractor Vibratory Roller	3-4	115-125	12-16
GM	Rubber-Tired Tamping Roller	3-5	120-135	8-13
GC	Tamping Roller Rubber-Tired	6-8	115-130	9-14
SW	Crawler Tractor Vibratory Roller	3-4	110-130	10-18
SP	Crawler Tractor Vibratory Roller	3-4	100-120	13-22
SM	Rubber-Tired Tamping Roller	6-8	110-125	10-16
SC	Tamping Roller Rubber-Tired	4-6	105-125	10-18
ML	Tamping Roller	4-6	95-120	12-22
CL	Tamping Roller	4-6	95-120	12-22
MH	Tamping Roller	4-6	70-95	22-40

Continue to next page

ACTIVITY 7 (continued) Summary of Compaction Characteristics of Unified Soil Classes				
UNIFIED CLASS	PREFERRED TYPE OF EQUIPMENT	NUMBER OF PASSES	TYPICAL DRY UNIT WEIGHTS (PFC)	TYPICAL WATER CONTENTS (%)
CH	Tamping Roller	4-6	75-105	20-40
OL	Tamping Roller	4-6	80-100	20-32
OH	Tamping Roller	4-6	65-100	20-45
Pt	Not suitable for most fills - usually placed with draglines and little compaction			

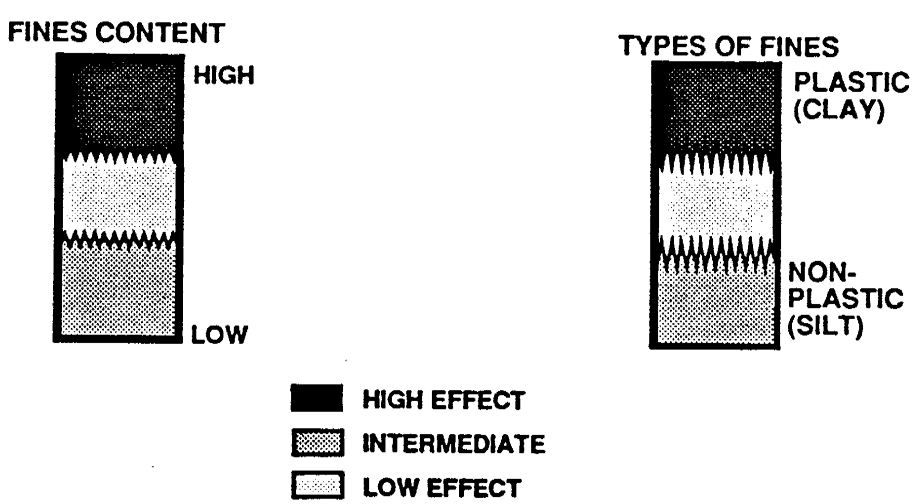
COMPACTION OF CLEAN COARSE - GRAINED SOILS SUMMARY

FACTOR I. SOIL TYPE



COMPACTION OF COARSE - GRAINED SOILS WITH FINES

FACTOR I.C. SOIL TYPE & ELECTRO - CHEMICAL FORCES

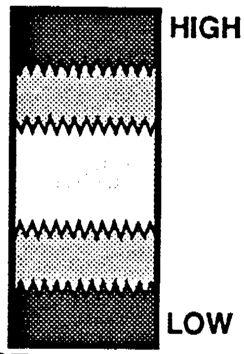


FACTORS AFFECTING COMPACTION OF SOILS WITH FINES

FACTOR II.

WATER CONTENT AT COMPACTION

WATER CONTENT



- DIFFICULT TO COMPACT
- EASIER TO COMPACT
- INTERMEDIATE DIFFICULTY

ACTIVITY 8 - REVIEW PROBLEMS

To test your understanding of the objectives in Part A, complete the following questions. If you have difficulty completing any questions, you should review the material involved before proceeding to the next part of the Module.

Match the definitions on the right with the terms on the left.

1. Compactive effort	A. The weight of soil solids per unit of volume.
2. Compacted lift thickness	B. The ability of a soil to deform without cracking.
3. Consolidation	C. The amount of energy applied to a soil mass.
4. Kneading compaction	D. The depth of soil after spreading and compaction.
5. Dry unit weight	E. The application of mechanical forces to a soil mass which results in densification of the soil mass.
6. Compaction	F. The primary action imparted by a tamping roller.
7. Flexibility	G. The gradual reduction in void space of a soil mass resulting from an increase in compressive stress.

Fill in the blanks for the following sentences:

1. The shear strength increase that usually results from the compaction of soil is a ______________________ effect of compaction. (beneficial/detrimental/supplemental)

2. Shear strengths of most fine-grained soils will be higher if the soils are compacted at ______________ water contents. (low/high/intermediate)

3. Relatively clean sands and gravels are compacted best with __________ rollers or ____________ tractors. (pneumatic/vibratory/tamping) ** (crawler/farm)

4. A ______________________ roller is one that has many tires and a ballast for load. (tamping/vibratory/pneumatic)

CONTINUE TO THE NEXT PAGE

ACTIVITY 8 - Continued

5. The flexibility of most soils is ____________________ by compacting at higher water contents. (unaffected/increased/decreased)

6. To reduce the swell potential of most soils you should compact them at ________________ water content. (low/high/intermediate)

7. The three major factors affecting compaction are ______________________ ______________________, and ______________________________.

8. The most efficient type of equipment for compacting fine-grained, plastic soils is a __________________. (tamping roller/pneumatic roller/scraper)

9. Compacted soil is usually less permeable because the __________________ is reduced. (void space/density/shear strength)

10. (Well-graded/Poorly graded) ___________________________ soil has higher tension forces, given a comparable water content for both.

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

1. Decreased consolidation potential is a desirable effect of the compaction of the fill for a foundation for a concrete structure. _____

2. Clean, coarse-grained soils are difficult to compact. _____

3. Density and dry unit weight are equivalent for practical purposes. _____

4. Compaction of plastic clays at low water contents at a given density substantially reduces their swell potential. _____

5. The dry unit weight of a soil mass is calculated from known values of its specific gravity and water content. _____

6. Thicker lifts are permissible for fine-grained, plastic soils than for clean, coarse-grained soils. _____

7. Well-graded coarse-grained soils cannot be compacted to as high dry unit weights as can poorly graded coarse-grained soils. _____

CONTINUE TO THE NEXT PAGE

ACTIVITY 8 - Continued

8. Four to six passes of a tamping roller per lift of soil are usually adequate to compact soil for most fills. _____

9. Vibratory rollers compact soil primarily by a kneading action. _____

10. The water content at which a GP soil is compacted is critical. _____

11. Surface tension forces are minor in a clean, fine, poorly graded sand at an intermediate water content. _____

12. Highly plastic clays are difficult to compact because of the high attraction of the clay minerals to water and because of the small void sizes. _____

13. Surface tension forces are low at both low and high water contents in clean, coarse-grained soils. _____

If you have difficulty in completing the Activity, or wish to check your answers to the problems, the answers are shown on the following page.

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

ACTIVITY 8 - Solution

Matching questions:

A-5, B-7, C-1, D-2, E-6, F-4, G-3

Fill in blank question:

1. beneficial
2. lower
3. vibratory/crawler
4. pneumatic
5. increased
6. high
7. kind of soil, water content, energy applied
8. tamping roller
9. void space
10. Well-graded

True/false questions:

1. T	6. F	11. F
2. F	7. F	12. T
3. T	8. T	13. T
4. F	9. F	
5. F	IO. F	

START THE TAPE WHEN YOU HAVE FINISHED

APPENDIX

SCS Logo

ENG-SOIL MECHANICS TRAINING SERIES--
BASIC SOIL PROPERTIES
MODULE 5 - COMPACTION
PART A
INTRODUCTION, DEFINITIONS, AND CONCEPTS

1

-

Soil Mechanics
Level II
Module 5

2

Soil Mechanics Module 5 covers compaction of soils for engineering uses. The standard compaction tests and applications of the test results are covered. Soil compaction is important in many Soil Conservation Service structures.

-

This module consists of five parts:

Module 5

Part A reviews terms and definitions, factors affecting compaction of soils, and the purposes of compacting soils.

Part B explains compaction test procedures used for soils that have a low gravel content and significant fines content.

3

Part C explains compaction test procedures used for soils that have a high gravel content and significant fines content.

Part D explains the tests for determining compaction characteristics of coarse-grained soils that have less than 12 percent fines.

Part E discusses the evaluation of compaction test data and methods of estimating compaction test data for fine-grained soils.

-

Objective 1

At the completion of Part A you will be able to meet the following objectives:

4

Objective 1:

Define the terms, symbols, and equations used with the compaction of soils.

-

Objective 2 5	Objective 2: State from memory how the engineering properties of the major Unified Soil Classification System groups are affected by compaction. State generally whether each effect is beneficial or harmful. -
Objective 3 6	Objective 3: List the three primary factors that affect the compaction characteristics of a soil. -
Objective 4 7	Objective 4: Describe the general compaction characteristics and most appropriate construction equipment for each major Unified Soil Classification System group. -
Activity 1 8	These objectives are listed in your Study Guide, Part A, Activity 1. Stop the tape player and carefully study the Activity before continuing. -
Terms/Definitions 9	First, the terms, symbols, and definitions needed to explain compaction will be discussed. -
Definition and Compaction 10	Compaction is the densification of a soil by mechanical means. -

Expulsion of Air

11

This densification results primarily from the expulsion of air from the soil mass. However, in relatively clean sands and gravels, and some non-plastic silts, water may also be expelled from the soil pores. In either case, the soil solids are more closely packed, and the density of the mass increases, since soil solids are much heavier than air or water.

Compaction = Consolidation

12

The terms compaction and consolidation should not be confused.

Contrast Compaction and Consolidation

13

Consolidation occurs when a static load is placed upon a soil mass and air or water, or both, are expelled from the voids of the soil mass caused by the load application. Compaction occurs when a dynamic load is applied to a soil mass. In compaction, substantial re-arrangement of the soil particles occurs, but in consolidation, particle re-arrangement is minimal. Consolidation is time-dependent, whereas compaction occurs rather instanteously.

Activity 2

14

Activity 2, Part A, covers the definitions of compaction and consolidation in more detail. Examples and problems are given. Stop the tape player and complete the Activity.

Definitions Borrow Area Fill

15

In construction of a compacted fill, soils are usually excavated at one location, transported to another location, spread in thin layers, and then compacted. The site where the soils are obtained is the borrow area. The compacted soils are called the fill.

Slide of Earth Dam

16

Examples of structures constructed with compacted soil are earthen embankments for flood prevention and water storage, highway fills, and levees for containing stream flows.

Slide of Highway Subgrade 17	Examples of compacted fills used as foundations for other structures are a compacted soil pad under a building, or a compacted soil base for a concrete or asphalt highway.
Purpose of Compaction 18	Soil that is not compacted usually has poor engineering properties. The purpose of compaction is to improve the soil and produce a product that has known engineering properties. Details on the effects of compaction on engineering properties are given later in the Module.
Types of Mechanical Forces 19	The application of mechanical forces to compact soil may be grouped into several categories as follows: 1. Static load. 2. Kneading action. 3. Vibratory action. 4. Impact loading. 5. Combinations of one or more of the above methods.
(4 slides) 20 21 22 23	Types of equipment that impart static loads for compaction include: 1. loaded scrapers, 2. smooth wheeled steel drum rollers, 3. heavily loaded rubber tired rollers (pneumatic rollers) that have closely spaced rollers. 4. Crawler tractors.
(1 slide) 24	Kneading compaction is usually accomplished with a tamping roller.

Examples of vibratory compaction equipment are:

(3 slides)

25 26 27

1. Vibratory rollers with a smooth steel drum,
2. A crawler tractor,
3. A vibrating rod - used to compact soil in place.

-

Impact compaction may be accomplished by:

(3 slides)

28 29 30

1. Dropping heavy weights from great heights onto a soil surface.
2. Hand-held, motorized compactors,
3. Hand tamping.

-

Combination of Forces

31

Most equipment used for compacting soil actually apply a combination of these methods of load application. For example, a crawler tractor or bulldozer applies static loading as well as vibratory load application to a soil. Tamping uses impact and kneading in combination.

-

Picture of Harvard Miniature Compaction Device

32

Laboratory equipment is often designed to simulate field load applications. This is a Harvard miniature compactor that simulates kneading compaction of soil specimens for laboratory tests.

-

ACTIVITY 3

33

Activity 3 summarizes the concepts just reviewed. It contains examples and discussion problems to test your understanding of these concepts. Stop the tape player and complete Activity 3 before continuing.

-

Volume-Weight Terms

Many of the terms and equations you learned in Module 4 - Volume-Weight Relations are used extensively in this Module. Some of the important terms you should know include:

Dry Unit Weight
Wet Unit Weight
Water Content
Saturated Water Content
34 Specific Gravity

-

ACTIVITY 4

To review your knowledge of these definitions and to review important equations that are used in this Module from the Volume-Weight Module, complete Activity 4 at this time. If you have trouble with this Activity, you should review Module
35 4 before continuing.

-

Engineering Properties Affected by Compaction

36

Compaction densifies a soil mass. Most of the important properties of a soil are changed by this densification. The primary engineering properties affected are shear strength, consolidation, and permeability. Other important properties that are affected include flexibility and shrink swell.

-

Effect of Compaction Water Content on Engineering Properties

37

The water content at which soils are compacted may also strongly affect the resulting engineering properties of the compacted soil. The effects of densification on soil properties will be discussed first, and then the effects of compaction water content are discussed last.

-

Effect of Compaction on Shear Strength

38

The shear strength of soils is increased by compaction or densification. The effect of densification on shear strength is usually more pronounced in fine-grained soils than in cleaner, coarse-grained soils.

-

Other Factors Affect Shear Strength

39

You should understand that other factors also affect the strength of soils in addition to unit weight. For example, clean angular sand usually has a higher shear strength than sand that has rounded particles even though both are compacted to the same unit weight. For a given soil, however, the shear strength will be increased as the soil is compacted to a higher unit weight at the same water content.

-

Effect of Compaction on Consolidation Potential

40

The consolidation or settlement potential of a soil is decreased by compaction. The primary reason many fills are compacted is to create a more suitable foundation for structures that cannot tolerate much settlement, such as buildings or rigid concrete structures. Excessive settlement could cause cracking or other distress in the structures.

-

Effect of Compaction on Permeability

41

Soils are also compacted to reduce permeability. Permeability is a measure of the soil's capacity to convey water through the pores of the soil mass. Compaction reduces the void space, making the pores smaller, so that less water can pass through the mass. For this reason, compacted fills are often used as dams and dikes to impound and retain water.

-

Definition of Flexibility

42

Flexibility is another property of soils that may be strongly affected by compaction. Flexibility is the ability of a soil to deform without cracking. Flexibility is important for fills constructed on yielding foundations. This fill has cracked due to foundation settlement.

-

Effect of Compaction on Flexibility

43

Compaction usually reduces flexibility. Fine-grained soils and sands and gravel that have significant amounts of fines are most strongly affected. Flexibility of compacted fills constructed of these soils is decreased by compaction.

-

Definition of Shrink-swell

44

Shrink-swell is another soil property that may be strongly affected by compaction. Soils that have plastic fines are most affected. Shrink-swell is the decrease and increase in volume of a soil caused by alternately drying and wetting the soil. Shrinkage cracks and large pressures exerted in swelling soil can be serious engineering problems. Compaction generally increases swell pressures and decreases the shrinkage potential.

-

Effect of Compaction Water Content

45

Shrink-swell behavior of plastic fine-grained soils is strongly affected by the water content at which the soils are compacted. Other engineering properties are also affected by compaction water content. These properties are discussed next.

-

Effect of Water Content on Shear Strength

46

Usually, a soil compacted at a higher water content is weaker in shear strength than the same soil compacted to the same unit weight at a lower water content. This effect is more pronounced for silts and clays and sands and gravel that have significant fines content. The shear strength of clean sands and gravel is not drastically affected by the water content at which the soils are compacted.

-

Effect of Water Content on Consolidation

47

Most soils will consolidate more if they are compacted to a higher water content. The effect of water content on consolidation potential is more pronounced in fine-grained soils and dirty sands and gravel and less pronounced in clean, coarse-grained soils.

-

Effect of Water Content on Permeability

48

A soil compacted at a higher water content is usually less permeable than the same soil compacted at a lower water content. Again, this effect is more pronounced for fine-grained soils and less important for clean, coarse-grained soils.

-

Effect of Water Content on Swell

49

The shrink-swell behavior of susceptible soils is strongly affected by compaction water content. Susceptible soils may develop high swell pressures when subsequently saturated if compacted at a low water content.

-

Effect of Water Content on Shrinkage

50

These soils are also susceptible to shrinkage cracking if compacted at a high water content and then subsequently dried.

-

Effect of Water Content on Flexibility

51

Flexibility of fine-grained soils and dirty sands and gravel is increased by compaction at a higher water content. This may be an important consideration for fills constructed on yielding foundations. Clean, coarse-grained soils have little flexibility.

-

TRADEOFFS

52

A designer must consider all of the effects of compaction and compaction water content on the resulting properties of soils used in a fill. Although a high degree of compaction may produce increased shear strengths and lower consolidation potential, flexibility and swell behavior of the fill may be adversely affected. These considerations are often referred to as trade-offs in the design of a compacted fill.

-

OTHER TRADEOFFS

53

Other trade-offs are involved in selection of compaction water content. Higher compaction water content will create more flexible soils, but the fill will have lower shear strength and higher consolidation potential.

-

ACTIVITY 5

54

Activity 5 of your Study Guide covers the effects of densification and compaction water content on the engineering properties of several basic groups. Stop the player and study Activity 5 before continuing.

-

Factors Affecting Compaction of Soils

The three factors that determine the compaction properties of soils are as follows:

I. The kind of soil being compacted.
II. The water content at which the soil is being compacted.
55 III. The type and amount of energy applied to the soil.

Soil Properties Affecting Compaction

The kind of soil compacted strongly affects its compaction characteristics. The soil's properties that are most important include:

A. The grain-size of the soil.
B. The size and distribution of voids in the soil.
56 C. The electro-chemical properties of the soil.

Clean Coarse-Grained Soil Groups

In discussing these factors, soils are grouped according to their Unified Soil Classification groupings. First, the relatively clean, coarse-grained soil groups, those that have twelve percent or less fines, are discussed.

57 This group includes the classes shown.

The two soil properties which are most important for clean, coarse-grained soils are the grain-size and size and distribution of the voids in the soils. The electro-chemical properties are not important, as these soils are largely inert. Electro-chemical properties will be covered later in discussion of fine-grained soils and dirty, coarse-grained
58 soils.

Some clean, coarse-grained soils, particularly fine, poorly graded sands, classifying as SP in the Unified System, are highly affected by a phenomenon known as surface tension. This picture shows a pyramid built of moist, clean, fine sands as you would find on a beach. The forces holding the sand together, permitting the structure to stand unsupported,
59 are called surface tension forces.

Surface tension forces are present where films of water exist
between soil particles. In clean, moist, fine-grained sands,
these films are so numerous that the total force created by
them is considerable, and difficult to overcome in compacting
60 the soils.

When the moist sand is flooded, all of the voids in the sand
become full of water, and no films between particles which
create surface tension are left. As a result, the sand
structure collapses. This principal is important in
61 compacting fine sands.

Flooding of clean sands prior to compaction is helpful in
achieving the greatest compaction with a given amount of
62 energy.

Bulking is the tendency of moist fine sands to maintain a
loose structure when placed. Bulking refers to the
increasing of the volume, or decreasing of the density.
Bulking is caused by surface tension forces which support a
loose structure in the loosely dumped sands. This photo
shows a calibrated cylinder into which loose, moist clean
sand has been dumped. As you can see, the sand occupies a
63 volume of about 500 cubic centimeters.

When this loose sand is flooded, the surface tension forces
are destroyed, and densification, or compaction, is easily
accomplished. Most of the densification that is attainable
occurs at the time the sand is flooded, although additional
vibration will cause additional densification. Note that
after flooding, the volume of the sand is now 330 cubic
64 centimeters.

This illustration summarizes the factors affecting compaction
of clean, coarse-grained soils. The more difficult soils of
this group to compact are fine, poorly graded sands. These
sands can only be effectively compacted at either very low or
nearly flooded water content conditions. Bulking at moist
conditions makes compaction much more difficult. Coarser
soils such as well graded gravels are relatively dense even
when loosely dumped, and vibration alone is usually effective
65 in densifying satisfactorily.

-

Compacting clean, coarse-grained soils is most effectively
done with vibratory rollers. The vibratory action helps to
break down the surface tension forces in the water films
between the particles, just as vibration of a bubble breaks
the bubble. Some coarse-grained soils can be effectively
66 compacted with crawler tractors which are heavy enough.

-

The next group of soils discussed are the dirty sands and
gravels, of the Unified Soil Classification System groups
67 shown.

-

In this group of soils, two types of forces may be present
which have to be considered in compaction. Dirty sands and
gravels may have both surface tension forces, and the
presence of clay fines may also contribute to forces between
the particles, referred to as electo-chemical forces. Water
68 content at compaction relates to both of these forces.

-

Clay fines in dirty sands and gravels may have powerful
internal forces. These forces are caused by the fact that
most clays are negatively charged, and they are attracted
69 strongly to water molecules.

-

Silt-size particles are not as electrically active as clay-size particles, but their small size, compared to sands,
70 results in high surface tension forces.

Soils with significant amounts of clay and silt fines are effectively compacted only within a narrow range of water contents. At very low water contents, there is insufficient water to lubricate the particles and permit rearrangement. At very high water contents, the soils can be compacted only
71 by expulsion of the water from the soil mass.

Expelling water from a very wet clay or silt is difficult due to the low permeability of the soil. The trapped water in the pores of the soil resists compaction, since water itself
72 is incompressible.

Soils with active clay minerals such as montmorillonite are the most difficult to compact, since these minerals have such a high electrical charge. Soils with less active minerals such as kaolinite, are easier to compact. Also, silts are generally less difficult to compact due to their lack of
73 electrically charged particles.

Soils with higher liquid limits and higher plasticity index values usually have more active clay minerals. Generally speaking, the higher these values are, the more difficult it
74 is to compact the soils.

This chart shows the preferred type of compaction equipment
for this group of soils. Tamping rollers are required for
sands and gravels with clay fines, because the tamping action
is necessary to destroy bonding of the clay particles.
75 Vibration or static load alone will not do the job.

The third group of the soil types to be discussed are the
fine-grained soil classifications. The Unified
76 Classification groups shown are included.

The primary factor affecting the compaction characteristics
of these soils is the electro-chemical properties. Although
the presence of sands and or gravels in the samples may have
some effect, the primary factor is that of the type and
77 amount of clay in the sample.

This chart summarizes the relative difficulty of compaction
of this group of soils. As you see, those soils with silty,
or non-plastic type of fines are easier to compact, and
compaction difficulty increases with increasing liquid limits
78 and plasticity.

This chart summarizes the types of construction equipment
suited to compaction of these soils. As you can see, a
tamping roller is essential to good compaction of most of
these soils. Pneumatic rollers are acceptable for some silts
79 with very low plasticity fines.

80 STOP THE TAPE AND CHANGE THE CAROUSEL TRAY

Activity 6 81	Activity 6 in your Study Guide summarizes compaction characteristics. Stop the tape and carefully study this Activity before continuing.
	-
Factors Affecting Compaction ENERGY 82	The third major factor affecting the compaction of soil is the amount and type of energy applied to the soil. The following items are involved in the amount of energy applied to a compacted fill: A. Lift thickness. B. Type, size, and weight of equipment. C. Number of passes and speed of travel of equipment.
	-
Loose Lift Thickness 83	Loose lift thickness is the thickness of the soil after it is transported and spread on a surface prior to compaction. It is important to spread the soil uniformly so that when compacted, an equal effort is applied to all of the soil.
	-
Loose Lift Thicknesses For Various Soil Groups 84	A loose lift thickness of about nine inches is often specified for fine-grained soils. A larger loose lift thickness may be acceptable for relatively clean sands and gravels. Loose lift thicknesses of as much as two feet may be used for these soils. Clean rockfill may be placed in loose lifts as thick as four feet.
	-
Compacted Lift Thickness 85	Compacted lift thickness refers to the thickness of the layer after it is compacted. The compacted lift may be from three-fourths to one-half the loose lift thickness, depending on the soil, the amount of energy applied, and the water content.
	-

Type of Equipment

86

The type of equipment and its weight also affect the amount of energy applied to a compacted soil. Usually, heavier equipment will produce more densification than light equipment. In some soil, equipment may be so heavy that soil shearing occurs with operation of the equipment, which is undesirable.

-

Contact Pressure

87

In addition to the total weight of the compaction equipment, the contact pressure of the equipment is important. Contact pressure of equipment is usually expressed in pounds per square inch. Equipment may be specified in terms of contact pressure rather than total weight, when this type of compaction specification is used. Tamping rollers may have contact pressures of as high as 500 psi.

-

Contact Pressure

88

When using pneumatic rollers the tire size, inflation pressure, and ballast load are usually specified.

-

Other Equipment Factors

89

The speed at which equipment traverses a fill and the number of passes of the equipment over each layer of the fill also affect the amount of energy applied to a compacted fill. The frequency of vibrations in vibratory rollers is also important.

-

Equipment Specifications

90

One method of specifying earth fill compaction is to specify the permissible loose lift thickness and the type of equipment, including its size. The number of passes of the equipment over each lift and the speed of travel of the equipment are also specified. These specifications are usually based on previous favorable experience with the soil being compacted.

-

ACTIVITY 7

91

Activity 7 of your Study Guide summarizes the factors involved in the energy application to soil in the compaction process. Stop the tape and carefully study the Activity before continuing.

-

REVIEW OBJECTIVES

92

Let's review the objectives of Part A to ensure that you have accomplished all of them. You should be able to define conceptually from memory the important terms, symbols, and equations associated with compaction of soil.

-

93

Objective 2 was to state conceptually from memory the effect of compaction and compaction water content on the engineering properties of the major USCS soil groups, and to state generally whether the effects are beneficial or harmful.

-

94

Objective 3 was to list the three primary factors affecting the compaction characteristics of soils.

-

95

Objective 4 was to describe the general compaction characteristics and the best suited compaction equipment for each major USCS soil group.

-

ACTIVITY 8

96

To test your completion of these objectives, stop the tape player and complete Activity 8.

-

THE END

97

You should now proceed to Part B of Module 5 on compaction.

United States
Department of
Agriculture

Soil
Conservation
Service

Soil Mechanics Training Series

Basic Soil Properties

Module 5 - Compaction

Part B - Compaction of Non-gravelly Soils

Study Guide

ENG-SOIL MECHANICS TRAINING SERIES--

BASIC SOIL PROPERTIES

MODULE 5 - COMPACTION

PART B

COMPACTION OF NON-GRAVELLY SOILS

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 reviews have helped make this training series one that will provide basic knowledge and skills to employees in soil mechanics.

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

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

CONTENTS

ENG-SOIL MECHANICS TRAINING SERIES--
BASIC SOIL PROPERTIES
MODULE 5 - COMPACTION
PART B
COMPACTION OF NON-GRAVELLY SOILS

INTRODUCTION

This is Part B of Module 5 - Compaction of Non-gravelly Soils 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 B 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 B 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.
4. Activity 8 requires you to perform a compaction test. You must coordinate this Activity with your Training Officer and Technical Leader.

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

At the completion of Part B you will be able to:

1. From a list, define the important terms associated with the procedures and equipment used in performing the compaction test.

2. Describe how compaction test results are affected by soil gradation and plasticity characteristics.

3. Describe the effects of different energy levels on compaction test results.

4. Using example data, compute and plot results of a compaction test and determine values of maximum dry density and optimum water content.

5. Explain conceptually from memory the purpose of laboratory and field compaction tests. Explain how compaction tests are used in design and quality control of earth fills.

6. Using field equipment and a soil sample provided, perform a compaction test by standard procedures.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 2 - COMPACTION THEORY INTRODUCTION

R. R. Proctor, an engineer in California, developed many of the important concepts relating to compaction in the 1930's. He was one of the first to recognize how important water content was to the resulting dry unit weight of compacted soil.

Three primary variables determine the compacted dry unit weight of a soil mass. These variables are:

1. The soil being compacted. Each soil has unique compaction characteristics. If one uses the same energy and water content to compact several soils, different dry unit weights will result.

2. The water content at which the soil is compacted. If the same soil is compacted using a uniform energy and the water content of several specimens is varied, then the resulting dry unit weight of the specimens will vary. This is the most common statement of the principal of compaction.

3. The amount and type of energy. If one compacts several specimens of soil at the same water contents and varies the energy used to compact them, then resultant dry unit weights of the specimens will vary.

Proctor developed a test apparatus that would apply a standard energy to a soil as it is compacted. By eliminating energy as a variable, the relationship between water content and compacted dry unit weight of a soil can be studied. By performing a series of tests on soil specimens at several water contents using a standard energy application to compact the specimens, a graphical relationship between water content and compacted dry unit weight can be developed for that soil and that energy. Two levels of energy are commonly used. They are discussed in detail later in the module.

The plotted data relating dry unit weight and water content is called a compaction curve or Proctor curve. Values of water content are plotted on the horizontal axis and values of dry unit weight are plotted on the vertical axis. Compaction curves typically have a parabolic shape with a peak value of dry unit weight occurring at some value of water content.

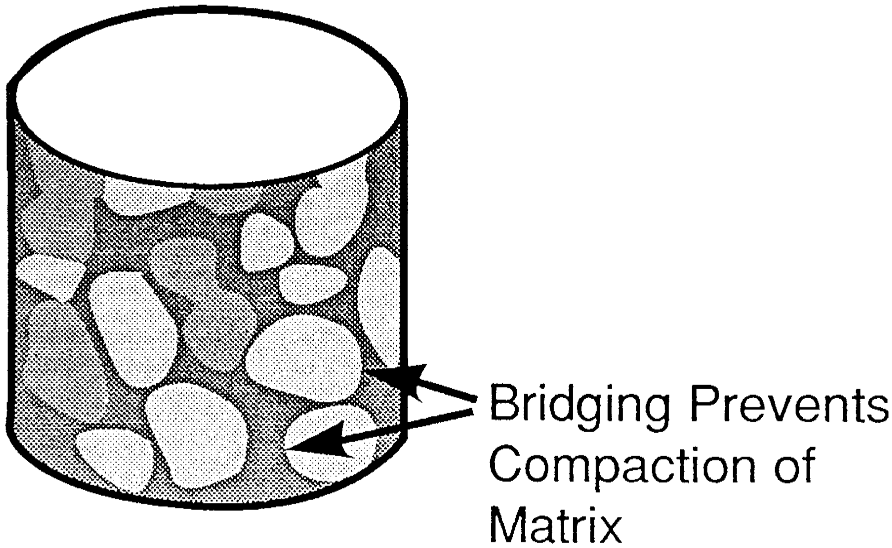
Compaction tests are difficult to perform on relatively clean, coarse-grained soils because of their inability to retain water. Testing a series of specimens at varying water contents is problematic because the soils will not retain added water. Sometimes, a single value of compacted dry unit weight is obtained for some arbitrary water content using the standardized energy application, but rarely can be a meaningful curve be developed. A "rule-of-thumb" used is that soils that have less than 12 percent finer than the number 200 sieve are difficult to test using Proctor's procedures.

To perform compaction tests on soils that have a significant percentage of large gravel-size particles is also problematic. A testing apparatus that would accomodate large gravel particles would be quite large, and standardized equipment has not been developed for such soils. Soils that have over 30 percent of particles larger than 3/4 inch cannot be tested using standardized compaction test procedures. Study Figure 2.1, page 4.

START THE TAPE WHEN YOU HAVE FINISHED

Figure 2.1

COMPACTION TESTS NOT APPLICABLE FOR SOILS WITH >30% LARGER THAN 3/4"



ACTIVITY 3 - DETERMINATION OF PROPER ASTM TEST METHOD

The selection of the proper test method for compaction tests is based on the gradation of the soil to be tested. These guidelines apply to ASTM Test D 698, called the "standard" compaction test, and to ASTM Test D 1557, often called the "modified" test. Each of these tests uses a different amount of energy to compact soils.

The information required on a soil's gradation are the percent passing the 3/4 inch sieve, the 3/8 inch sieve, the number 4 sieve, and the number 200 sieve.

Remember that ordinarily, compaction tests are not performed on soils that have less than 12 percent finer than the number 200 sieve. Soils that have a low fines content do not readily retain moisture in their pores, and it is difficult to obtain a series of test specimens at successively higher water contents.

Because of limitations on the size of laboratory equipment, standardized test methods are not presently available for soils that have more than 30 percent of particles larger than 3/4 inch.

The two standardized ASTM compaction tests, D 698 and D 1557, have 3 variations that can be used. These are referred to as Methods A, B, and C. The differences in the test methods are in the size of particles included in the test specimens and the size of mold in which the soil is compacted.

Tests performed by Method A are covered in this portion of Module 5, Part B. Tests performed using Methods B and C are covered in the next part of the Module, Part C.

The flow chart shown on page 9 is useful for determining which ASTM variation should be used for a particular soil. Carefully examine the chart, and then follow these example uses of the chart.

Example 1:

A soil has 89 percent finer than use 3/4 inch sieve, 76 percent finer than the 3/8 inch sieve, 69 percent finer than number 4 sieve, and 37 percent finer than the number 200 sieve. Using the flow chart, the correct test method is C.

Example 2:

A soil has 95 percent finer than 3/4 inch sieve, 88 percent finer than 3/8 inch sieve, 82 percent finer than the number 4 sieve, and 49 percent finer than the number 200 sieve. Using the flow chart, correct test method is A.

CONTINUE TO NEXT PAGE

ACTIVITY 3 - Continued

Selection of Proper ASTM Test Method:

Given the gradations of each of the following soils, use the flow chart on page 9 to determine which ASTM test variation, or Method should be used to perform a compaction test on that soil. Complete the column listing the proper method.

Soil Number	Percent Finer By Dry Weight #200	#4	3/8"	3/4"	ASTM Test Method
1	42	73	82	93	
2	8	69	76	89	
3	78	98	100	100	
4	27	49	56	67	
5	22	70	74	79	

WHEN YOU HAVE COMPLETED THE ACTIVITY, REVIEW THE ANSWERS PROVIDED ON PAGE 8

ACTIVITY 3 - Solution

Soil 1:

Method B is the correct Test Method to use for a compaction test on this soil.

Soil 2:

The soil has less than 12 percent finer than the number 200 sieve, so that compaction tests would be difficult to perform. Test procedures covered in Part D of this Module should be followed.

Soil 3:

Method A is the correct Test Method for this soil.

Soil 4:

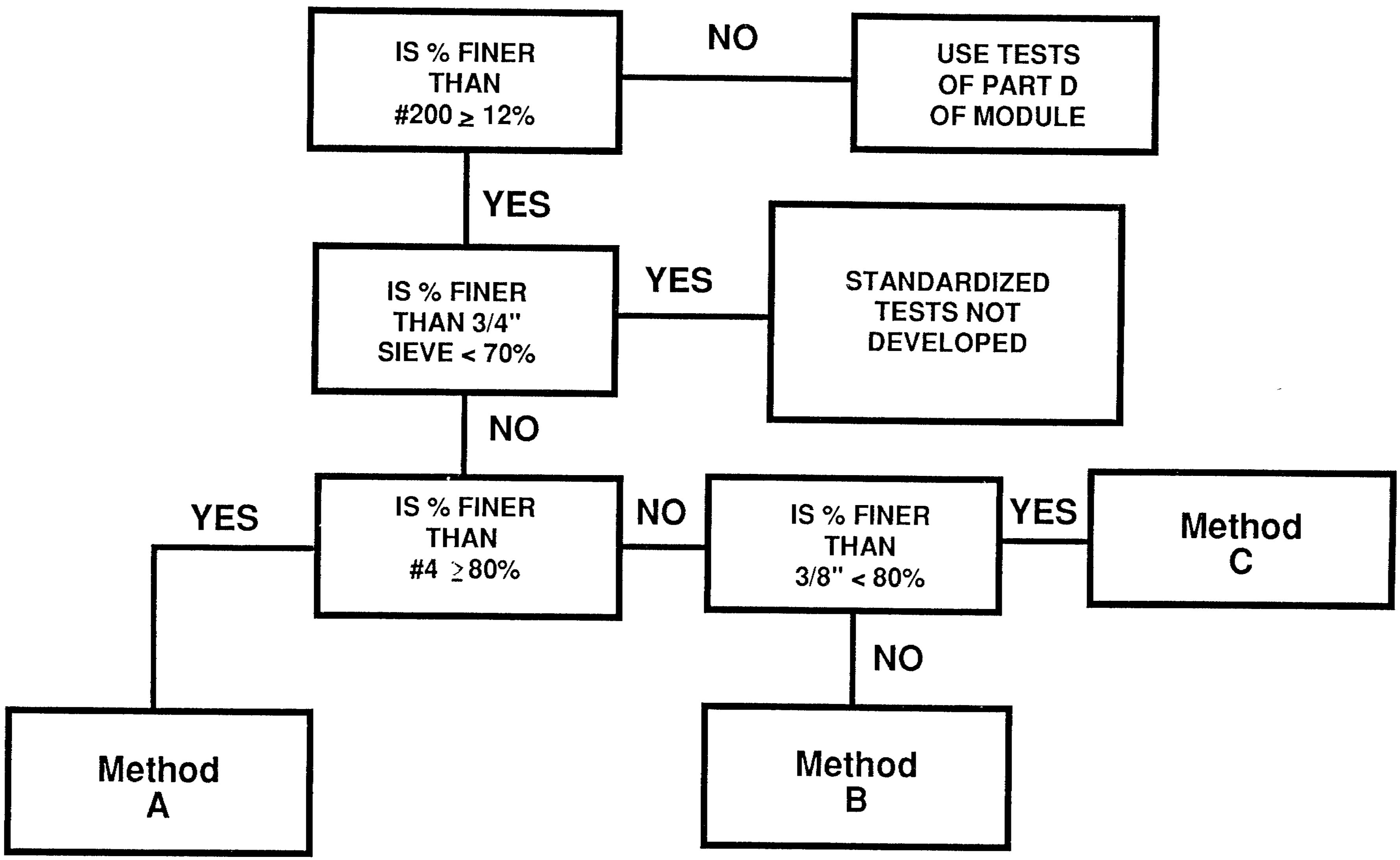
The soil has more than 30 percent of particles larger than the 3/4 inch sieve, so standard compaction test procedures do not apply. (69% or less is finer than the 3/4 inch sieve)

Soil 5:

Method C is the correct Method.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 3


IS % FINER THAN #200 ≥ 12%
NO
USE TESTS OF PART D OF MODULE
YES
IS % FINER THAN 3/4" SIEVE < 70%
YES
STANDARDIZED TESTS NOT DEVELOPED
NO
IS % FINER THAN #4 ≥ 80%
YES
Method A
NO
IS % FINER THAN 3/8" < 80%
YES
Method C
NO
Method B

ACTIVITY 4 - SUMMARY OF COMPACTION TEST PROCEDURES

This Activity introduces the standard test methods for performing compaction tests. Remember that standardized methods are not presently available for soils that have more than 30 percent by dry weight of particles larger than a 3/4 inch sieve. Also, compaction tests are difficult to perform on soils that have less than 12 percent finer than the number 200 sieve.

Two ASTM test standards are available for compaction tests of soils. The two test standards vary primarily in the amount of energy used to compact the soil samples in the test. ASTM Test D 698 is often referred to as the "standard" energy test, and Test D 1557 is referred to as the "modified" energy test. Additional details on energies used in each of these tests will be given in a later Activity.

Each of these ASTM tests has three variations that can be used to test a particular soil sample. As you learned in Activity 3, selection of the proper method depends on the gradation of the soil. The three Methods of performing compaction tests are denoted A, B, and C. Method A tests require gravel-size particles to be removed before testing. These test procedures are covered in this part of the Module. The Method B and C procedures include some gravel-sized particles in the compaction test sample, and these procedures will be covered in the next part of the Module, Part C.

In preparation for Method A compaction tests, the soil sample is screened through a number 4 sieve to remove all gravel-size particles. Corrections to test results for the density of the excluded oversize gravels may be made as detailed in part C of this module. Soils may be prepared either at their natural water contents, or they may be air-dried before processing. Some laboratories prefer to air-dry the soil before sieving because of the difficulty in sieving out gravel particles from a plastic clay matrix when the soils are at natural water content. One should realize that the compaction properties of some soils may be changed by air-drying, and these soils should be processed at natural water content. Soil samples should never be oven-dried before testing because this will almost certainly alter their properties.

For the test, after sieving, four to five specimens are separated, each weighing about 5 pounds (air-dry weight), and then are moistened to water contents about 1-1/2 or 2 percent apart. Selection of the water contents for the specimens requires judgement and experience. Higher water contents are used for plastic, fine-grained soils than are used for lower plasticity and sandier soils. If one uses poor judgement in selecting the water contents of the prepared specimens, additional specimens may be prepared to complete the test. Occasionally, as many as eight specimens are used when poor judgement is used in preparing the initial four to five specimens. See Figure 4.5, p. 21.

Each of the prepared specimens is then allowed to "cure" in a moisture-proof container for a specified period. The curing time required is based on the Unified Soil Classification System class of the soil being tested. Curing allows the water added to the soil to equilibrate, or to become equally distributed throughout the sample.

CONTINUE TO THE NEXT PAGE

ACTIVITY 4 - Continued

The length of curing time required is specified as follows in ASTM procedures:

Unified Soil Classification Group	Minimum Curing Time (hours)
SM, GM	3
ML, CL, OL, GC, SC	16 (overnight)
MH, CH, OH	40

Each specimen is then compacted into a circular mold. The soil is compacted by dropping a hammer of specified weight from a specified height for a specified number of times. Several "lifts" are used to fill the mold with compacted soil. Details on hammer weights, height of drop, number of blows of the hammer per lift, and number of lifts of soil used to fill the mold are given in a later Activity. These details determine the amount of energy used to compact the soil, with ASTM Tests 698 and 1557, using different amounts of energy.

The volume of the mold into which the soil is compacted and the weight of the mold are carefully determined before testing. These values are needed to compute the compacted density of each specimen. Method A tests use a mold that has a diameter of about 4" and a volume of about 1/30 a cubic foot.

The moist unit weight of each compacted specimen is determined by weighing the specimen and the mold into which it has been compacted, subtracting the weight of the mold, and then dividing by the volume of the mold, with the following equation:

$$\text{Moist Unit Weight} = \frac{(\text{Weight of Mold + Soil}) - (\text{Weight of Mold})}{\text{Volume of Mold}}$$

Units of pounds per cubic foot or kilograms per cubic meter are used to measure moist unit weight. The system used depends on the devices used to weigh the samples and measure the volume of the mold.

The water content of each specimen is determined by drying a representative portion in an oven to a constant weight. The oven is usually set to 110 degrees Centigrade. However, soils that contain hydrated minerals, such as gypsum, must be dried at temperatures that will not drive off hydrated water, usually 60 degrees Centigrade.

The dry unit weight of each specimen may then be calculated from the following equation:

$$\text{Dry Unit Weight} = \frac{\text{Moist Unit Weight}}{(1 + (\text{water content } \%/100))}$$

If the proper range of water contents was selected for the preparation of the test specimens, the values of the soil's compacted dry unit weights will show an increase for the first several specimens, and then at higher water contents, the value will decrease.

CONTINUE TO THE NEXT PAGE

ACTIVITY 4 - Continued

With the data obtained, a curve may be plotted showing the relationship between water content and dry unit weight for that soil and that energy application. Ordinarily, water content is used for the horizontal scale and dry unit weight for the vertical scale. The curve typically has a parabolic shape that has a defined peak in dry unit weight. If a peak does not occur in the plotted data, the proper range of water contents was not selected for the test specimens, and additional specimens should be prepared.

The water content at which the peak in the curve occurs is called the optimum water content. The value of dry unit weight at the peak of the curve is referred to as the maximum dry unit weight of the soil for that energy application. See Figure 4.1, p. 15.

<u>Problem</u>:

Problem 4.1, page 18, contains data obtained from a Method A compaction test performed on a silty clay soil classifying as CL. The test was performed using "standard" ASTM D 698, energy. The form is a laboratory worksheet used by SCS technicians to record compaction test data.

Row 1 contains the weight of the compacted soil and mold for each specimen tested.

Row 2 has the weight of the mold, or cylinder into which the soil was compacted.

Row 3, the weight of the compacted soil, is obtained by subtracting Row 2 and Row 1.

Row 4 is the moist density of the compacted specimen, obtained by dividing Row 3 by the volume of the mold.

Row 5 is the computed dry unit weight of the specimen, obtained by dividing the moist unit weight (Row 4) by 1 plus the water content expressed as a decimal (Row 9 divided by 100).

Rows 10 through 15 contain weights of water content samples taken from each compacted specimen. The wet weight of the sample plus can, the dry weight of the soil plus can, and the can weight, are used to calculate the water content, Row 9.

To complete this problem, (1) calculate the moist unit weight of each specimen. (2) Then, calculate the water content of each specimen. (3) Then, calculate the value of dry unit weight for each point. (4) When you have computed the data, prepare the blank data form provided on page 19 to plot this data. (5) Select a suitable scale for water content for the horizontal axis, and a suitable scale for dry unit weight for the horizontal axis.

CONTINUE TO THE NEXT PAGE

ACTIVITY 4 - Continued

The same scales for plotting compaction test data must be used each time data is plotted. This allows you to develop an experience based on the typical shapes of different soil types and energies used to perform the tests. SCS engineers have found the following scales to be appropriate:

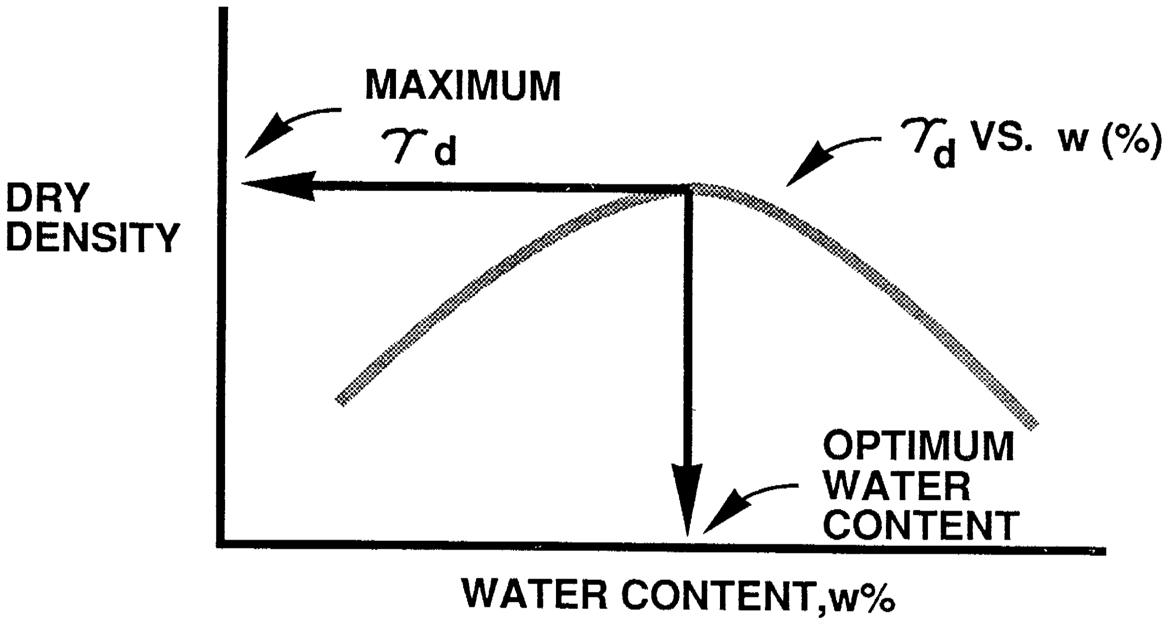
For water content - Use 1" = 4% water content

For Unit Weight - Use 1" = 10 pounds per cubic foot

Figure 4.4, p. 21 illustrates the scales suggested for use.

(6) Finally, plot the problem data on the blank form provided on page 19. The data should enable you to construct a smooth curve connecting the data points. (7) From this curve, determine the value of water content at which the peak in the curve occurs, and determine the value of maximum dry unit weight at the peak of the curve. Round your answers to the nearest 0.5 pcf for dry density and to the nearest 0.5% for water contnet.

WHEN YOU HAVE COMPLETED THE ACTIVITY, REVIEW THE ANSWERS PROVIDED ON PAGE 20



Note: γ_m curve not shown

Figure 4.1-- Typical Compaction Test Results.

CONTINUE TO THE NEXT PAGE

ACTIVITY 4 - PART B - PROBLEM 4.1

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

WORK SHEET FOR COMPACTION AND PENETRATION RESISTANCE DATA

Sample No.: ____________

COMPACTION DATA (Record Weights in Pounds)

1	Wt. of Cyl. + Soil	8.26	8.51	8.63	8.51		
2	Wt. of Cylinder	4.20	4.20	4.20	4.20		
3	Wt. of Soil = (1) - (2)						
4	Wt. per Cu. Ft. (Wet) = (3) ÷ Vol. of Cyl.						
5	Wt. per Cu. Ft. (Dry) = $\frac{(4) \times 100}{100 + (9)}$						
6	Proctor Needle Readings						
7	Size Needle (Sq. in.)						
8	Penetration (Lbs./sq. in.) Resistance = (6) ÷ (7)						

MOISTURE DETERMINATION DATA (Record Weights in Grams)

9	Percent Moisture = $\frac{(13)}{(15)} \times 100$						
10	Can Number	20	21	22	23		
11	Wet Wt. - Can + Soil	185.62	178.24	172.14	238.48		
12	Dry Wt. - Can + Soil	171.86	162.48	154.84	209.48		
13	Moisture Weight = (11) - (12)						
14	Weight of Can	37.62	37.78	38.30	38.50		
15	Dry Weight of Soil = (12) - (14)						

Vol. of Cyl. .03337 cu. ft.	
	Standard Proctor
	Modified AASHO
	Other ____________

PROCEDURE DATA:

Wt. of Hammer 5.5 Pounds

Drop 12 Inches

No. of Lifts 3

Completed by: ____________ Date: ____________

Computed by: ____________ Date: ____________

Checked by: ____________ Date: ____________

Recorded by: ____________ Date: ____________

Density		% H_2O
Wet	Dry	

Project ACTIVITY 4 - PROBLEM 4.1

Site MODULE 5 - PART B

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: Problem 4.1

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)

PENETRATION RESISTANCE, psi: 2500, 2000, 1500, 1000, 500, 0

Plot water content versus dry unit weight using data on previous page.

Construct curve and select maximum dry density and optimum water content.

If you wish to check your solution, see the next page.

MAX. γ_d ________ pcf

OPT. MOIST. ________ %

NATURAL MOIST. ________ %

DENSITY OF COMPACTED SOIL, pcf

MOISTURE CONTENT, PERCENT OF DRY WEIGHT

REMARKS

USDA-SCS-HYATTSVILLE MD 1986

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

ACTIVITY 4 - PART B

LABORATORY NO ______

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

PROJECT and STATE: Problem 4.1 Solution D Figure 4.3

FIELD SAMPLE NO. ______ LOCATION ______ DEPTH ______

GEOLOGIC ORIGIN ______ TESTED AT ______ APPROVED BY ______ DATE ______

CLASSIFICATION ______ LL ______ PI ______

MAX. PARTICLE SIZE INCLUDED IN TEST # 4 "

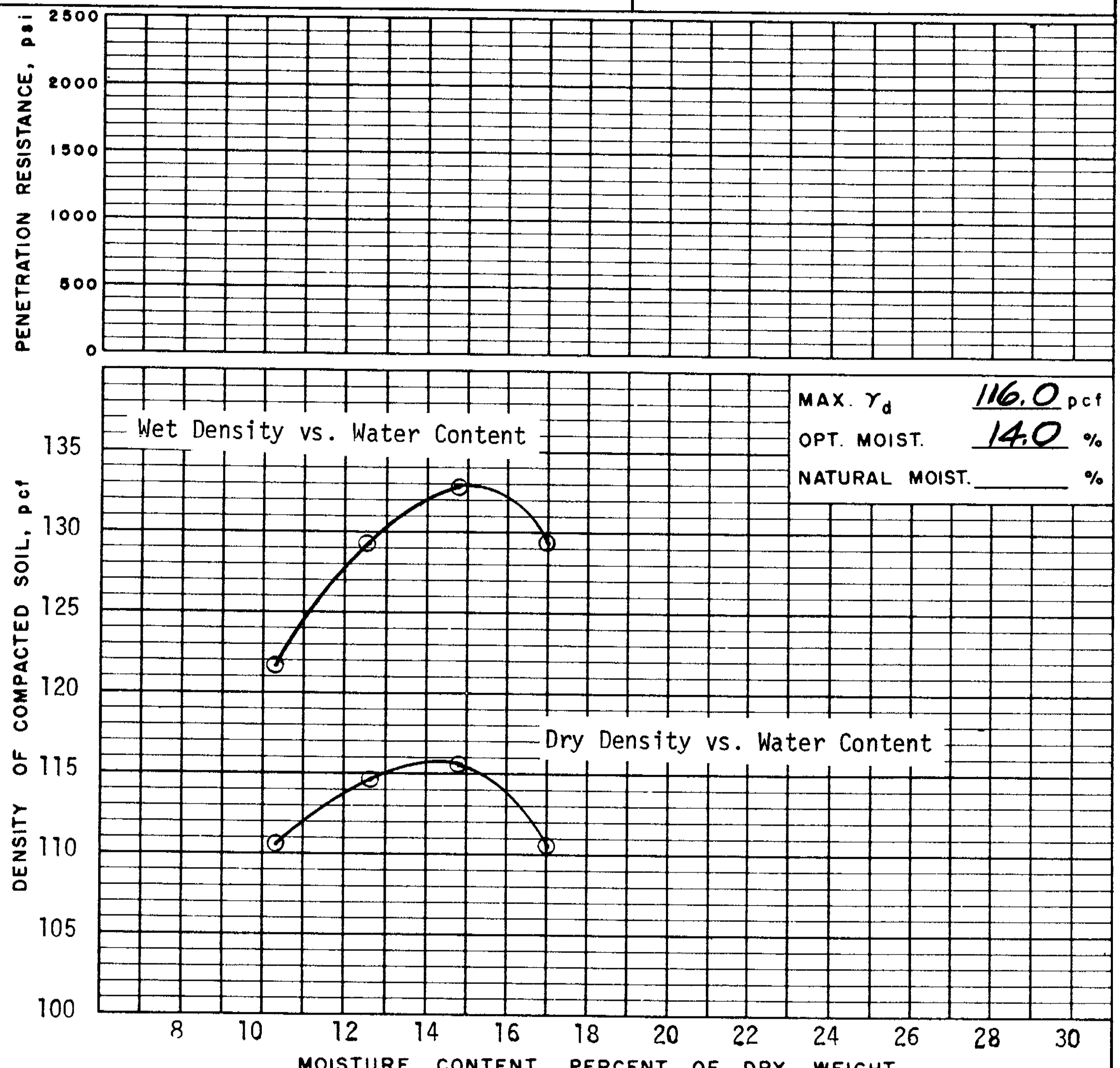
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 ______ ; PLUS NO. 4 ______

CURVE NO. ______ OF ______

STD. (ASTM D-698) ☒; METHOD A

MOD. (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)



MAX. γ_d 116.0 pcf

OPT. MOIST. 14.0 %

NATURAL MOIST. ______ %

REMARKS

START THE TAPE PLAYER WHEN YOU HAVE FINISHED

USDA-SCS-HYATTSVILLE MD. 1968

PROPER SCALES FOR PLOTS

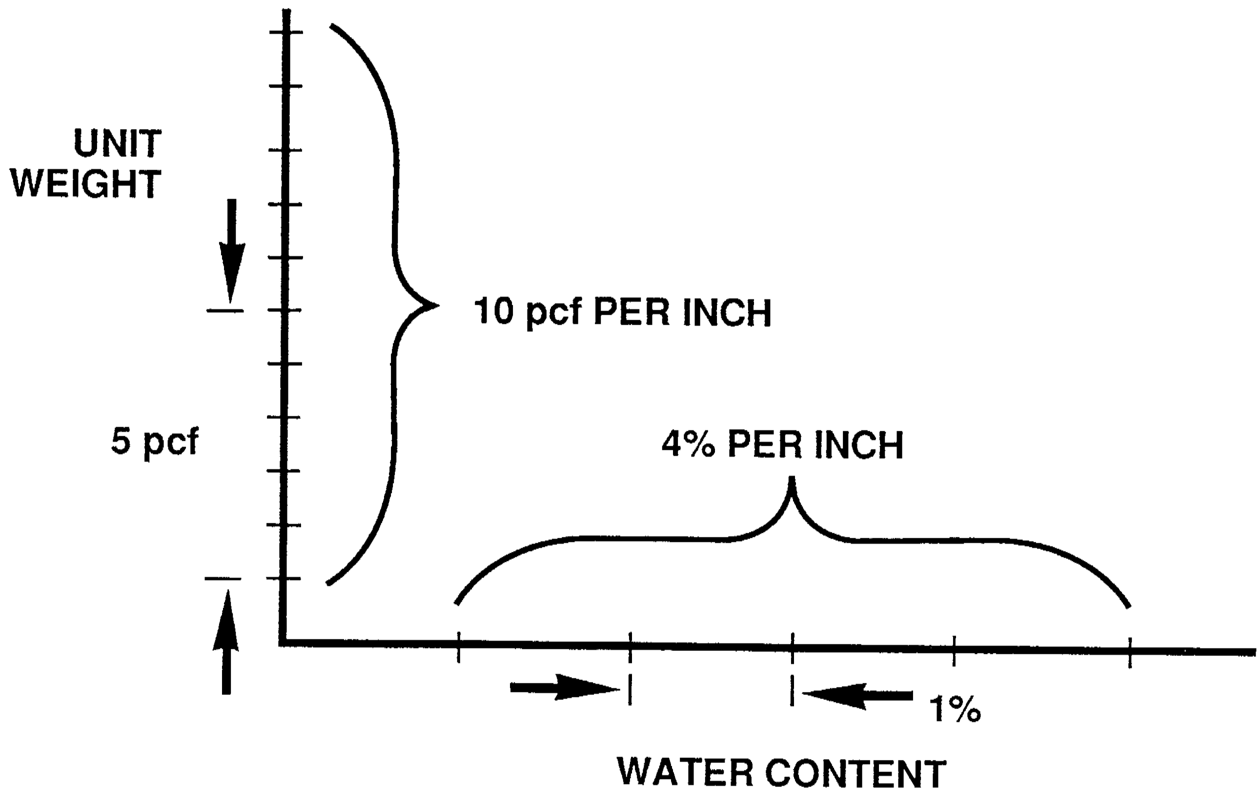


Figure 4.4

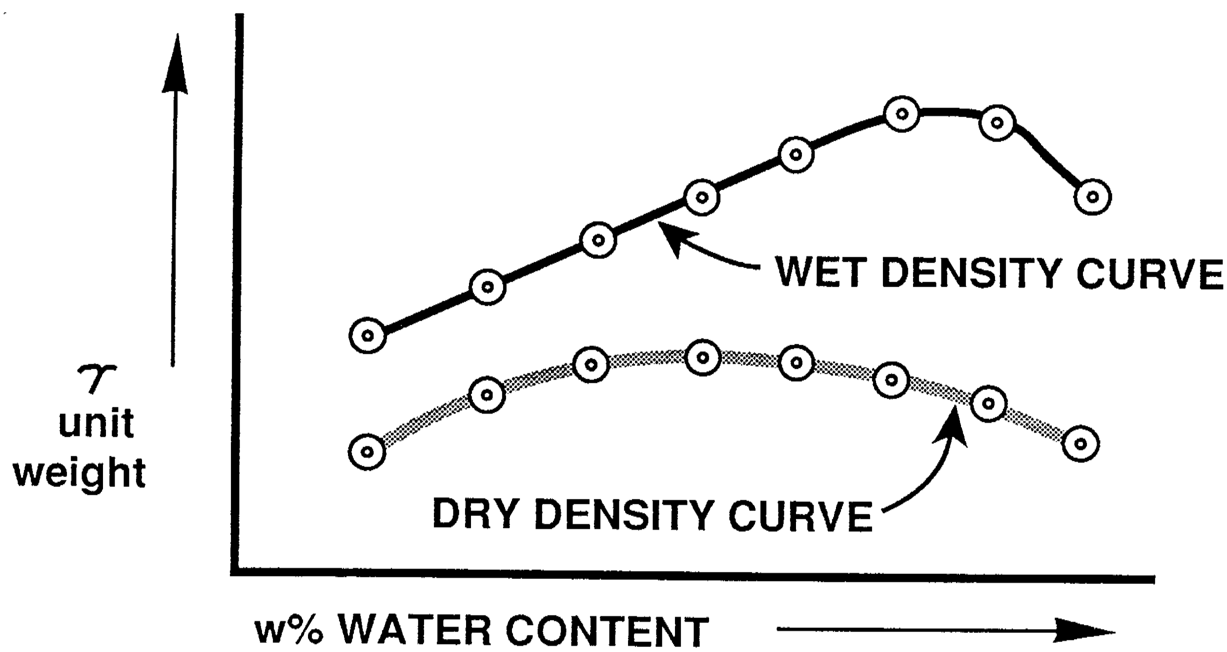


Figure 4.5--Excessive number of test points required due to low starting point

ACTIVITY 5 - STANDARDIZED ENERGY TESTS

Two different standard energy applications are commonly used to perform compaction tests. A standard test has been developed for each energy application. The standard tests are published in the American Society for Testing and Materials, ASTM, annual book of standards. Standards for testing soils are in Section 4, Volume 04.08. The more important aspects of the test procedures are summarized in this Activity and in the previous Activity. Detailed instructions necessary for one to actually perform a test are contained in the ASTM test standard, covered in a later Activity. Test methods are periodically reviewed and revised by ASTM, and you should always be sure you are using the most current one.

The first compaction test to be discussed is ASTM D 698. This is often referred to as the "standard" Proctor test. You should recall that each test standard contains three variations depending on the gradation of the soil being tested. Method A tests are covered in this part of the Module.

The equipment used to compact soils using ASTM D 698 Method A procedures is shown on Figure 5.1. This test uses a hammer weighing 5.5 pounds which is dropped a vertical distance of 12 inches a total of 25 times per lift of compacted soil. Soil is compacted into a mold that has a volume of about 1/30 of a cubic foot in three lifts.

The amount of energy applied then may be calculated as follows:

$$\frac{\text{5.5 pounds x 1 foot x 25 blows per lift x 3 lifts}}{\text{1/30 cubic foot}} = \text{12,375 foot-pounds per cubic foot}$$

ASTM Test Method D 1557 uses a hammer weighing 10 pounds that is dropped a distance of 18 inches a total of 25 times per lift of compacted soil. The mold is filled using 5 lifts of compacted soil. A mold with a volume of about 1/30 a cubic foot is used. Figure 5.2 depicts this test. This is a much higher energy application than the Standard Method covered previously. This test method is often referred to as the Modified Proctor test.

The amount of energy applied to the soil in this test is:

10 pounds x 1.5 foot x 25 blows per lift x 5 lifts/(1/30 cubic foot)
= 56,250 foot-pounds/cubic foot

CONTINUE TO NEXT PAGE

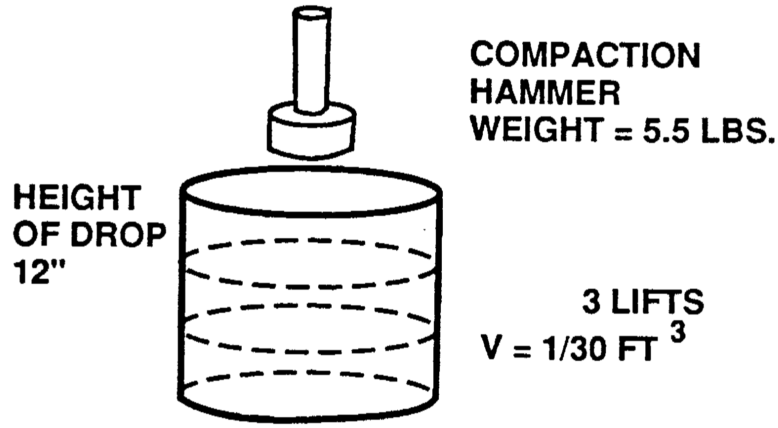
ACTIVITY 5 - Continued

The following table summarizes the test procedures and equipment used for each compaction test. Each specimen in a test is compacted using the same energy. The purpose of standardizing equipment and procedures is to obtain an energy application which is the same for each test. This enables one to examine only the influence of water content on the compacted dry unit weight of the specimens being tested.

Test Method	Hammer Weight (pounds)	Distance Dropped (ft.)	Blows/Lift	No. of Lifts	Energy (foot/pounds) cubic yards
D 698 A	5.5	1.0	25	3	12,375
D 1557 A	10.0	1.5	25	5	56,250

START THE TAPE WHEN YOU HAVE STUDIED THE FOLLOWING PAGE

STANDARD PROCTOR ENERGY APPLICATION



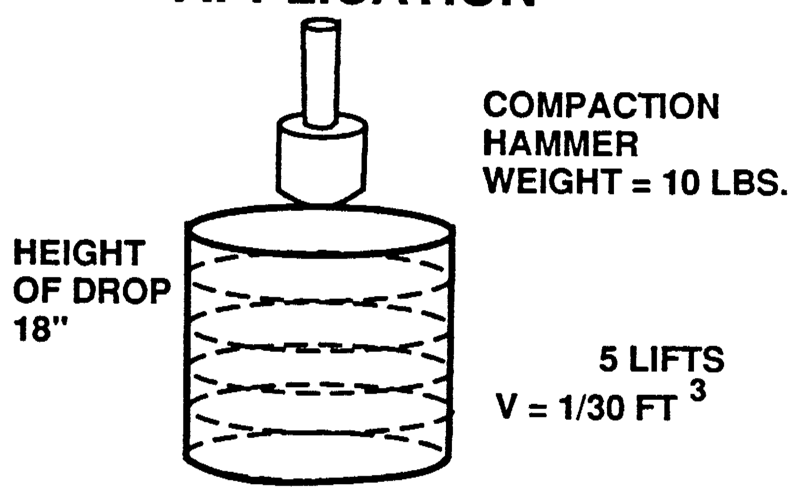
Standard Proctor Energy - ASTM D698

$$= \frac{5.5 \text{ lbs.} \times 1 \text{ ft.} \times 25 \text{ blows/lift} \times 3 \text{ lifts}}{1/30 \text{ ft.}^3}$$

$= 12{,}375 \text{ ft.} - \text{lbs./ft.}^3$

Figure 5.1

MODIFIED PROCTOR ENERGY APPLICATION



Modified Proctor Energy - ASTM D1557

$$= \frac{10 \text{ lbs.} \times 1.5 \text{ ft.} \times 25 \text{ blows/lift} \times 5 \text{ lifts}}{1/30 \text{ ft.}^3}$$

$= 56{,}250 \text{ ft.} - \text{lbs./ft.}^3$

Figure 5.2

ACTIVITY 6 - EFFECT OF VARYING ENERGY LEVELS ON COMPACTION TEST RESULTS

If compaction tests were performed on the same soil using different energy levels, different compaction curves would result. In general, the higher the energy used in compacting a soil, the higher will be the unit weight of the compacted soil, and the optimum water content will be lower.

The curves developed for the different energies have the most significant differences for plastic, fine-grained soils, and are less pronounced on less plastic, sandy soils.

One must realize that the energies used in these laboratory tests do not have a direct correlation to the energy applied to soils by field compaction equipment. The intent of this test is not to simulate field compaction characteristics. Results of the laboratory compaction test are used primarily to form the basis for the design of a compacted fill. A desirable degree of compaction can by established by testing soils at different design densities for engineering properties such as shear strength, consolidation, and permeability. The laboratory compaction test provides a uniform reference base for a given soil, and field control can then be tied to this reference base.

Typical test results for two different energy level compaction tests for several different Unified Soil Classification soil groups are shown on the following pages. Carefully examine the curves. Note the typical values for maximum dry unit weight and optimum water content obtained for each energy. Note also the typical shapes of the curves for each soil type.

For each soil, list the values of maximum dry unit weight and optimum water content obtained for each energy source by filling out the following table. (Round off values of density to the nearest 0.5 pcf and water content to the nearest 0.5%).

	Standard Energy (D 698)		Modified Energy (D 1557)	
Soil Type	Maximum Dry Unit Weight pounds/ft³	Optimum Water Content %	Maximum Dry Unit Weight pounds/ft³	Optimum Water Content %
Figure 6.1 CH				
Figure 6.2 CL				
Figure 6.3 ML				
Figure 6.4 MH				
Figure 6.5 SC				
Figure 6.6 SM				

WHEN YOU HAVE COMPLETED THE ACTIVITY, REVIEW THE ANSWERS PROVIDED ON PAGE 34

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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 6.1 Typical compaction test results for CH soil

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

CLASSIFICATION CH LL 67 PI 43

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

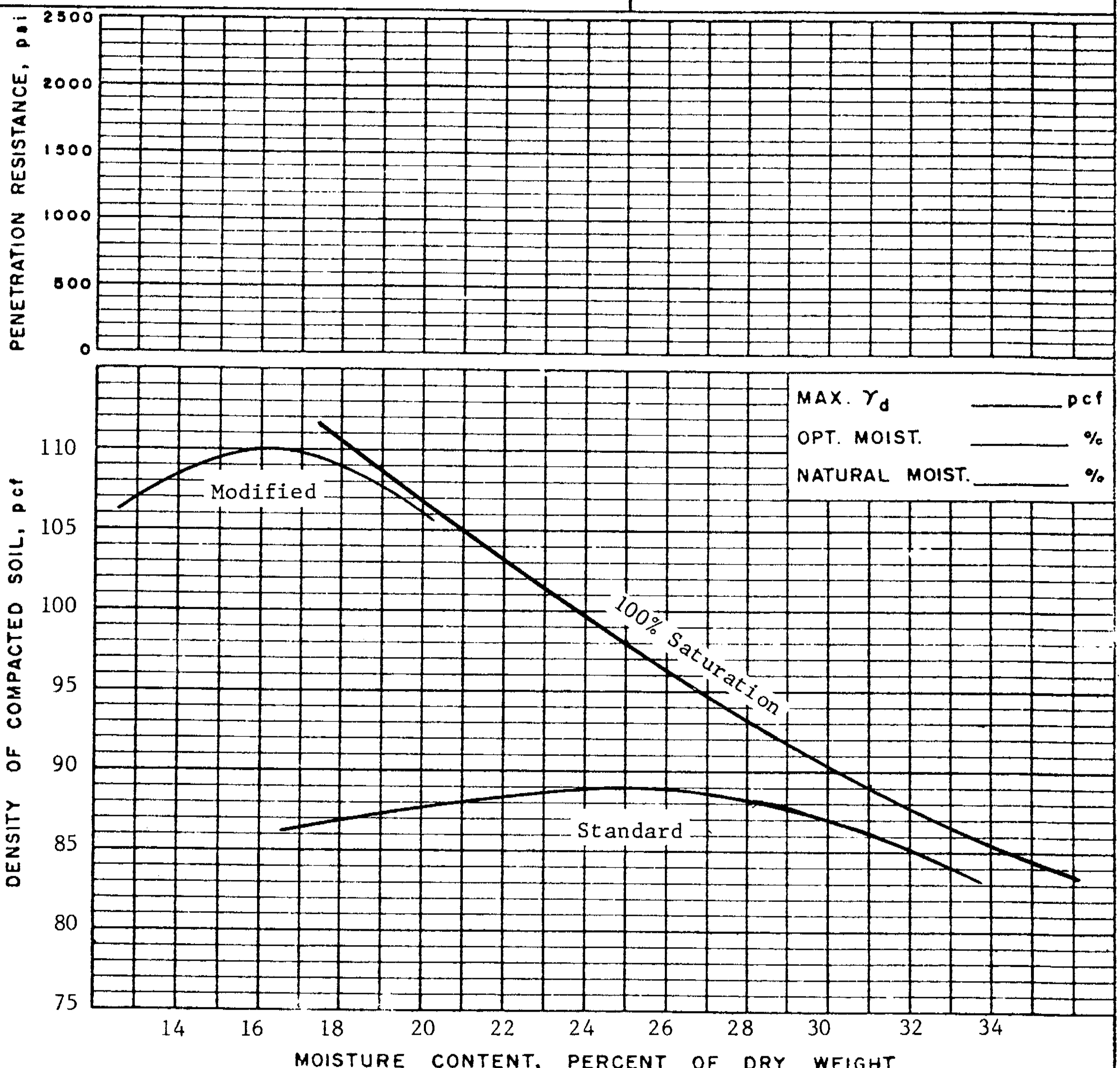
SPECIFIC GRAVITY (G_s) MINUS NO. 4 2.65; PLUS NO. 4 ______

CURVE NO. 1 OF 6

STD. (ASTM D-698) [X]; METHOD A

MOD. (ASTM D-1557) [X]; METHOD A

OTHER TEST [ ] (SEE REMARKS)



REMARKS

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

ACTIVITY 6 - PART B

LABORATORY NO ____

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

PROJECT and STATE Figure 6.2 Typical compaction test results for CL soil

FIELD SAMPLE NO.	LOCATION	DEPTH

GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION CL LL 31 PI 15

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

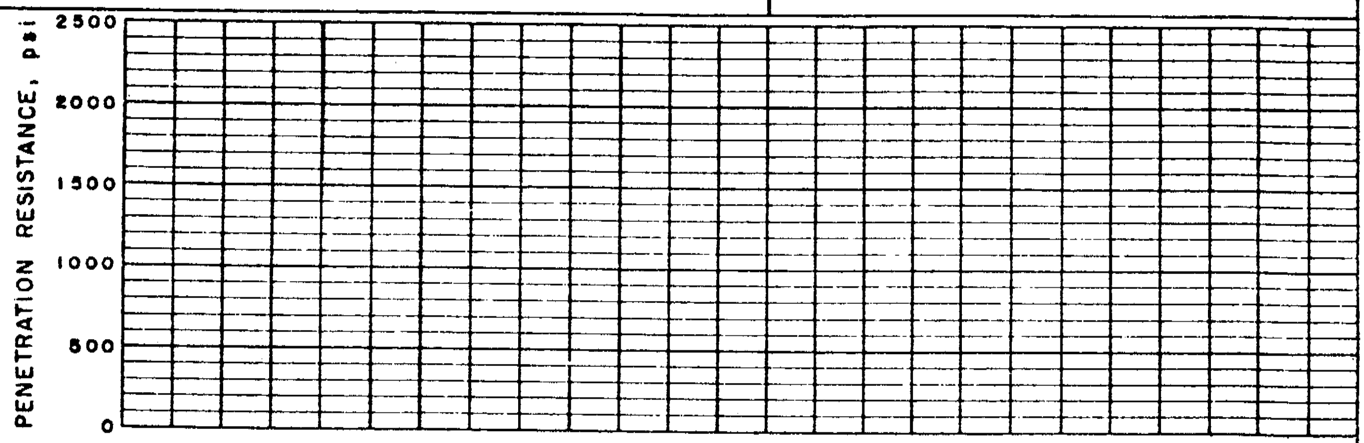
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.66 / PLUS NO. 4 ____

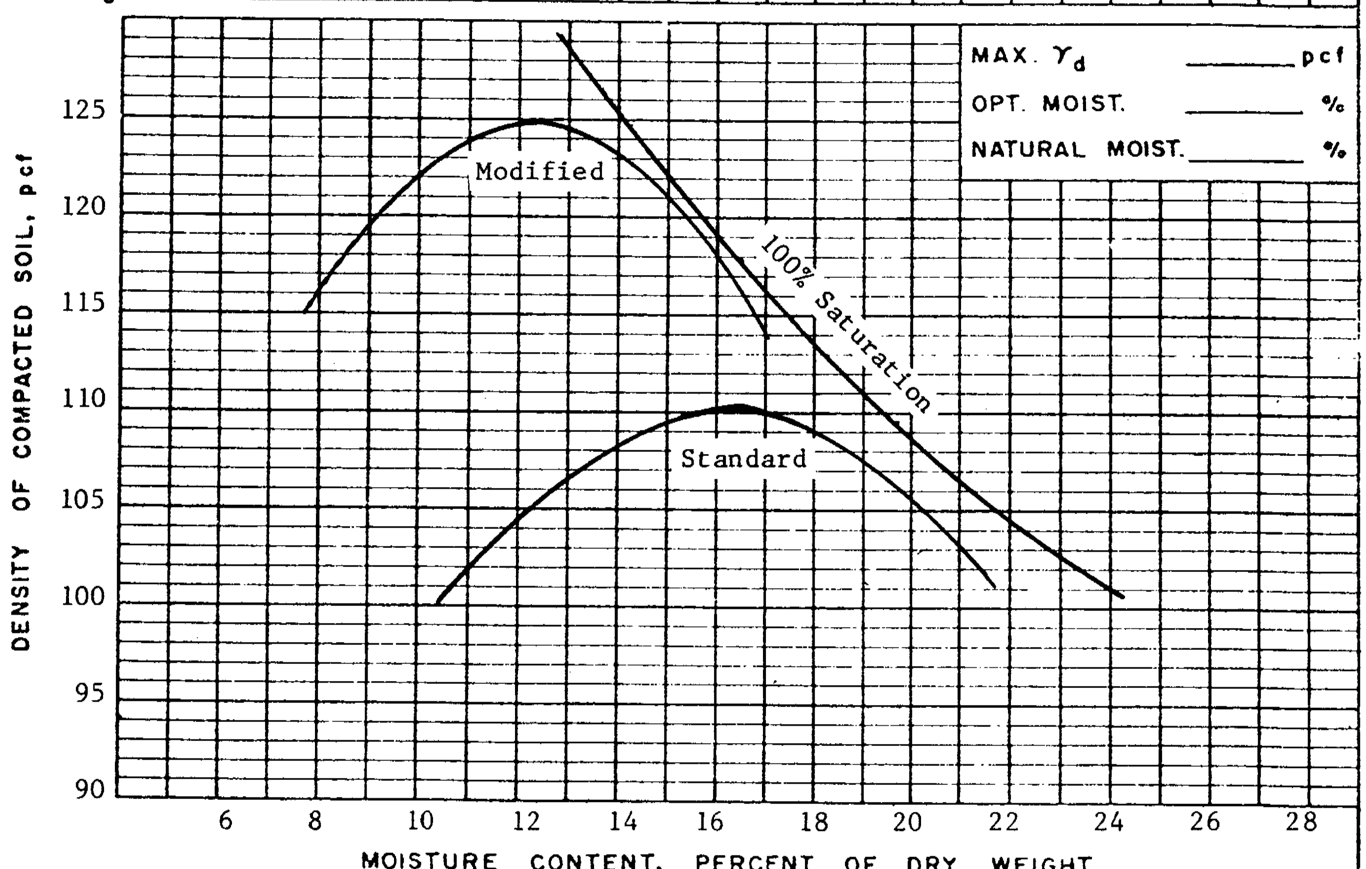
CURVE NO. 2 OF 6

STD. (ASTM D-698) ☒; METHOD A

MOD. (ASTM D-1557) ☒; METHOD A

OTHER TEST ☐ (SEE REMARKS)





REMARKS

USDA-SCS-HYATTSVILLE MD 1944

LABORATORY NO ________

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

PROJECT and STATE: Figure 6.3 Typical compaction test results for ML soil

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

CLASSIFICATION ML LL - PI NP

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

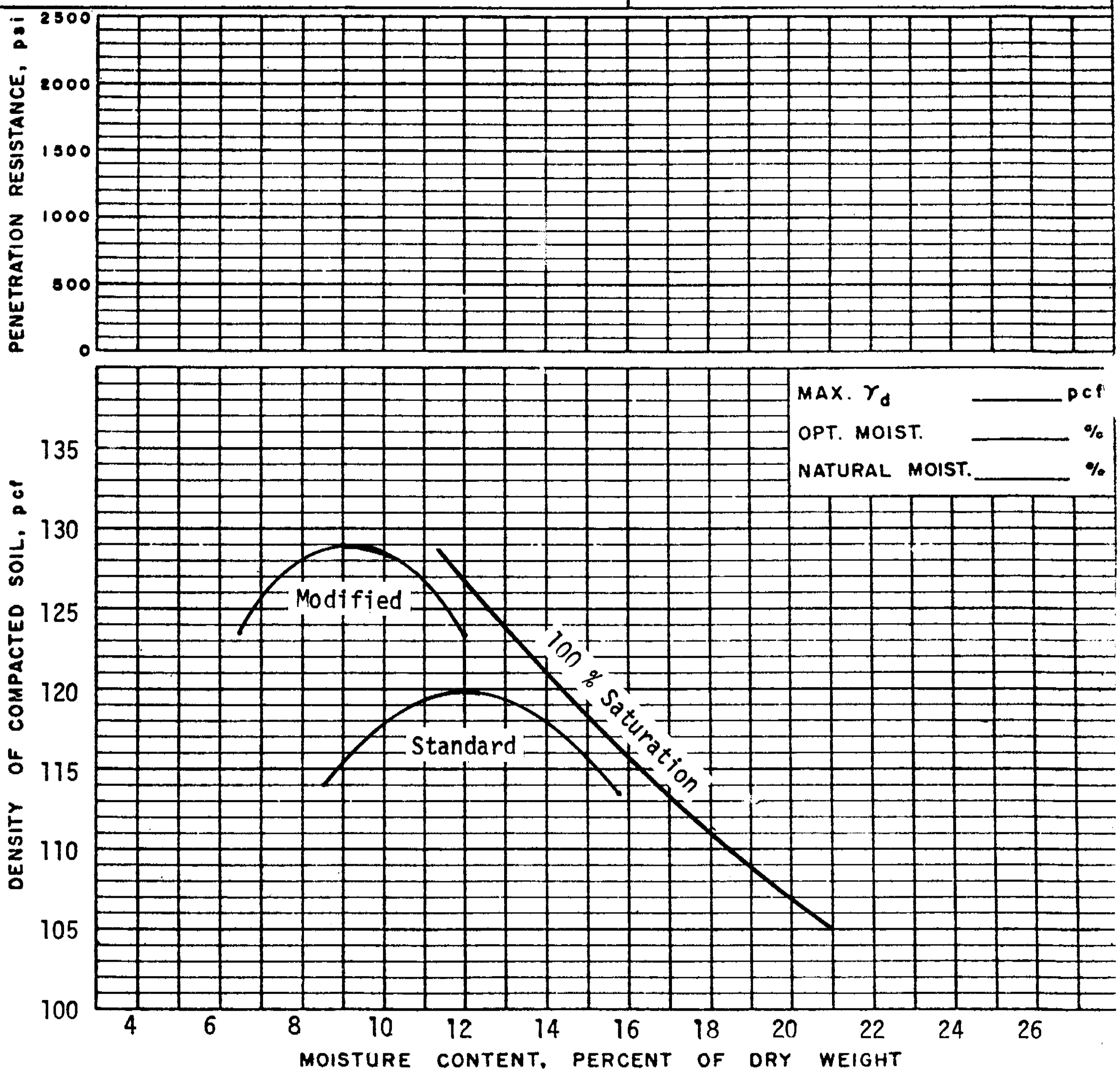
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.68 ; PLUS NO. 4 ________ }

CURVE NO. 3 OF 6

STD. (ASTM D-698) ☒; METHOD A

MOD. (ASTM D-1557) ☒; METHOD A

OTHER TEST ☐ (SEE REMARKS)



REMARKS

ACTIVITY 6 - PART B

LABORATORY NO ______

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

PROJECT and STATE: Figure 6.4 Typical compaction test results for MH soil

FIELD SAMPLE NO.	LOCATION	DEPTH

GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION MH LL 76 PI 32

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

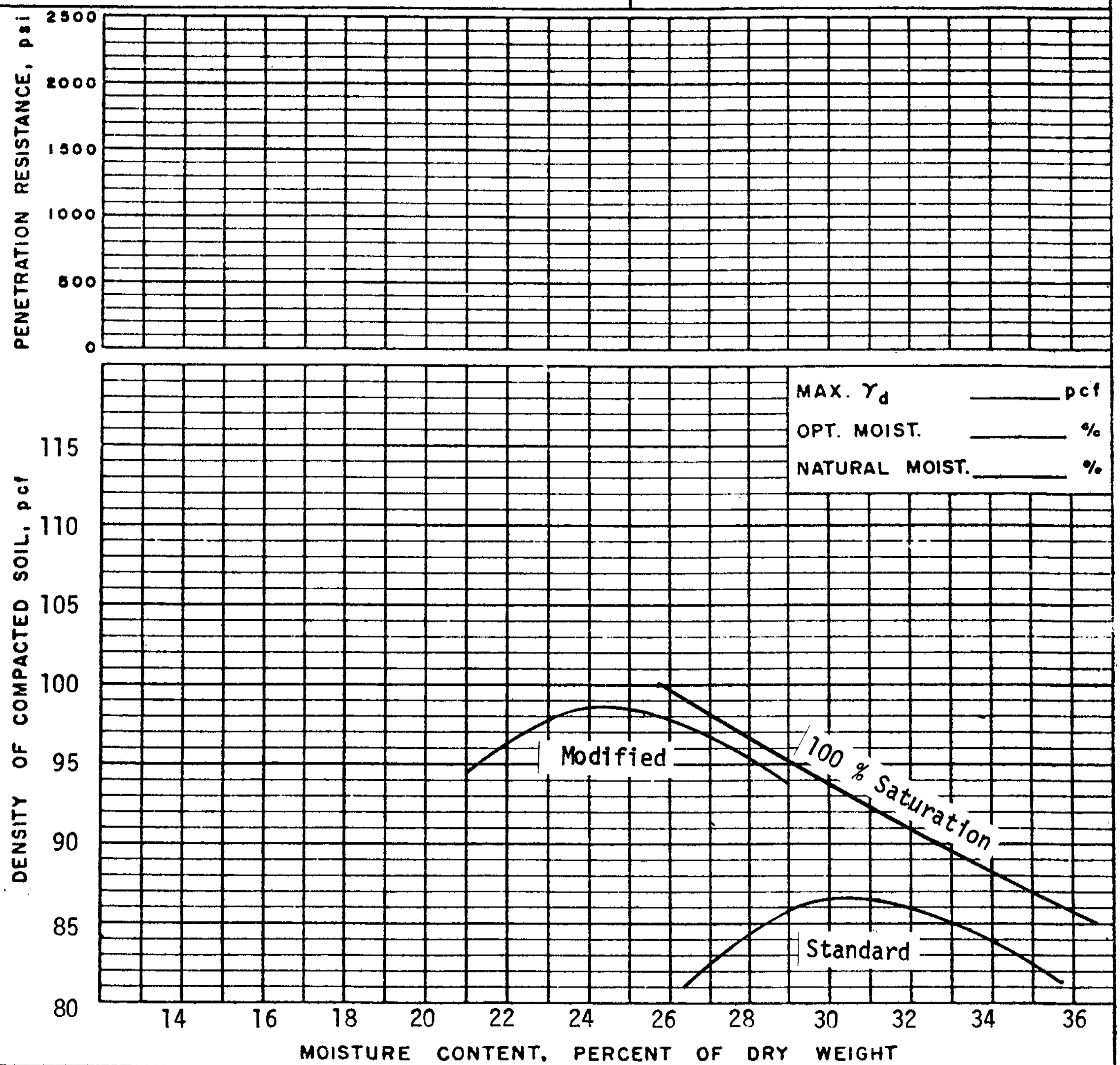
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.72 ; PLUS NO. 4 ______

CURVE NO. 4 OF 6

STD. (ASTM D-698) ☒; METHOD A

MOD. (ASTM D-1557) ☒; METHOD A

OTHER TEST ☐ (SEE REMARKS)



REMARKS

ACTIVITY 6 - PART B

LABORATORY NO ______

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

PROJECT and STATE: Figure 6.5 Typical compaction test results for SC soil

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

CLASSIFICATION SC LL 31 PI 12

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

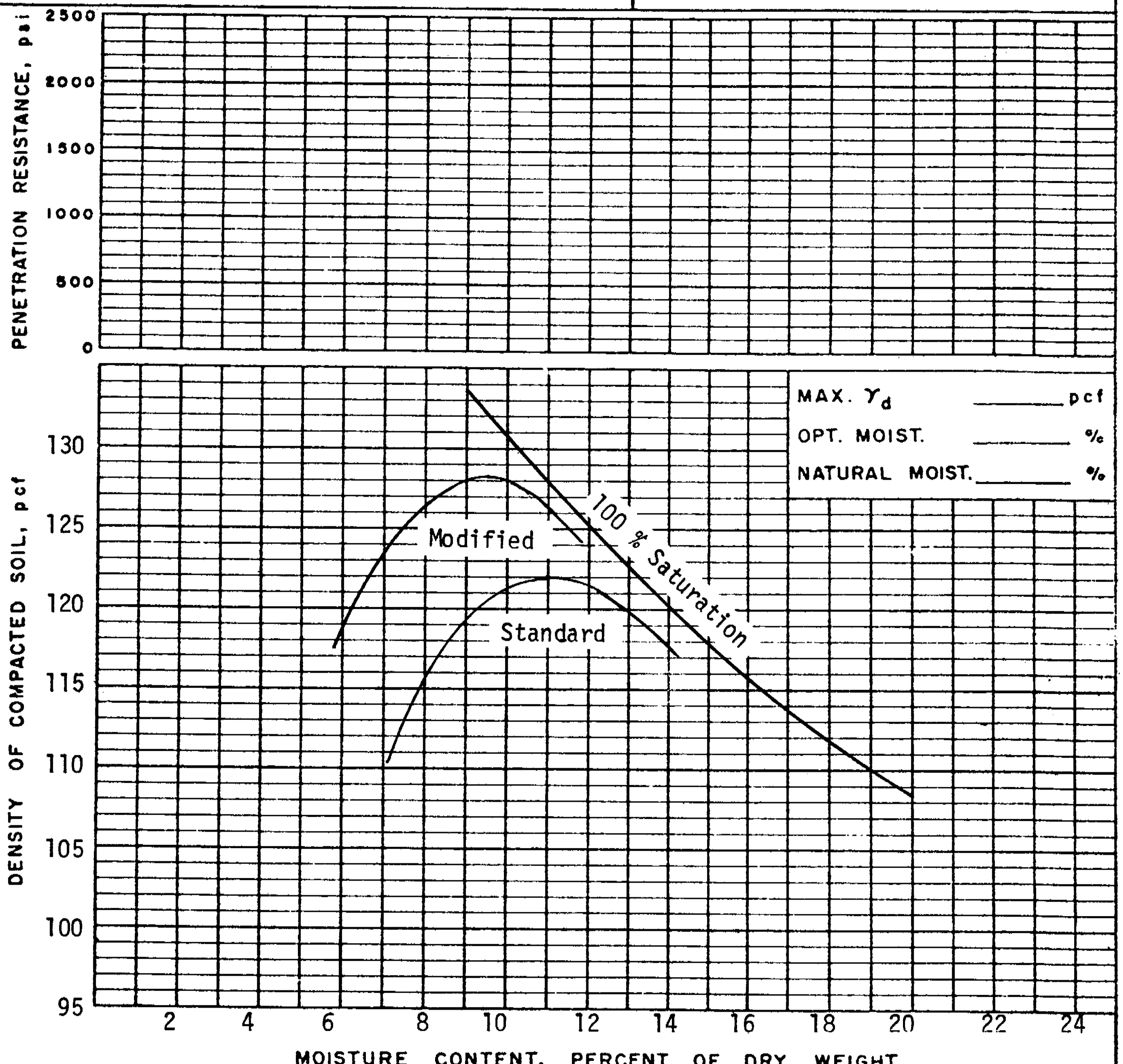
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.66 ; PLUS NO. 4 ______ }

CURVE NO. 5 OF 6

STD. (ASTM D-698) ☒; METHOD A

MOD. (ASTM D-1557) ☒; METHOD A

OTHER TEST ☐ (SEE REMARKS)



MAX. γ_d ______ pcf

OPT. MOIST. ______ %

NATURAL MOIST. ______ %

REMARKS

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

ACTIVITY 6 -- PART B

LABORATORY NO ______

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

PROJECT and STATE
Figure 6.6 Typical compaction test results for SM soil

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

CLASSIFICATION SM LL 17 PI 1

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

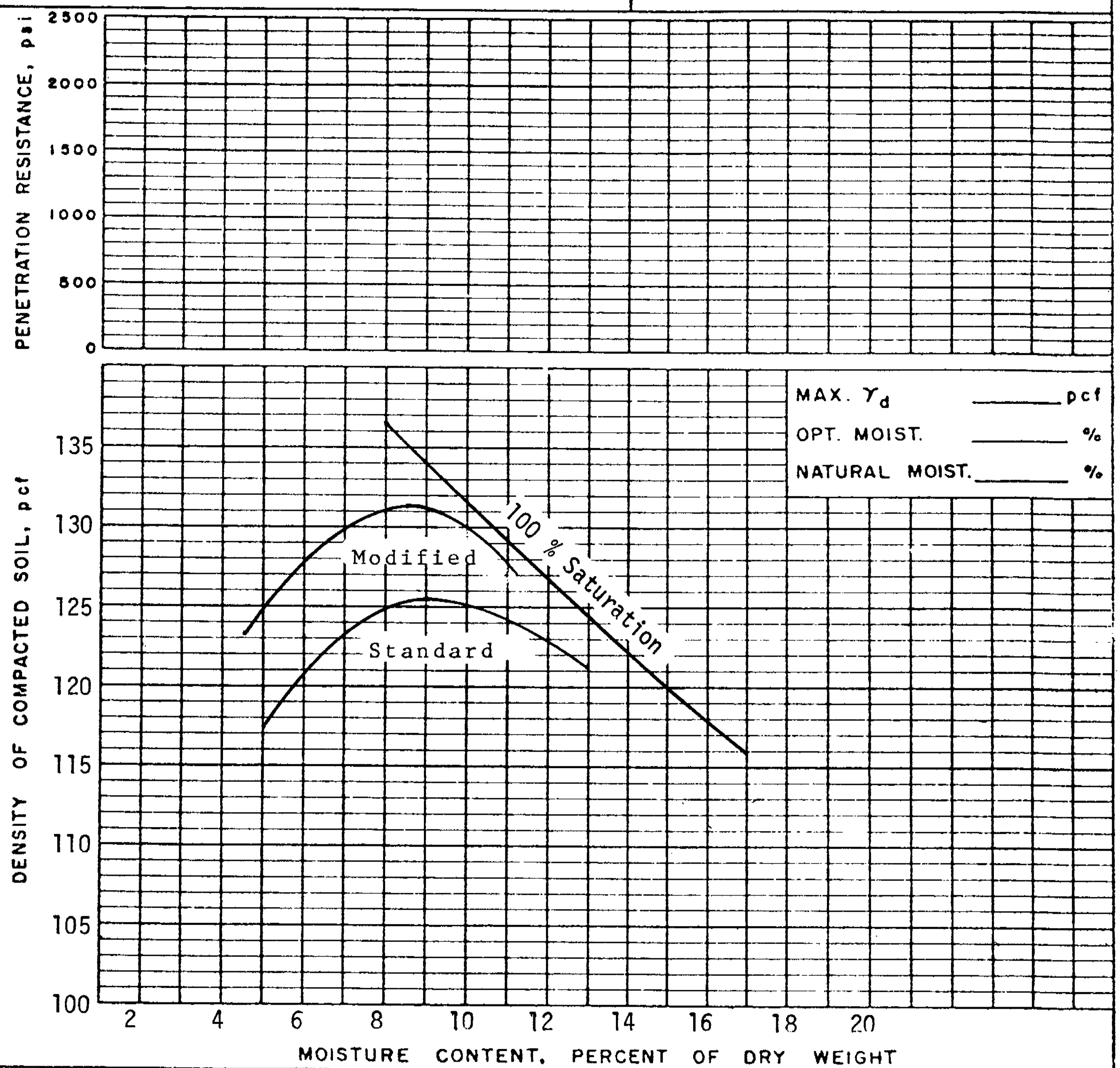
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.66 ; PLUS NO. 4 ______

CURVE NO. 6 OF 6

STD. (ASTM D-698) [x]; METHOD A

MOD. (ASTM D-1557) [x]; METHOD A

OTHER TEST [ ] (SEE REMARKS)



REMARKS

USDA-SCS-HYATTSVILLE MD. 1966

ACTIVITY 6 - PROBLEM SOLUTION

	Standard Energy (D 698)		Modified Energy (D 1557)	
Soil Type	Maximum Dry Unit Weight pounds/ft³	Optimum Water Content (%)	Maximum Dry Unit Weight pounds/ft³	Optimum Water Content (%)
CH	89.0	25.0	110.0	16.0
CL	110.5	16.5	125.0	12.5
ML	120.0	12.0	129.0	9.0
MH	86.5	30.5	98.5	24.5
SC	122.0	11.0	128.5	9.5
SM	125.5	9.0	131.5	8.5

Study Figures 6.7, 6.8, and 6.9, before you continue.

START THE TAPE WHEN YOU HAVE FINISHED

Figure 6.7

TYPICAL COMPACTION TEST RESULTS LESS PLASTIC, SANDY SOILS

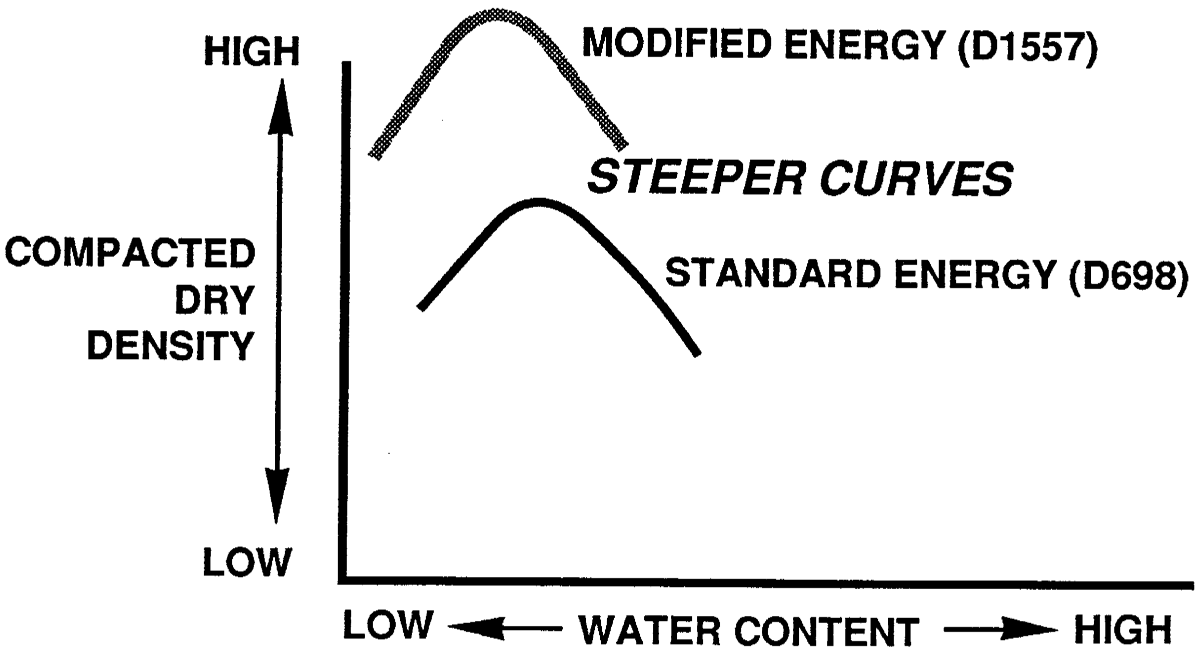


Figure 6.8

COMPACTION TEST RESULTS

Actual construction equipment may apply higher energies than standard laboratory compaction tests

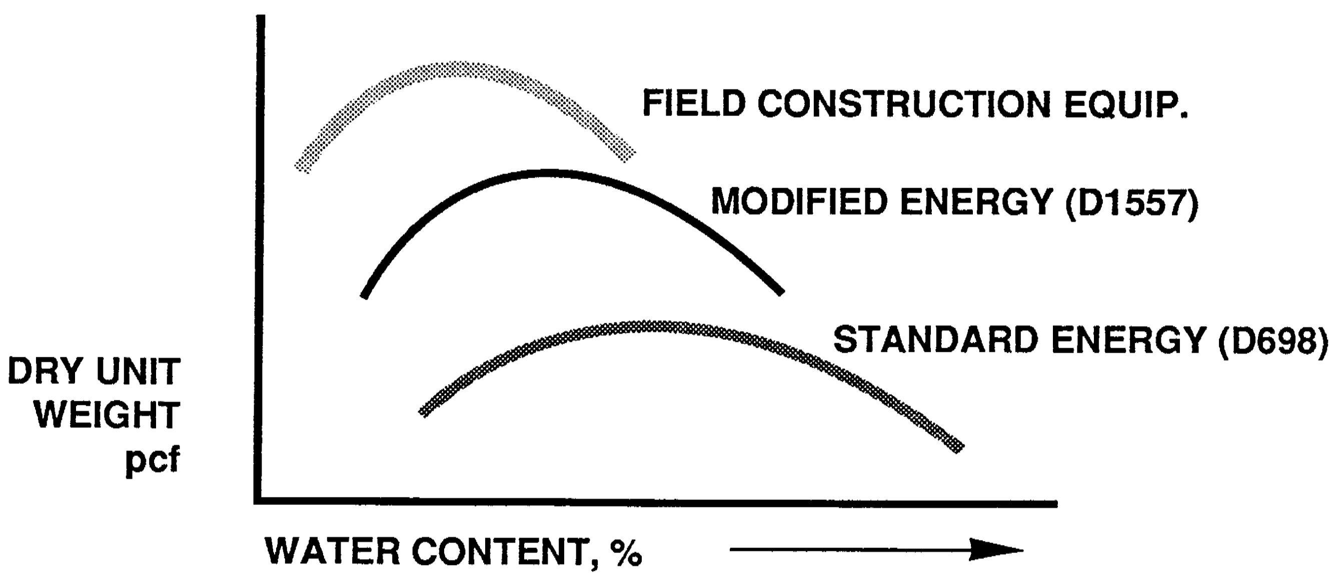
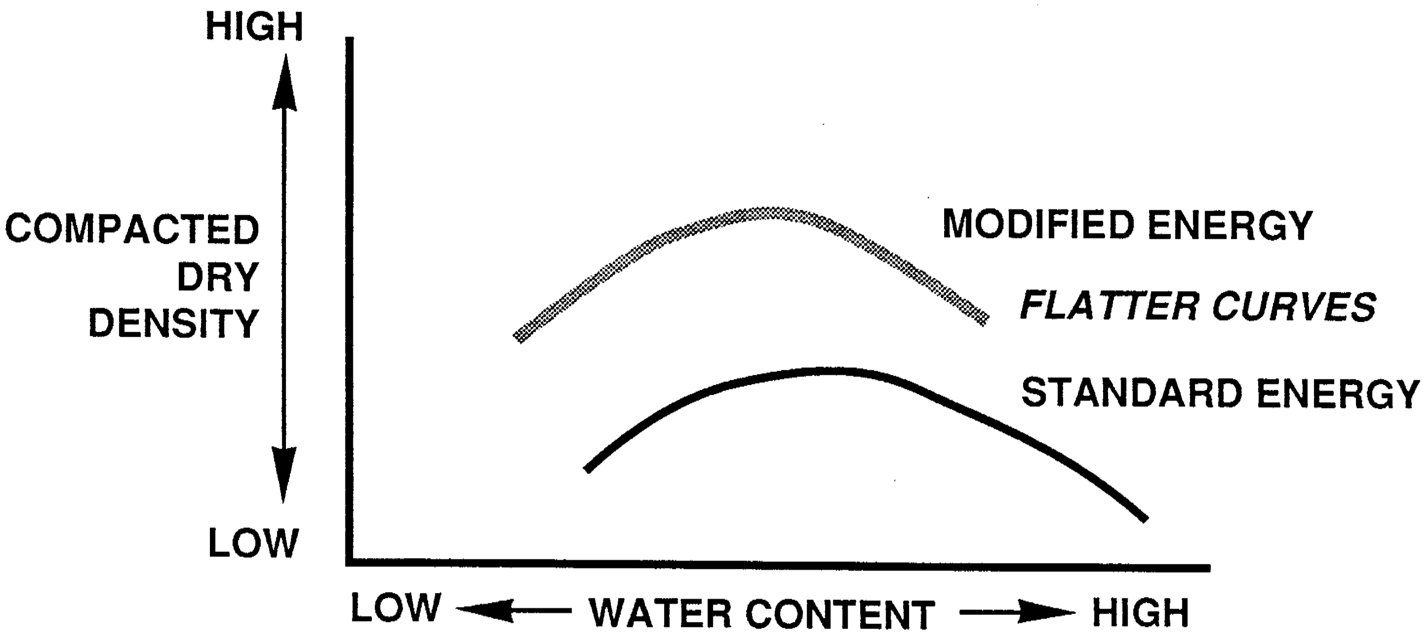


Figure 6.9

TYPICAL COMPACTION TEST FOR PLASTIC FINE - GRAINED SOILS



ACTIVITY 7 - USE OF COMPACTION TEST IN DESIGN AND CONSTRUCTION

The use of the compaction test in the design of an earth fill and in the quality control of the constructed fill are discussed in this Activity. One must understand the purpose for performing this test in the laboratory as part of the design process and the subsequent use of the test during construction for quality control and contract compliance.

Soil samples for a proposed fill construction are usually obtained during the site investigation for a project. The number of samples required depends on the uniformity of the borrow source soils and the anticipated yardage of fill required. Very few samples may be required if a small fill is to be constructed using soils from a uniform deposit of similar soils. A large number of samples may be needed to represent a large earth fill constructed from borrow sources with widely varying kinds of soils. One rule-of-thumb that has been used is that a sample should be obtained if it is likely that the soil type will represent over 10 percent of the completed fill.

The size of sample obtained is critical if adequate quantities are to be available for performing the necessary laboratory tests. The following table gives recommended sample sizes needed for laboratory testing of proposed borrow soils. The table is based on a needed dry weight, and wet samples should be larger.

Estimated Gradation of Soil	Minimum Sample Size, Pounds
less than 10% gravel	25
10% to 50% gravel	50
more than 50% gravel	150

Compaction tests may not be required on all samples submitted to a laboratory for testing. Samples may be grouped on the basis of Unified Classification, Atterberg limit data, gradation, and geologic origin. Representative samples from each group may then be tested. Usually, soils with similar gradation and Atterberg limit data that have similar geological origin will have similar compaction characteristics.

The compaction test standard used is usually based on an organization's experience and precedence. The Soil Conservation Service usually bases its designs upon compaction tests performed using the ASTM D 698, or Standard, compaction test. Many highway departments use the Modified Proctor (ASTM D 1557) method for compaction tests in their designs because a higher density is used for highway subbases.

After performing compaction tests on representative samples, the designer then selects an arbitrary percentage of the maximum dry unit weight as the preliminary basis for the design.

CONTINUE TO THE NEXT PAGE

In Soil Conservation Service projects a preliminary design often assumes soils to be placed at 95 percent of their maximum Standard dry unit weight. Using this value of dry unit weight, then, engineering tests such as shear strength, consolidation, permeability, and shrink swell tests are performed in the soils laboratory. Tests may also be performed at several different water contents. These test results and various analyses are used to determine if the preliminary design placement densities and water contents are satisfactory.

If an acceptable design results, the final design will then include specifications for placement of the fill soils at these design percentages of the reference compaction test method within the range of water contents selected. If analyses indicate that soil engineering properties are unsatisfactory at the preliminary design densities and water contents, then a higher value of design density may be assumed, perhaps 100 percent of maximum Standard Proctor density. Additional tests and analyses are then performed to determine whether satisfactory engineering properties result from the revised design densities and water contents.

As mentioned, water content is usually as important a consideration as design densities. Remember that a number of tradeoffs must be considered. Placement wet of optimum will usually result in a more flexibile product with lower swell properties, but there is some sacrifice in shear strength, and compressibility may be higher. Design placement water contents are usually referenced to optimum water content. A typical design would be to place soils at water contents from 1 percent dry of optimum to 3 percent wet of optimum. On many small Soil Conservation Service projects where shear strength is a minor consideration, placement is specified as any water content equal to optimum water content or higher. This results in good flexibility.

On projects where embankments are to be constructed that are greater than about 50 feet in height of plastic, fine-grained soils, an upper limit is often placed on placement water contents. This is necessary to prevent the development of internal pore pressures during construction. If allowed to develop, these pressures can adversely affect the stability of the embankment. Methods are available for calculating the probable development of these pore pressures for each placement water content and dry unit weight in the preliminary design.

Each kind of soil representative of a significant zone of the fill is usually tested to determine acceptable placement densities and water content range. Ordinarily, all of the soils in a fill are specified to be placed at the same degree of compaction. On some projects, some fine-grained soils may need to be placed at higher percentages of maximum dry unit weight than other, less plastic soils to obtain a similar engineering quality.

The approach of specifying a percentage of maximum dry unit weight and a water content range referenced to optimum water content from compaction tests is necessary when different kinds of soil are on a site. Specifying a single value of dry unit weight or water content for all the soils in a fill is not desirable when different kinds of soil are available with which to construct the fill. A compacted dry unit weight of 100 pounds per cubic feet might be

CONTINUE TO THE NEXT PAGE

quite adequate for a plastic clay soil, but be inadequate for a less plastic, sandy soil. By referencing the required density to a standard test method, quality control is possible even though different soils may be encountered during construction than were sampled for design. A placement water content of 24 percent might be desirable for a plastic clay, but impractical to obtain for a silty sand. Specifying water contents in terms of each soil's optimum water content is the only practical method of obtaining uniformity in fill materials.

During construction of a fill, one must ensure that soils are compacted to the same degree and at the designed water content as was assumed during design of the project. Tests of the compacted fill are performed to determine what are the dry unit weight and water contents. These values are then compared to the compaction test curve and the construction specifications for that soil. If the compacted soil in the fill is determined to have been placed at a dry unit weight at least as high as specified, and the water content is within the range specified, then the portion of the fill represented by that test is regarded as acceptable. If tests indicate that the soils are not compacted adequately, or that the water contents are not within the specified range, then some change in equipment type or methods of operation is usually necessary. Fill that has been improperly compacted must be removed and re-compacted to the required specifications.

Compaction tests must be performed in the field during construction because it is difficult to determine whether the same soils were tested in the laboratory as are used to construct the fill. One must not assume that laboratory compaction tests adequately represent all available fill soils and to rely solely on the laboratory test results for quality control. Factors that may cause samples submitted during design to be unrepresentative of the constructed fill include: (1) obtaining samples from auger borings, (2) mixing of soil deposits by construction equipment, (3) use of borrow areas which were not investigated.

Study Figures 7.1 and 7.2 before you continue.

START THE PLAYER WHEN YOU HAVE FINISHED

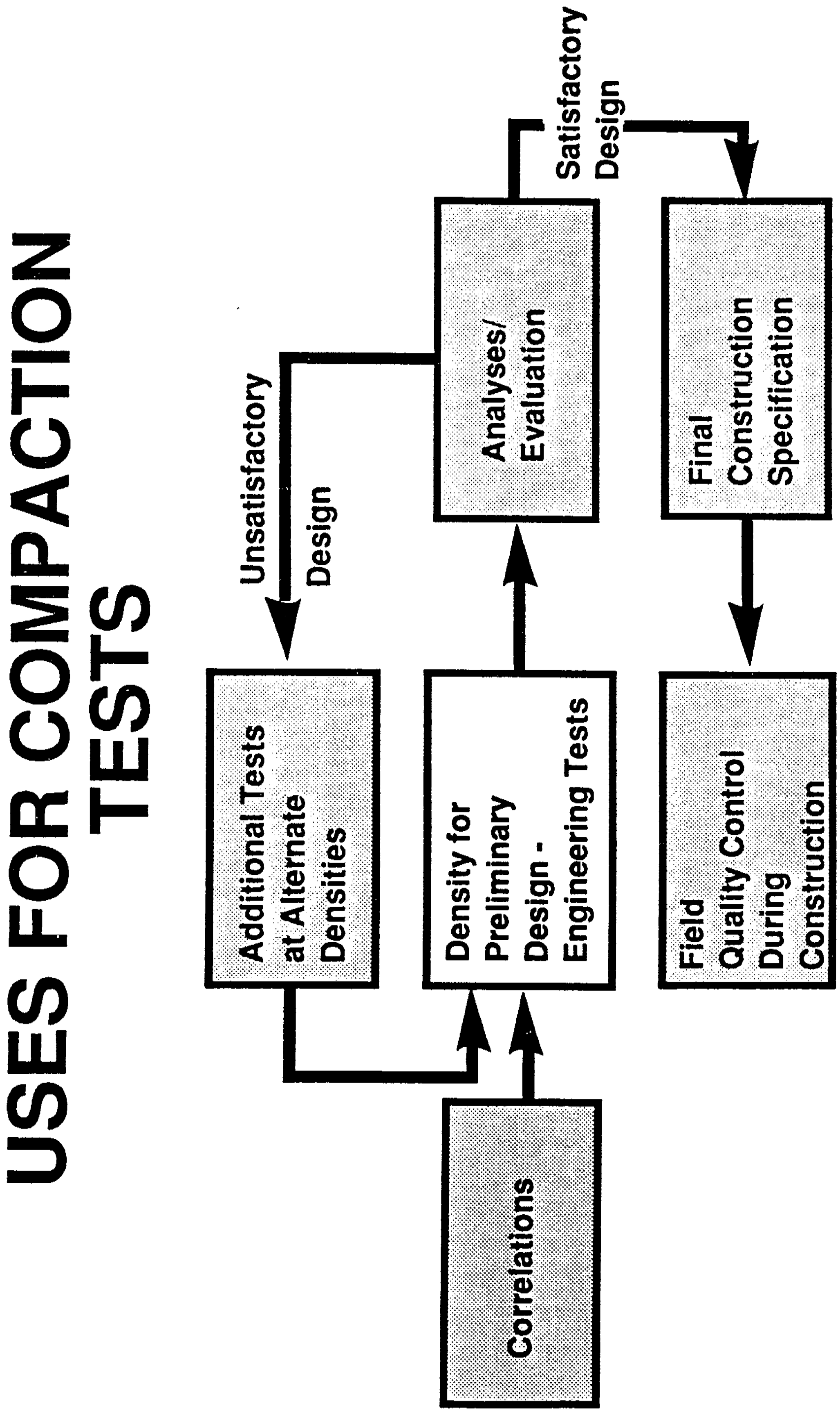
Figure 7.1

USES OF COMPACTION TESTS
CORRELATIONS

Soil No.	% Finer Than .005 mm	% Finer Than #200	Liquid Limit	Plastic Limit	γ_d max pcf	w_{opt} %
1	32	69	32	14	110.5	14.5
2	63	96	62	41	89.5	24.5
3	18	73	--	NP	121.5	10.5
4	29	75	33	15	111.5	14.0
5	59	86	59	38	90.5	23.5

Soils 2 and 5 are similar

Figure 7.2


USES FOR COMPACTION TESTS
Additional Tests at Alternate Densities
Unsatisfactory Design
Density for Preliminary Design - Engineering Tests
Analyses/ Evaluation
Satisfactory Design
Correlations
Final Construction Specification
Field Quality Control During Construction

ACTIVITY 8 - PERFORMING A COMPACTION TEST

In Activity 8 you will perform a complete compaction test using ASTM Test procedure D 698 Method A. You will be furnished the necessary equipment and suitable soil sample for testing. A copy of the D 698 Standard Test Method is included as a supplement to this Manual. You should insert this Standard into the provided plastic envelope, because information will be lost by using a three-hole-punch on it. A detailed video tape instruction is shown at the time you take Activity 8, by the Technical Facilitator.

Data forms for recording the test data as you perform the test are attached to this Activity on following pages. Also included is a blank Form SCS-352 which you should use to plot the completed test. Retain this test data and plotted compaction curve for use in Part E of this Module, Evaluation of Compaction Test Data.

This Activity will require you to coordinate with your Technical Facilitator in your state or NTC to determine a suitable time and location for completing the Activity. You may wish to complete Activity 9 and the rest of the Module if there is a considerable delay before you are able to schedule Activity 8. However, you should complete this activity no later than 6 months after completing the rest of the Module. You cannot receive credit for completing this Module until you complete this Activity.

WHEN YOU HAVE COMPLETED STUDYING THIS INFORMATION PROCEED WITH THE MODULE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

WORK SHEET FOR COMPACTION AND PENETRATION RESISTANCE DATA

Sample No.: ____________

COMPACTION DATA (Record Weights in Pounds)

1	Wt. of Cyl. + Soil						
2	Wt. of Cylinder						
3	Wt. of Soil = (1) - (2)						
4	Wt. per Cu. Ft. (Wet) = (3) ÷ Vol. of Cyl.						
5	Wt. per Cu. Ft. (Dry) = $\frac{(4) \times 100}{100 + (9)}$						
6	Proctor Needle Readings						
7	Size Needle (Sq.in.)						
8	Penetration (Lbs./sq. in.) Resistance = (6) ÷ (7)						

MOISTURE DETERMINATION DATA (Record Weights in Grams)

9	Percent Moisture = $\frac{(13)}{(15)} \times 100$						
10	Can Number						
11	Wet Wt. - Can + Soil						
12	Dry Wt. - Can + Soil						
13	Moisture Weight = (11) - (12)						
14	Weight of Can						
15	Dry Weight of Soil = (12) - (14)						

Vol. of Cyl. ______ cu. ft.	
	Standard Proctor
	Modified AASHO
	Other ____________

PROCEDURE DATA:

Wt. of Hammer ____________ Pounds

Drop ____________ Inches

No. of Lifts ____________

Completed by: ____________ Date: ____________

Computed by: ____________ Date: ____________

Checked by: ____________ Date: ____________

Recorded by: ____________ Date: ____________

Density		% H_2O
Wet	Dry	

Project ________________________

Site ________________________

59M-81

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			
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)

PENETRATION RESISTANCE, psi

2500
2000
1500
1000
500
0

DENSITY OF COMPACTED SOIL, pcf

MAX. γ_d ______ pcf

OPT. MOIST. ______ %

NATURAL MOIST. ______ %

MOISTURE CONTENT, PERCENT OF DRY WEIGHT

REMARKS

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ACTIVITY 9 - TEST FOR OBJECTIVES

To test your understanding of the material in Part B and the completion of the desired objectives, complete the following questions:

Match the terms on the left with the correct definition on the right:

1. Mold_____	A. 12,375 foot-pounds/cubic foot
2. Modified Energy _____	B. Peak value from compaction curve
3. Compaction Curve _____	C. Container used to hold compacted soil in the compaction test
4. Maximum Dry Unit Weight _____	D. Typical shape of a compaction curve
5. Optimum Water Content _____	E. To cure or evenly distribute moisture within a compaction sample
6. Standard Energy _____	F. Curve showing relationship between dry unit weight and water content
7. Parabolic _____	G. Water content at which compaction curve peaks
8. Equilibrate _____	H. 56,250 foot-pounds/cubic foot

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

1. The maximum dry unit weight from a modified compaction test on a CH soil will probably be much lower than the maximum dry unit weight from a standard compaction test on the same soil. _____
2. Compaction tests should not be attempted on clean, coarse-grained soils. _____
3. The hammer weight in a Standard compaction test is 10 pounds. _____
4. The optimum water content from a Modified compaction test will usually be lower than that from a Standard compaction test. _____
5. A compacted dry unit weight of 80 pounds per cubic foot would probably be quite high for an SM soil. _____
6. The compaction curve for a Standard test on a CH soil will usually have a very sharp peak at the optimum water content. _____
7. Field compaction tests are not necessary if laboratory compaction tests have been performed. _____
8. Compacting soils to dry unit weights higher than 100 percent of their maximum dry unit weight obtained in a Standard compaction test is possible. _____

CONTINUE TO THE NEXT PAGE

ACTIVITY 9 - Continued

9. Modified energy is about equal to 4 times Standard energy. ____

Fill in the blanks in the following statements:

1. A common assumed design on compacted fills in SCS projects is _____ percent of maximum Standard dry unit weight.

2. The _______________ compaction test is often used for design of highway projects.

3. The volume of the mold used in the compaction test for soils that have no gravel particles is about ____________ cubic foot.

4. In the Modified compaction test, _______ lifts are used to fill the compaction mold.

5. Standard test methods are published by a national organization with the abbreviation __________ which stands for __________________________ ____.

6. In preparing specimens for a compaction test, water must be allowed to _______________ in the soil before performing the test.

7. Usually __________ to __________ specimens are needed to develop a compaction curve.

8. Plastic soils will have a ______________ optimum water content and a ________________ maximum dry unit weight than slightly plastic soils.

9. In preparation for Method A compaction tests, soils are first screened through a __________________ sieve.

10. The test method that uses 12,375 foot-pounds per cubic foot is also called the ______________________ method.

11. Complete the following table.

Test Method	Size Mold	Hammer Weight	Drop Ht.	No. Blows Per Lift	No. Lifts	Maximum Particle Size	Maximum Gravel Content
ASTM D 698 A							
ASTM D 1557 A							

12. An earth fill is being constructed of a CL soil on which a standard (ASTM D 698 Method A) compaction test has been performed. Design and construction specifications require the soil to be placed at dry densities of 95.0 percent of maximum dry density at water contents in the range of 1% dry of optimum to 3% wet of optimum. The compaction test for the soil is shown on page 53.

A test on the compacted fill resulted in a measured dry density value of 103.9 pcf and a water content of 16.3%. Is the fill acceptable?

WHEN YOU HAVE COMPLETED THE ACTIVITY, REVIEW THE ANSWERS PROVIDED ON PAGE 50

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

ACTIVITY 9 - PART B

LABORATORY NO ______

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

PROJECT and STATE
Figure 9.1 Compaction test results for CL soil

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

CLASSIFICATION CL LL 31 PI 15

MAX. PARTICLE SIZE INCLUDED IN TEST #4 "

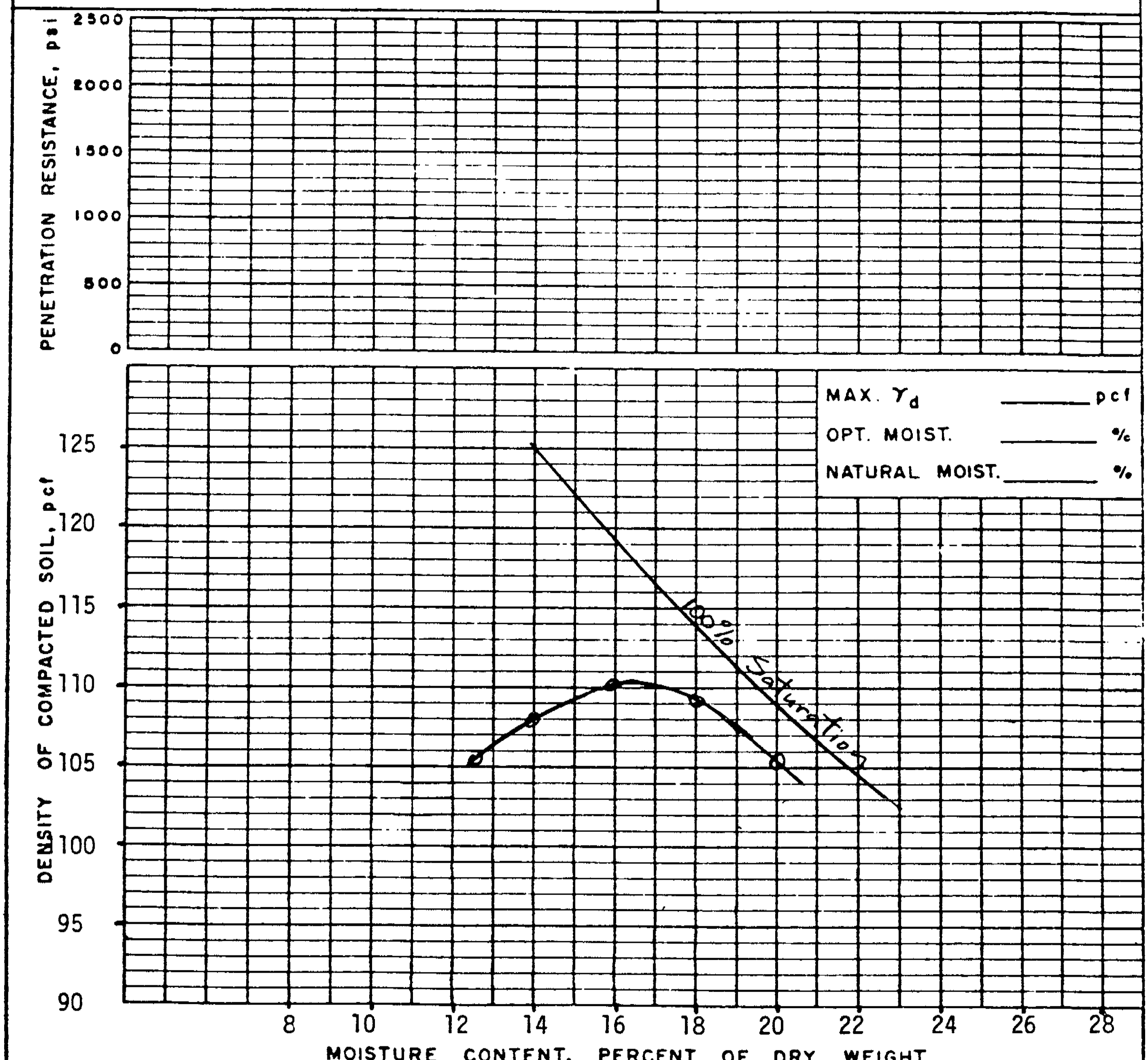
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.66; PLUS NO. 4 ______

CURVE NO. 2 OF 6

STD. (ASTM D-698) ☒; METHOD A

MOD. (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)



REMARKS

USDA-SCS-HYATTSVILLE MD 1966

ACTIVITY 9 - Solution to Problems

Matching terms:

1. C 5. G
2. H 6. A
3. F 7. D
4. B 8. E

True/False statements:

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

Fill in blanks:

1. 95
2. Modified (ASTM D 1557)
3. 1/30
4. 5
5. ASTM, American Society for Testing and Materials
6. equilibrate or cure
7. 4 to 5
8. higher, lower
9. number 4
10. Standard or ASTM D698 Method A

11.

Test Method	Size Mold (ft^3)	Hammer Weight (lbs.)	Drop (in.)	No. Blows/ Lift	No. Lifts	Maximum Particle Size	Maximum Gravel Content
ASTM D 698 A	1/30	5.5	12	25	3	#4	20
ASTM D 1557 A	1/30	10	18	25	5	#4	20

12. The plotted compaction curve has a maximum dry density of 110.5 pcf and an optimum water content of 16.5%.

The fill density of 103.9 pcf is equal to

$$\frac{103.9}{110.5} \times 100 = 94.0\% \text{ of maximum}$$

The water content is -0.2 dry of optimum and is acceptable.

Because the fill dry density is not equal to or greater than 95% of the compaction curve maximum dry density, the fill is not acceptable.

APPENDIX

1 ENG-SOIL MECHANICS TRAINING SERIES--
BASIC SOIL PROPERTIES
MODULE 5 - COMPACTION
PART B
COMPACTION OF NON-GRAVELLY SOILS

-

Part B of Module 5 covers standard compaction tests for soils that have low gravel content and more than 12 percent fines. Major topics include the history of the development of the
2 compaction test and standard procedures for performing a test.

-

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

Objective 1:

From a list, define the important terms associated with the procedures and equipment used in performing compaction tests.
3

-

Objective 2:

4 Describe how compaction test results are affected by soil gradation and plasticity characteristics.

-

Objective 3:

Describe the effects of different energy levels on compaction
5 test results.

-

Objective 4:

Using example data, compute and plot results of a compaction test and determine values of maximum dry density and optimum
6 water content.

-

Objective 5:

Explain the purpose of laboratory and field compaction tests. Explain how compaction tests are used in design and quality
7 control of earth fills.

-

Objective 6:

8 Using field equipment and a soil sample provided, perform a compaction test by standard procedures.

-

Activity 1 These objectives are listed in your Study Guide, Activity
9 1. Stop the tape and review that Activity before continuing.

-

The important principles of soil compaction theory were first stated by R. R. Proctor, in the 1930's. He first recognized that the dry unit weight of a compacted soil varied with the amount of energy used to compact the soil and the water
10 content at which the soil was compacted.

-

Proctor designed and built an apparatus that could deliver a standardized energy while compacting a soil. By eliminating the variable of energy, then the relationship between compaction water content and dry unit weight can be examined
11 separately.

-

Proctor discovered that for any given soil, a unique relationship exists between water content and compacted
12 density, for a given energy application.

-

13

As a "rule-of-thumb", soils with less than 12 percent fines are difficult to test using Proctor's test procedures. Tests on these relatively clean, coarse-grained soils will be covered in a later part of this Module. Standard procedures are also not available for soils that have a high percentage of large gravel-size particles.

-

Activity 2

14

Activity 2, in your Study Guide summarizes the main points covered in this introduction to compaction. Stop the tape and review this Activity before continuing.

-

ASTM

15

The procedures used to perform compaction tests, and the terminology associated with the tests will now be covered. Standard test procedures are established by the American Society for Testing and Materials. The organization publishes standard test methods for soils and other materials. These test standards are necessary so that all laboratories follow the same procedures.

-

D 698
D 1557

16

Two standardized energy levels are commonly used to perform compaction tests. Details on the tests are covered later in the Module. The two standardized tests are referred to by their ASTM designations, tests D 698 and D 1557.

-

Method A
B
C

17

Within each of these standardized tests, there are variations of procedures. These variations depend on the gradation of the soil to be tested. Each ASTM compaction test procedure has three variations, referred to as Methods A, B, and C.

-

Method Used Depends On:
% FINER THAN
#4
3/8"
3/4"
#200

18

To determine the proper variation to be used, you must first determine the gradation of the soil to be tested. Data required include the percent passing the three-quarter inch, the three-eighths inch, the number four, and the number 200 sieves. Gravel particles larger than three-quarters inch are not used in normal compaction tests.

-

Activity 3

19

The flow chart shown in Activity 3 is useful for determining which of the test variations should be used for performing a compaction test. The activity also contains example soil gradation data and problems on use of the flow chart to select the proper test method. Stop the tape and complete the Activity before continuing.

Method A Tests

20

This Part of Module 5, Part B, will cover tests performed by Method A of the ASTM procedures. As you have seen, test method A applies to soils that have 20 percent or less gravel content. Test methods B and C apply to soils with more than 20 percent gravel. These test methods will be covered in the next part of this Module, Part C.

Standard Procedures Not Available For Soils With < 12% Fines Or > 30% Plus 3/4"

21

Remember from the previous Activity that standard compaction test procedures are not available for soils with less than 12 percent fines or more than 30 percent of particles larger than three-fourths inch.

Remove Gravel

Rock Corrections Used If % Gravel Is > 5%

22

To perform a Method A test using either test procedure ASTM D 698 or D 1557, a soil sample is first processed through a number four sieve to remove any gravel sized particles. If a sample has more than five percent gravel, corrections may be made to test results as covered in Part C of the module. No corrections are necessary if the sample has five percent percent or less gravel.

Air-Drying May Affect Test Results On Some Unusual Soils

23

Many soils may be air-dried to facilitate sieving out any gravel present, but some unusual soils may be drastically affected by air-drying. Those soils should not be air-dried prior to testing. The test requires about 25 pounds of soil on a dry weight basis.

epare 4 To 5 Specimens .\t Successively Higher Water Contents Initial Water Content Of Series Of Specimens 24	In preparation for performing a compaction test, a series of 4, or preferably, 5 samples of soil are prepared at successively higher water contents. The water contents used are selected as follows. The initial water content, or the water content of the first specimen, is obtained by either adding or removing water from the prepared sample.
Soil Forms Ball When Squeezed 25	The water content of the initial sample in the series of prepared samples should be that at which the soil will just form a coherent mass or ball when squeezed.
4 To 5 Pounds Of Soil Needed For Each Test Specimen 26	Usually, from four to five pounds of moist soil are required for each prepared specimen. This amount needed varies with the soil type and water contents used.
Water Contents Should Be 1-1/2% Apart 27	Specimens at successively higher water contents are prepared by adding water so that the water content of the specimens are spaced about one and one-half to two percentage points apart. Each specimen is placed in an airtight container for curing.
Curing Period From 3 To 40 Hours 28	The curing period required is based on the plasticity of the soil, and varies from 3 to 40 hours. Curing of water content is required to permit thorough wetting of all soil particles.
Specimen Compacted Into Mold With Hammer 29	After the samples are cured, the first specimen to be tested is compacted into a cylindrical mold. Compaction of the soil results from dropping a hammer of standard weight and dimensions a specified distance for the required number of times. Several lifts of soil are used to completely fill the mold. The weight of hammer, height of drop, number of blows of the hammer, and number of lifts of soil required to fill the mold are variables in the two standard tests, D 698 and D 1557.

Photo Of Mold — Method A tests use a mold with a diameter of about 4 inches, which has a volume of about one-thirtieth of a cubic foot. The volume of the mold is carefully determined before

30 testing, and its weight also predetermined.

-

Photo — After compacting the soil into the mold using specified

31 procedures, the excess soil is carefully removed.

-

Photo

32 The mold and compacted moist soil are then weighed.

-

Equation For Moist Unit Weight — Using the equation shown, the wet unit weight of the compacted specimen is calculated. Units commonly used for wet unit weight are pounds per cubic feet or kilograms per

33 cubic meter.

-

Photo — A representative portion of the soil in the mold is obtained and the water content is determined by drying in an oven,

34 usually overnight.

-

Photo — Soil is dried in an oven set to the proper temperature - usually 110 degrees Centigrade. Soils with hydrated minerals, such as gypsum, must be dried at a lower temperature to prevent driving off hydrated water. Usually,

35 sixty degrees Centigrade oven temperature is used for those soils.

-

Dry Unit Weight Equation — If the wet unit weight and the water content of the compacted

36 soil is known, then a dry unit weight may be calculated by the equation shown:

-

;urve With 1 Point Shown 37	The values of dry unit weight and water content represent one point on the compaction curve that is being developed by the test.
Curve With 5 Points Shown 38	The remaining specimens are then compacted using the same procedures. Values for wet unit weight, water content, and dry unit weight are obtained for each specimen. By plotting values of dry unit weight versus water content, a compaction curve is developed for the soil and energy level used in the test. As you will see, this curve is unique for every soil and energy level used.
Test Showing Excessive Number of Points Due To Low Initial Water Content 39	To develop a complete test, specimens must be tested at successively higher water contents until a decrease in wet unit weight occurs. If good judgement is used in selecting a starting water content, four or five specimens will develop a good curve. If poor judgement is exercised, the test may be re-run, or additional test specimens may be prepared at higher, or lower, water contents.
Typical Curve 40	The plotted curves of dry unit weight versus water content typically have a parabolic shape as shown. Depending on the scales used to plot the data, and the kind of soil being tested, the curves may be quite flat or quite steep.
Illustrated Scales 41	Using the same scale is important for dry unit weight and water content each time you plot the data. This will allow you to develop an experience base for the typical curve shapes of different soil types. The scales shown here have been found by SCS engineers to be satisfactory for most tests.

Maximum Dry Unit Weight Optimum Water Curve 42	This is a typical compaction test curve. Several terms are defined from the curve. The peak value of dry unit weight is called the maximum dry unit weight. It may be reported in pounds per cubic foot or kilograms per cubic meter. The water content at which this peak occurs is called optimum water content.
Wet Unit Weight Versus Water Content Used For Some Field Applications 43	Although wet density versus water content may be plotted as well as dry unit weight, the plot of wet unit weight is used only for special applications in field control, and its use is not covered here.
Activity 4 44	Activity 4 of your Study Guide has example test data for a compaction test performed on a soil with gravel removed - Test Method A, using ASTM D 698, procedures. Using the test data, compute and plot values of dry unit weight and water content and plot the test data. Determine the value of maximum dry unit weight and optimum water content for the soil tested. Stop The Tape And Complete The Activity.
ASTM D 698 Method A Illustration Of Hammer Weight Height Of Drop Blows Per Lift Lifts To Fill Mold 45	Next, details on the standard energy tests are covered. The first to be discussed is ASTM D 698, commonly referred to as "standard" energy. This test uses a hammer weighing five and one-half pounds that is dropped a distance of twelve inches for 25 drops per lift of soil compacted in the mold. The mold is compacted in 3 equal lifts. Using the equation shown, the energy applied in compacting the soil is 12,375 foot-pounds per cubic foot of soil.
D 698 Used or Design of Most SCS Structures 46	ASTM D 698 compaction tests are most commonly used in design of SCS structures. For some applications, one may want to know the relationship between dry weight and water content for a higher level of energy application. The ASTM test for a higher energy is ASTM D 1557, also called the "Modified" compaction test.

ASTM D 1557 Weight of Hammer Height of Drop Blows per lift Lifts to Fill Mold 47	In the ASTM D 1557 test, 56,250 foot-pounds of energy per cubic foot are applied to each specimen in the test. A hammer weighing ten pounds is used. It is dropped a distance of 18 inches a total of 25 times per lift, with 5 lifts of soil used to fill the mold.
	-
Activity 5 48	Activity 5 summarizes the two standardized energies used for compaction tests. Stop the tape and review the activity.
	-
Index Property 49	The compaction test curve developed for a particular soil and energy level used is essentially an index property of the soil tested, just as are Atterberg limits and gradation. Each soil tested has unique values and curve shapes.
	-
Compaction Curves For CH Soil For Both D 698 Method A and D 1557 Method A 50	A soil's maximum dry unit weight will be higher for a Modified test compared to a Standard test because of the higher energy used. ASTM D 1557 compaction test curves will also typically have a lower optimum water content than D 698 tests. These compaction tests are for a CH soil using both test energy levels on the same soil. Note the drastic differences in the values of maximum dry unit weight and optimum water content.
	-
Other Energy Tests California Compaction Test 51	Other energy levels have been used for performing compaction tests by some engineering organizations. These test methods are not completely standardized at present and infrequently used in the SCS. Therefore, they are not discussed in this Module. One example is the "California" compaction test, which uses 20,300 foot-pounds per cubic foot of energy.
	-

Effect of Plasticity on Test Results

52

The values obtained for maximum dry unit weight and optimum water content vary with the type of soil being tested and the energy used. Fine-grained, plastic soils have relatively low values of maximum dry unit weight and high values for optimum water content for a given energy.

-

Effect of Plasticity on Test Results

53

Sandier soils and soils that have less plasticity, have higher values of maximum dry unit weight and lower values of optimum water content for a given energy.

-

Curve Shape Depends

54

The shape of the compaction curve also depends on the kind of soil tested and the energy applied during the test.

Typically, fine grained, plastic soils will have a broad, very flat curve. Less plastic soils or sandier soils will have a steeper curve with a more pronounced peak. Higher energies usually produce a curve with a more pronounced peak than lower energies.

-

ACTIVITY 6

55

Activity 6 shows typical values for compaction test results for selected Unified Soil Classification groups. Only the Unified Classes to which procedures of this Part of the Module apply are covered. Stop the tape and complete Activity 6.

-

Higher Energies Result In Higher Unit Weights and Lower Optimum Contents

56

Heavy construction equipment and intensive processing of earth fills often result in compacted soil that has dry unit weights greater than those given by standard laboratory tests. The illustration shows a compaction curve obtained by compacting samples of soil in an earth fill with large equipment at several water contents. Note that this curve has a higher value of maximum dry unit weight than the standardized laboratory compaction tests. The field equipment has applied more energy than the laboratory tests. Note also that optimum water content is lower for the higher energy application.

-

No Absolute Value for Dry Unit Weight - Depends On Amount and Type of Energy
57

This should help you realize that a given soil does not have an absolute value of maximum dry unit weight or optimum water content. Values depend on the energy used to compact the soil. Maximum dry density and optimum water content are relative terms for a particular energy.

-

Purposes of Compaction Tests
58

The uses and purposes of compaction testing will now be covered. Some uses are:

1. Correlating soils.
2. Preliminary design densities for engineering property tests.
3. Construction specifications.
4. Quality control of constructed fills.

-

Correlations
59

Compaction test values, together with other index properties such as gradation and Atterberg limits may be useful for grouping soils for correlation purposes. Soils 2 and 5 of the soils shown are very similar based on index properties shown.

-

Uses of Correlation
60

Correlations are helpful in grouping similar soils that are expected to have similar engineering behavior properties. This reduces the number of complex property tests needed, simplifies analyses, and reduces the testing cost for a site design.

-

Preliminary Design Densities and Water Contents
61

Compaction tests furnish preliminary design values for dry unit weight and water content that are used in assigning laboratory tests such as shear strength, consolidation, permeability, and shrink-swell. A designer usually assumes that soil for a proposed fill be placed at some percentage of its maximum dry unit weight at water contents within a prescribed water content range.

Common Preliminary Design Assumes Compaction to 95% of Maximum D 698 Density
62

Commonly, in SCS designs, a preliminary design assumes that soils will be compacted to 95 percent of maximum dry unit weight at water contents of optimum water content or higher, referenced to the ASTM D 698 compaction test.

-

Design Density Re-Evaluated After Analyses
63

If subsequent testing and analysis indicates that the preliminary design is inadequate, additional engineering property tests may be performed at higher densities or other water contents.

-

Highway Construction Designs Commonly Referenced to Modify Compaction Tests D 1557
64

Some applications, particularly highway construction using plastic, fine-grained soils, routinely use ASTM D 1557 compaction as the reference test for design. A higher design unit weight results, which produces more rigid soil more suitable for highway sub-bases. Typical preliminary designs for these applications are for dry unit weights equal to 90 percent to 95 percent of maximum D 1557 dry unit weight.

-

Satisfactory Design Specified for Construction
65

The degree of compaction and range of water content that produce the desired engineering properties for the soils on a particular site will then form the basis for the design of a site. A construction contract can be written requiring that all fill soils will be placed at the designed percentage of maximum dry unit weight within the range of specified water contents.

-

66

Using the compaction test as a reference for specifying fill placement unit weights and water contents is necessary because of the variability of soils on most sites. If one could be assured that all of the soils to be used in a fill were exactly alike, then a designer could specify only a single value for dry unit weight and water content which would produce an acceptable fill.

-

For instance, a placement dry unit weight of 100 pounds per cubic foot would probably be excellent for a plastic clay, but would be very low for a slightly plastic silt. Placement at twenty percent water content might be acceptable for a plastic CH soil, but would be a very wet placement water
67 content for a slightly plastic ML soil.

-

Compaction tests are also used in quality control of earth fills during construction. By performing tests to determine what are the dry unit weights of the completed fill, and comparing them to the compaction curves and design requirements for those soils, quality control of the earth fill is accomplished. Quality control of earth fills is
68 covered in Module 11 of this series.

-

Activity 7 Activity 7 covers the main points just covered.
69 Stop the tape and review the Activity before continuing.

-

Activity 8 Activity 8 requires you to actually perform a compaction test using test Method ASTM D 698 Method A. Your Technical leader will furnish you with the necessary equipment and a suitable soil sample. Carefully study the test procedures given in Activity 8 of your Study Guide, and complete the test. When you have completed this exercise, resume the tape at the next
70 slide.

-

Let's review the objectives of Part B of this Module.

Objective 1 was to define the important terms used in describing the procedures and equipment used in performing
71 the compaction test.

-

Objective 2 was to describe how compaction test results are
72 affected by soil gradation and plasticity characteristics.

-

Objective 3 was to describe the effects of different energy
73 levels on compaction test results.

-

Objective 4 was to compute and plot results of a compaction test and determine values of maximum dry density and optimum
74 water content using example test data furnished.

-

Objective 5 was to explain conceptually from memory the purpose of laboratory and field compaction tests and explain how compaction tests are used in design and quality control
75 of earth fills.

-

Objective 6 was to perform a compaction test using standard procedures and equipment furnished on a sample of soil furnished, and determine accurate values of maximum dry unit
76 weight and optimum water content.

-

To test your completion of the objectives of this part of the
77 Module, complete Activity 9 in your Study Guide. Stop the tape and complete the Activity.

-

You are now ready to continue to Part C of the Module covering compaction tests of soils with more than twenty per
78 cent gravel.

-

United States
Department of
Agriculture

Soil
Conservation
Service

Soil Mechanics Training Series

Basic Soil Properties

Module 5 - Compaction

Part C - Compaction of Gravelly Soils

Study Guide

ENG-SOIL MECHANICS TRAINING SERIES--

BASIC SOIL PROPERTIES

MODULE 5 - COMPACTION

PART C

COMPACTION OF GRAVELLY SOILS

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--
BASIC SOIL PROPERTIES
MODULE 5 - COMPACTION
PART C
COMPACTION OF GRAVELLY SOILS

INTRODUCTION

This is Part C of Module 5 - Compaction of Gravelly Soils 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 C has three 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 C 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

At the completion of Part C you will be able to:

1. State which ASTM compaction test method is applicable for soils that have given gravel contents.

2. Explain conceptually the differences between the three ASTM compaction test methods.

3. Define each of the terms in the rock correction equations.
   Use the equations to solve simple problems from given compaction data and gradation data.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 2 - COMPACTION TESTS WITH GRAVEL INCLUDED

When soils to be used in an earth fill contain significant amounts of gravel, the engineering properties of the soil are likely to be appreciably different from similar soils that do not have gravel. Usually, 5 percent or more by dry weight of gravel particles are considered significant. The dry unit weight of a soil containing gravel will be higher than a similar, non-gravelly soil, and the water content will be less.

In the design of a project to be constructed with gravelly soils, the engineering properties of the compacted soil should be based on shear strength, consolidation, and permeability tests performed on samples that contain similar amounts of gravel as the proposed borrow soils. To obtain preliminary design densities and water contents for these engineering property tests, you must have compaction test data on samples that contain the proper amount of gravel particles. If soils to be tested have oversize particles which are not included in the compaction test specimens, then rock correction equations may be used to theoretically consider the effect of the excluded oversize particles on the density and water content of the soil.

Several standard test methods are available for testing soils that have small gravel particles. However, standard tests are not available for samples that have more than 30 percent by dry weight of particles larger than the 3/4 inch sieve. (Soils with less than 70 percent passing the 3/4 inch sieve.)

Another need for compaction test procedures which incorporate gravels, or particles larger than the number 4 sieve, is in construction quality control of compacted fills. Compaction tests which include proper amount of gravel more closely model the compacted fill and the degree of compaction of the completed fill can be more reliably assessed if comparison to the proper test method is made. Again, if gravel particles larger than permitted in standard procedures are present, rock correction equations may be useful for determining the theoretical combined density and water content of the compaction test specimens and the excluded oversize materials. These equations and their use are illustrated later in this module.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 3 - SELECTION OF TEST METHOD

Different standardized compaction test methods are used depending on the gravel content of the sample being tested, as you learned in Activity 3 of Part B, of this module.

In Part B, test methods for compaction of soils containing less than 20 percent gravel size particles were covered. This Part of the Module covers compaction test procedures for soils that contain more than 20 percent gravel.

You should recall that standard methods are not available for soils that have less than 70 percent of the sample finer than the 3/4 inch sieve. Also, remember that to perform compaction tests on soils that have less than 12 percent fines is difficult. Such soils should be tested using procedures covered in Part D of this Module.

Soils that contain less than 80 percent fines should be tested by ASTM Test Methods B or C. Method B procedures are used for soils that have less than 80 percent fines (particles smaller than the number 4 sieve) and 80 percent or more finer than the 3/8 inch sieve.

Soils that have less than 80 percent fines and less than 80 percent finer than the 3/8 inch sieve are tested by Method C procedures.

The selection of the proper Test Method applies to tests performed using either Standard (ASTM D 698) or Modified (ASTM D 1557) energy levels.

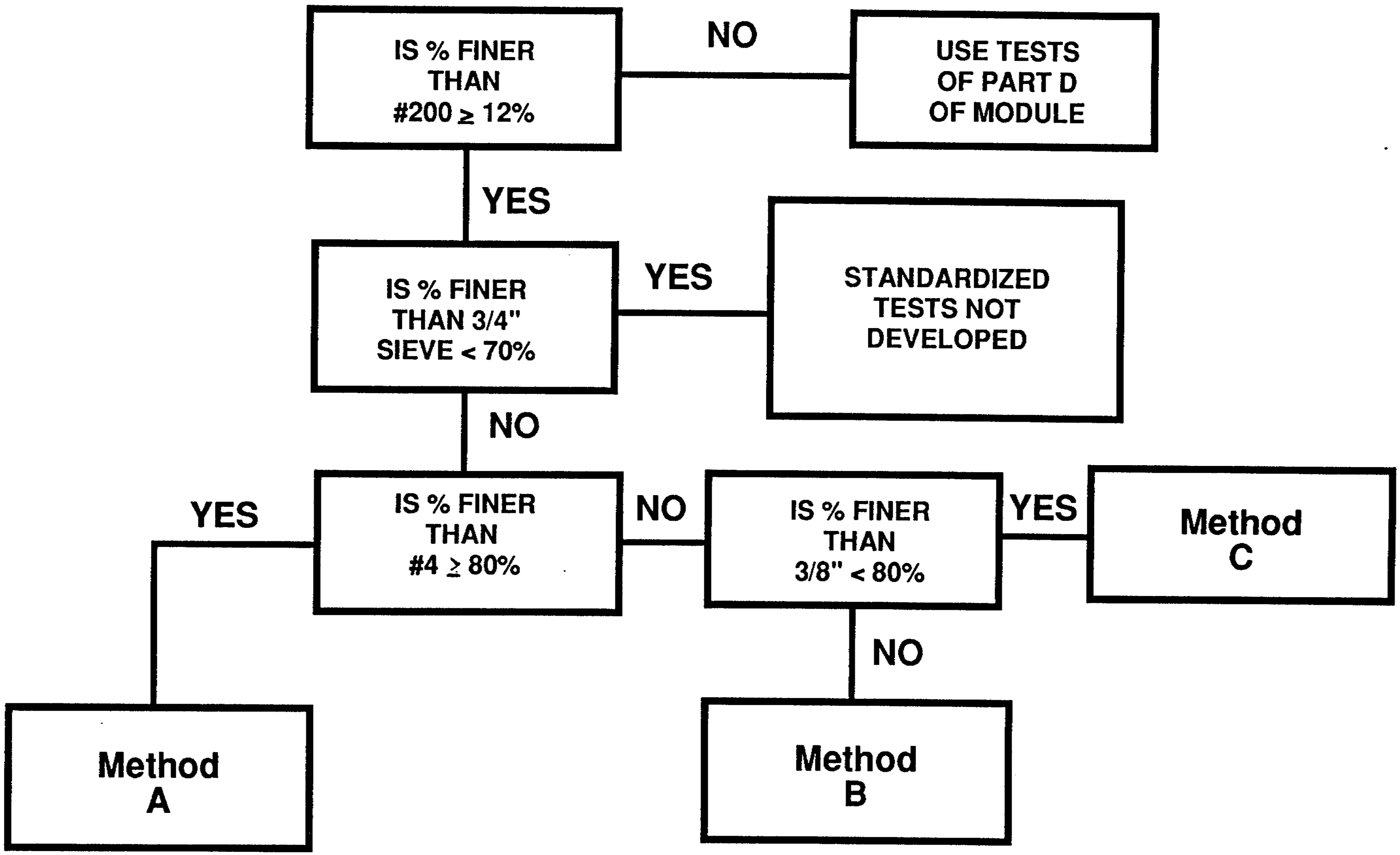
A summary of the criteria for selection of Test Method is as follows:

Percent Finer than #200	Percent Finer than #4	Percent Finer 3/8"	Percent Finer 3/4"	ASTM Test Method
≥12	>79	---	≥70	A
≥12	<79	≥80	≥70	B
≥12	<79	<80	≥70	C
≤12	Use Methods of Part D - Compaction test procedures not applicable			

The flow chart shown in Activity 3 of Part B may also be useful in illustrating these criteria and selecting the proper test method to be used for the soil sample being examined. It is reproduced here for reference, on the following page.

CONTINUE TO PAGE 7

ACTIVITY 3


IS % FINER THAN #200 ≥ 12%
NO
USE TESTS OF PART D OF MODULE
YES
IS % FINER THAN 3/4" SIEVE < 70%
YES
STANDARDIZED TESTS NOT DEVELOPED
NO
IS % FINER THAN #4 ≥ 80%
YES
Method A
NO
IS % FINER THAN 3/8" < 80%
YES
Method C
NO
Method B

ACTIVITY 3 - PROBLEM

To review your understanding of the proper selection of the ASTM Method for performing a compaction test, complete the following table. Use the gradation data provided for each sample and use the flow chart provided to determine the appropriate test method.

Soil No.	Percent Finer 3"	3/4"	1/2"	3/8"	#4	#200	Appropriate Test Method
1	100	98	89	72	64	28	
2	98	68	43	36	29	16	
3	100	100	100	86	79	62	
4	100	82	73	62	49	31	
5	100	100	100	100	98	10	

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

ACTIVITY 3 - SOLUTION

Soil No.	3"	3/4"	Percent Passing 1/2"	3/8"	#4	#200	Appropriate Test Method
1	100	98	89	72	64	28	C
2	98	68	43	36	29	16	Standard tests N/A
3	100	100	100	86	79	62	B
4	100	82	73	62	49	31	C
5	100	100	100	100	98	10	Compaction tests may be difficult to perform

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 4 - METHOD B COMPACTION TESTS

ASTM Test Method B is used for those soils that have less than 80 percent finer than the #4 sieve and 80 percent or more finer than the 3/8 inch sieve.

To prepare soil for Method B tests, the sample is first sieved through a 3/8 inch sieve. If the sample has more than 5 percent plus 3/8 inch size gravel content, the Method B test values will be corrected by equations shown later in the module. Corrections are not necessary if the sample has less than 5 percent larger than the 3/8 inch sieve. The soil to be tested should not have been air-dried before testing if it contains fines that are affected by air-drying. Soils should never be oven-dried before testing.

After sieving out the particles larger than 3/8 inch, four to five specimens are prepared at water contents about 1-1/2 to 2 percent apart in water content. The range of water contents selected is based on experience and feel of the sample. The specimens are then allowed to "cure" an appropriate length of time before compaction. ASTM standards specify the minimum length of curing time depending on the classification of the soil being tested as follows:

Unified Soil Classification Group	Minimum Curing Time (hours)
GM, SM	3
ML, CL, OL, GC, SC	16 (overnight)
MH, CH, OH	40

The compaction test for Test Method B uses the same equipment and procedures as you learned for Test Method A in Part B of this Module. The mold volume is about 1/30 a cubic foot. A value for dry unit weight and water content is determined after compaction of each specimen and a curve is drawn showing the relationship between dry unit weight and water content. The peak of the curve defines the maximum dry unit weight and the optimum water content of the sample for that test method.

The effect of the inclusion of the small gravel particles in Test Method B is to increase the values of dry unit weight and decrease the values of optimum water content, compared to a test of similar soil that does not have the gravel particles.

Typical test results are shown on the following page for a sample tested using Test Method B compared to the same sample tested using Test Method A. The only difference in the two tests is the inclusion of gravel particles smaller than 3/8 inch and larger than the #4 sieve in the Method B test. The Method A test is on soil smaller than a #4 sieve.

Compaction tests may be performed by Method B using both of the standardized energies - Standard and Modified. Details are given in the ASTM Test Method descriptions D 698 and D 1557.

START THE TAPE WHEN YOU HAVE STUDIED FIGURE 4.1 ON PAGE 10

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FILE CODE ENG-22

ACTIVITY 4

LABORATORY NO ______

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

PROJECT and STATE: Figure 4.1 - Typical Compaction Test Results for Method A and Method B Tests

FIELD SAMPLE NO	LOCATION	DEPTH

GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION CH LL 60 PI 40

MAX. PARTICLE SIZE INCLUDED IN TEST ______"

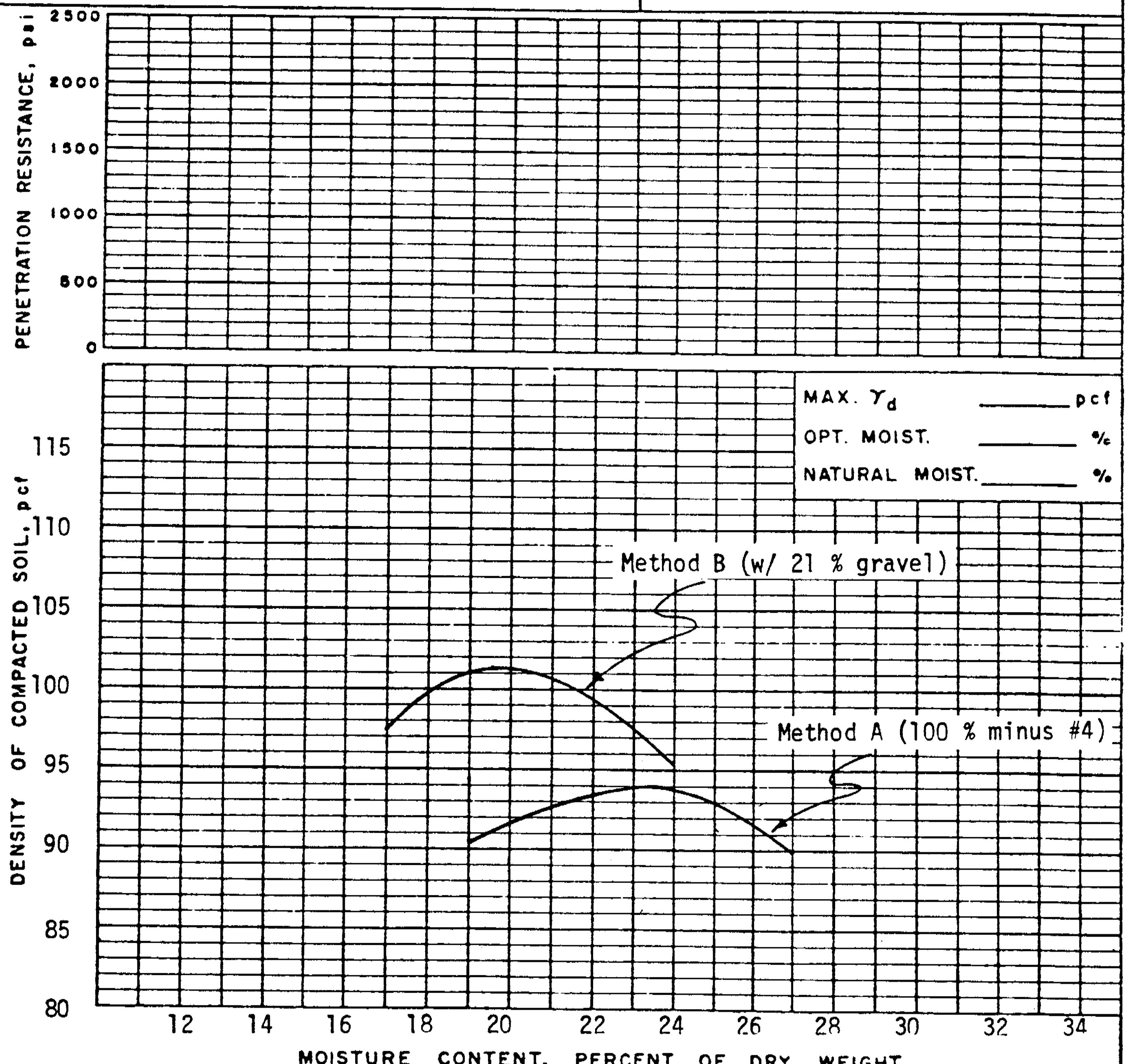
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.66 ; PLUS NO. 4 123.2 (pcf)

CURVE NO. 1 OF 1

STD. (ASTM D-698) ☒; METHOD A&B

MOD. (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)



REMARKS

USDA-SCS-HYATTSVILLE MD 1966

ACTIVITY 5 - METHOD C COMPACTION TESTS

ASTM Test Method C is used for those soils that have less than 80 percent finer than the #4 sieve and less than 80 percent finer than the 3/8 inch sieve.

Soils to be tested by Method C are first sieved through a 3/4 inch sieve. The soil should not be air-dried before testing if the soil has properties that are altered by air-drying. Soils should never be oven-dried before testing.

If the gravel particles in the Method C test are shales or other types of gravels that could be degradable in a compaction test, assess the degree of breakdown of the gravel by determining the gradation of the sample after compaction as well as before compaction. These types of gravels probably should not be air-dried prior to testing.

The next step in performing a compaction test using Method C is to prepare four to five specimens that have successively higher water contents. Base the range of water contents selected on experience and feel of the sample. The specimens are then allowed to "cure" an appropriate length of time before performing the test. Samples that have plastic fines may need to be cured as much as 40 hours. ASTM test methods have specific curing requirements depending on the sample's classification as follows:

Unified Soil Classification Group	Minimum Curing Time (hours)
GM, SM	3
ML, CL, OL, GC, SC	16 (overnight)
MH, CH, OH	40

The compaction test for Test Method C differs in several important respects from Test Methods A and B. Method C uses a 6-inch diameter mold, which has a volume of about 1/13.33 cubic foot. Because a constant energy source is the purpose of the test, and a larger volume of soil is compacted in this Test Method, the number of times the hammer is dropped must be altered to achieve the same energy application per cubic foot of compacted soils.

In Test Method C, each layer is compacted with 56 drops of the hammer. Compare this to the 25 drops of the hammer for the tests that use a 4-inch mold using Standard and Modified energies.

A value of dry unit weight and water content is measured for each specimen tested. A curve is then drawn showing the relationship between dry unit weight and water content. The peak of the curve defines the maximum dry unit weight and optimum water content of the sample tested.

CONTINUE TO NEXT PAGE

The gravel included in the Method C test specimens results in higher values of dry unit weight and lower values of optimum water content than Method A tests on the same soils. The purpose of using Method C tests is to attempt to more closely model borrow soils' densities and water contents when they contain significant quantities of gravels.

Typical test results are shown on the following page for a sample tested using Test Method C compared to the same sample tested using Test Method A. The only difference in the two samples is the inclusion of gravel particles in the Method C test.

Compaction tests may be performed using Method C procedures for either Standard (ASTM D 698) or Modified (ASTM D 1557) energies. You should refer to the actual ASTM test standards for details that are adequate for actually performing these tests. Equipment is available for performing these tests in field as well as laboratory situations.

If the sample from which the test soil was selected contained oversize particles which were screened out in preparation for the test, corrections for density and water content may be desirable. Since oversize particles excluded from the compaction test are usually more dense and lower in water content than the compaction specimen, the corrected test results will usually have a higher value of maximum dry unit weight and a lower value of optimum water content.

Oversize corrections are usually desirable when the percentage of oversize particles is greater than 5 percent. Corrections for oversize particles are not considered accurate, however, if more than about 40 percent of the proposed fill sample is oversize particles. Also, remember that standard compaction tests are not performed on soils with more than 30 percent particles larger than the 3/4 inch sieve. Corrections for oversize particles are not considered accurate, however, if more than about 40 percent of the proposed fill sample is oversize, or 30 percent, if the oversize particles are greater than 3/4 inches in diameter. Oversize correction equations are covered later in this module. To determine whether oversize corrections are appropriate, determine what percentage of the total sample was excluded from the test specimen. For Method C tests, the oversize fraction is that percent of the total sample larger than the 3/4 inch sieve.

A summary of the differences in the various test methods is shown below:

Test method (ASTM)	Volume of mold (ft^3)	Weight of hammer (pounds)	Height of drop (ft)	No. of blows per lift	Number of lifts	Maximum particle size
D 698 A	1/30	5.5	1.0	25	3	#4 sieve
D 698 B	1/30	5.5	1.0	25	3	3/8"
D 698 C	1/13.33	5.5	1.0	56	3	3/4"
D 1557 A	1/30	10.0	1.5	25	5	#4
D 1557 B	1/30	10.0	1.5	25	5	3/8"
D 1557 C	1/13.33	10.0	1.5	56	5	3/4"

START THE TAPE WHEN YOU HAVE FINISHED

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FILE CODE ENG-22

ACTIVITY 5

LABORATORY NO ______

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

PROJECT and STATE: Figure 5.1 - Typical Compaction Test Results for Method A and Method C Tests

FIELD SAMPLE NO	LOCATION	DEPTH

GEOLOGIC ORIGIN	TESTED AT	APPROVED BY	DATE

CLASSIFICATION GC LL 32 PI 13

MAX. PARTICLE SIZE INCLUDED IN TEST 3/4"

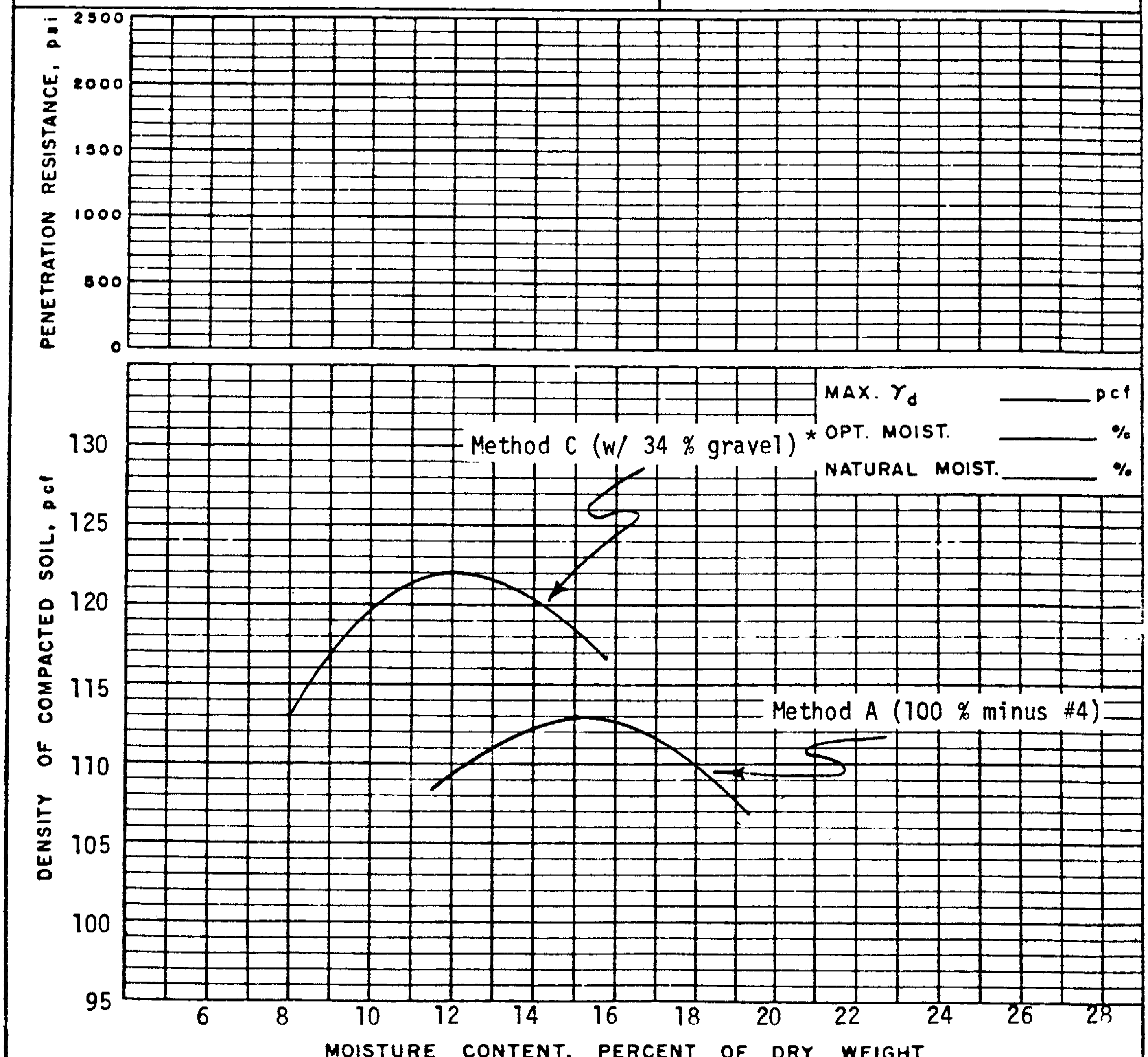
SPECIFIC GRAVITY (G_s) MINUS NO. 4 2.69; PLUS NO. 4 2.33

CURVE NO. 1 OF 1

STD. (ASTM D-698) [x]; METHOD A&C

MOD. (ASTM D-1557) [ ]; METHOD ______

OTHER TEST [ ] (SEE REMARKS)



REMARKS * Gravel is up to 3/4" in size

USDA-SCS-HYATTSVILLE MD 1964

ACTIVITY 6 - SUMMARY OF TEST METHOD DIFFERENCES

This Activity summarizes the differences in the three test methods for compaction. Each of the methods can be used for the standard energy tests, ASTM D 698, and the modified energy test, ASTM D 1557.

Selection of the test method to be used is based on the amount of gravel in the test specimen, as follows:

Test method	Amount of gravel (+ #4)	Size of gravel
A	<20%	Not a Factor
B	≥20%	More than 80% of sample is larger than the 3/8" sieve
C	≥20%	Less than 80% of sample is finer than 3/8" sieve

Notes: (1) Compaction tests are not usually performed if a sample has less than 12 percent fines.

(2) Standardized tests are not developed for soils that have less than 70 percent finer than the 3/4 inch sieve.

To accomodate soils that have a significant amount of larger gravel, a different size mold is used for Method C tests. To achieve the same energy application per volume of soil compacted, the number of hammer blows per lift is adjusted. The following table summarizes this.

Test method (ASTM)	Volume of mold (ft^3)	Weight of hammer (pounds)	Height of drop (ft)	No. of blows per lift	Number of lifts	Maximum particle size
D 698 A	1/30	5.5	1.0	25	3	#4 sieve
D 698 B	1/30	5.5	1.0	25	3	3/8"
D 698 C	1/13.33	5.5	1.0	56	3	3/4"
D 1557 A	1/30	10.0	1.5	25	5	#4
D 1557 B	1/30	10.0	1.5	25	5	3/8"
D 1557 C	1/13.33	10.0	1.5	56	5	3/4"

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 7 - ROCK CORRECTION EQUATIONS, UNIT WEIGHT

This Activity covers the use of the rock correction equation for dry unit weights in soils which contain an oversize fraction which is excluded from the test specimen. Oversize particles excluded may be gravels larger than the number 4 sieve in the case of Method A compaction tests, or may be larger than the 3/8 inch sieve in the case of Method B compaction tests, or gravels larger than the 3/4 inch sieve for Method C tests.

An example of one application of this procedure is as follows: A density test is performed on a compacted fill in the field. The density test may have been performed using a nuclear density gauge, a sand cone device, or another method. The soil in the compacted fill contains oversize particles which were not included in the compaction tests performed representing these soils. The rock correction equations may be used to determine the theoretical density of the soil matrix exclusive of the more dense oversize particles, so as to compare the degree of compaction of the soil matrix to the test standard. The soil at the location where the fill density test was taken will have to be sampled so that the percentage of oversize particles and their bulk specific gravity can be obtained. The density test gives the value needed for the combined soil matrix-oversize mass.

Another application of the use of the rock correction equations and this procedure is during design and engineering testing of soils for a fill project. Suppose that the proposed fill soils contain a significant amount of particles larger than the number 4 sieve. Method A compaction tests are performed on the portion of the sample smaller than the number 4 sieve. To model the shear strength of the soil as closely as possible, however, it is desired to perform shear tests on samples which include the oversize particles. By knowing the percentage of oversize particles and their bulk specific gravity, using the rock correction equations, one may estimate what the combined dry unit weight of the compaction test fraction (finer than the number 4 sieve) and the oversize particles would be. Shear test specimens containing the correct percentage of oversize particles can then be prepared compacted to this density, and the fill soils will be more closely modeled.

The mathematical equation shown below accounts for the different densities of the compaction test fraction and the oversize particles. This equation should not be used for soils with more than 40 percent oversize particles. Also, since compaction tests are not applicable for soils with more than 30 percent of particles larger than the 3/4" sieve, the equations should not be used for those soils, either. Usually, if the percentage of oversize particles is less than 5 percent, corrections are not considered necessary.

$$W_{rs} = \frac{W_s \times W_r}{(p)\ W_s + (1-p)\ W_r}$$

where,

W_{rs} = Combined dry unit weight of the test fraction and the oversize particles, pounds per cubic foot or kilograms per cubic meter

W_r = Bulk specific gravity of oversize particles (determined by ASTM Test Method C 127) (Converted to bulk unit weight. Units are pounds per cubic foot (Gm x 62.4) or kilograms per cubic meter (Gm x 1000)).

CONTINUED TO THE NEXT PAGE

W_s = Dry unit weight of test fraction (For Method A tests this is the portion smaller than the #4 sieve; for Method B tests, it is the portion of a sample smaller than the 3/8 inch sieve; and for Method C tests, it is the portion smaller than the 3/4 inch sieve, pounds per cubic foot or kilograms per cubic meter.

p = Percentage of oversize particles not included in the test fraction. It is expressed as a decimal p = p(%)/100

If one knows any three terms in the equation, then you may solve for the remaining fourth unknown term. The primary use of this equation is to calculate a value for the combined dry unit weight of a test fraction and oversize particles. Use the values obtained for the dry unit weights of the test fractions from a Method A, B, or C compaction. This allows one to estimate what a compaction test result might be if the oversize particles could have been included in the test fraction.

Example: Given the following information, determine what the dry unit weight of the combined test fraction and oversize particles would theoretically be.

An ASTM D 698, Method C compaction test was performed. A maximum dry unit weight value of 132.5 pounds per cubic foot was determined. A bulk specific gravity test on the oversize particles measured a value of 2.234 (145.0 pcf). The sample had 22 percent oversize particles removed before testing.

Solution: The rock correction equation is solved by substituting the given values in the equation:

$$W_{rs} = \frac{W_s \times W_r}{(p)\ W_s + (1-p)\ W_r}$$

Substituting the known values in the equation, we have:

$$W_{rs} = \frac{132.5 \times 145.0}{(0.22)\ (132.5) + (0.78)\ (145.0)}$$

$$W_{rs} = \frac{19{,}212.5}{142.25}$$

W_{rs} = 135.1 pounds per cubic foot

Problem: A compaction test was performed using Test Method A. Only the soil fraction of the sample (the portion of the sample finer than the #4 sieve) was used. A value of maximum dry unit weight of 89.0 pounds per cubic foot was determined. In a field density test, the soil had 18 percent particles larger than the number 4 sieve, which have a bulk specific gravity of 155.0 pounds per cubic foot. What would be an estimate of the maximum dry unit weight of that soil with the gravel particles included?

WHEN YOU HAVE COMPLETED THE ACTIVITY,
REVIEW THE ANSWERS PROVIDED ON PAGE 20

ACTIVITY 7 - Worksheet

ACTIVITY 7 - Solution

The following information is given in the problem:

W_s = 89.0 pounds per cubic foot

W_r = 155.0 pounds per cubic foot

p = 18%, or 0.18 as a decimal substituting in the rock correction equation:

$$W_{rs} = \frac{W_s \times W_r}{p \times W_s + (1-p) \times W_r}$$

$$W_{rs} = \frac{89.0 \times 155.0}{(.18 \times 89.0) + (.82 \times 155.0)}$$

$$W_{rs} = \frac{13,795}{143.12}$$

W_{rs} = 96.4 pounds per cubic foot

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 8 - ROCK CORRECTION EQUATIONS, WATER CONTENT

This Activity covers the use of the rock correction equation for water contents in soils which contain an oversize fraction which is excluded from the test specimen. Oversize particles excluded may be gravels larger than the number 4 sieve in the case of Method A compaction tests, or may be larger than the 3/8 inch sieve in the case of Method B compaction tests, or gravels larger than the 3/4 inch sieve for Method C tests.

An example of one application of this procedure is as follows: A water content test is performed on a compacted fill in the field. The water content test may have been performed using a nuclear density gauge, or other acceptable procedures. The soil in the compacted fill contains oversize particles which were not included in the compaction tests performed representing these soils. The rock correction equations may be used to determine the theoretical water content of the soil matrix exclusive of the drier oversize particles, so as to compare the water content to optimum water content for the soil. The soil at the location where the fill water content test was taken will have to be sampled so that the percentage of oversize particles and their percent absorption value can be obtained.

Another application of the use of the rock correction equations and this procedure is during design and engineering testing of soils for a fill project. Suppose that the proposed fill soils contain a significant amount of particles larger than the number 4 sieve. Method A compaction tests are performed on the portion of the sample smaller than the number 4 sieve. To model the consolidation properties of the soil as closely as possible, however, it is desired to perform consolidation tests on samples which include the oversize particles. By knowing the percentage of oversize particles and their percent absorption, using the rock correction equations, one may estimate what the combined water content of the compaction test fraction (finer than the number 4 sieve) and the oversize particles would be. Consolidation test specimens can then be prepared containing the correct percentage of oversize particles, compacted to this water content, and the fill soils will be more closely modeled.

The mathematical equation shown below accounts for the different water contents of the compaction test fraction and the oversize particles. This equation should not be used for cases where the percentage of oversize particles exceeds 40 percent in any case, and should not be used when over 30 percent of oversize particles are greater than 3/4 inches in size. Usually, if the percentage of oversize particles is less than 5 percent, corrections are not considered necessary.

$$w(\%)rs = w(\%)s \times (1-p) + w(\%)r \times p$$

where,

$w(\%)rs$ = water content of combined test fraction and oversize particles, as a percentage

CONTINUE TO THE NEXT PAGE

w(%)s = water content of the test fraction, as a percentage

w(%)r = water content of oversize particles, also referred to as percent absorption, as a percentage. This value is obtained in performing an apparent specific gravity test (ASTM C 127) on the oversize particles.

p = percent of sample excluded from test fraction, expressed as a decimal - [p = p(%)/100]

CONTINUE TO THE NEXT PAGE

Example 1: A compaction test performed using test method C obtained a value of dry unit weight of 122.5 pounds per cubic foot and an optimum water content of 13.5 percent. The test specimen excluded 15 percent gravel particles larger than the 3/4 inch sieve. The oversize gravels had a water content, or percent absorption of 4.2 percent. Find the theoretical optimum water content of the combined Method C test material and the oversize particles.

The following information is given:

$$w(\%)s = 13.5\%$$

$$w(\%)r = 4.2\%$$

$$p = .15$$

To solve for w(%)rs, the values are substituted as follows:

$$w(\%)rs = ws(\%) \times (1-p) + w(\%)\ r \times p$$

$$w(\%)rs = 13.5 \times (1-0.15) + 4.2 \times 0.15$$

$$= 13.5 \times 0.85 + 0.63$$

$$= 12.1\%$$

CONTINUE TO THE NEXT PAGE

ACTIVITY 8 - Continued

Problem: A compaction test was performed on a sample using Test Method A, on the minus #4, or soil, fraction of the sample. A value of 22.5 percent was obtained for optimum water content. Estimate the optimum water content of the soil combined with 15 percent gravel, where the gravel particles have a percent absorption value of 3.2 percent.

WHEN YOU HAVE COMPLETED THE ACTIVITY,
REVIEW THE ANSWERS PROVIDED ON PAGE 26

ACTIVITY 8 - Worksheet

ACTIVITY 8 - Solution

The following information is given:

$$w(\%)s = 22.5\%$$

$$w(\%)r = 3.2\%$$

$$p = .15$$

Substituting in the water content correction formula:

$$w(\%)rs = w(\%)s \times (1-p) + w(\%)r \times p$$

$$= 22.5 \times (1-.15) + 3.2 \times .15$$

$$= 22.5 \times .85 + .48$$

$$= 19.125 + .48$$

$$= 19.6\%$$

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 9 - REVIEW PROBLEMS

To see whether you have met the objectives of the Module, complete the following questions:

A. Label each of the following statements as true or false (T/F)

1. Compaction tests are performed on specimens containing gravel particles only by Standard (ASTM D 698) energy methods. _____

2. Standard test procedures are not presently available for soils containing more than 30 percent by weight of particles larger than 3/8 inches. _____

3. The value of maximum dry unit weight from a compaction test on a sample with no gravel will be lower than the value obtained on a test of the same soil with gravel included. _____

4. Compaction tests are difficult to perform and obtain meaningful test results if a soil contains less than 12 percent finer than the number 200 sieve. _____

5. The rock correction equations may be used to estimate test results for a Method C compaction test if one knows values obtained in a Method A test and has values for specific gravity of gravel particles and knows the percent of gravel. _____

6. In Method B tests, a 6" diameter mold with a volume of 1/13.33 cubic foot is used. _____

7. The number of hammer blows per lift is different between Method A and Method C tests. _____

CONTINUE TO THE NEXT PAGE

B. Determine which ASTM Test Method should be used to perform a compaction test on each of the soils with gradations shown:

Soil Number	Percent Finer Than #200	#4	3/8"	1/2"	3/4"	1"	3"	Test Method
1	46	65	73	81	85	95	100	
2	58	72	82	93	98	100	100	
3	39	82	88	92	96	99	100	
4	68	78	88	92	97	100	100	
5	27	56	67	69	72	85	98	

C. Problem: An ASTM D 1557 Test Method C compaction test was performed on a sample. The sample had 15% oversize gravels removed before testing. The oversize particles have a specific gravity of 138.5 pounds per cubic feet and a percent absorption value of 9.8 percent. The Method C test resulted in a maximum dry unit weight value of 127.5 pounds per cubic feet and an optimum water content of 14.5 percent.

Find the theoretical maximum dry unit weight and optimum water content of the sample if the oversize particles were included in the specimen.

D. Match the definition on the left with the proper symbol on the right. Terms are from the Rock Correction Equations.

1.	Specific gravity of oversize particles in test, in pcf.	A. W_s
2.	Percent of oversize particles excluded from test, in percent.	B. $w(\%)_r$
3.	Dry unit weight of test fraction, pcf.	C. W_{rs}
4.	Percent absorption of oversize fraction, percent.	D. $w(\%)_s$
5.	Theoretical combined density of test fraction and oversize fraction, pcf.	E. $w(\%)_{rs}$
6.	Water content of test fraction, percent.	F. W_r
7.	Theoretical water content of combined test fraction and oversize particles, percent.	G. p

WRITE YOUR ANSWERS ON THE WORKSHEET ON THE FOLLOWING PAGE

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

ACTIVITY 9 - PROBLEM SOLUTION

A. True/false questions:

1. F
2. F
3. T
4. T
5. T (if oversize % is less than 30)
6. F
7. T

B. Selection of Test Method Problems:

Soil 1 - Method C
Soil 2 - Method B
Soil 3 - Method A
Soil 4 - Method B
Soil 5 - Method C

C. Numerical Problem Solution:

The following information is given in the problem:

W_s = 127.5 pounds per cubic foot
W_r = 138.5 pounds per cubic foot
p = 15%/100 = 0.15
w(%)s = 14.5%
w(%)r = 9.8%

Find W_{rs}, w (%) rs

$$W_{rs} = \frac{W_s \times W_r}{p \times W_s + (1-p) \times W_r}$$

$$= \frac{127.5 \times 138.5}{(0.15 \times 127.5) + (0.85 \times 138.5)}$$

$$= \frac{17{,}658.75}{136.85}$$

= 129.0 pounds per cubic foot

Solving for water content:

w(%)rs = w(%)s x (1-p) + w(%)r x p

w = 14.5 x (0.85) + 9.8 x 0.15

= 13.8%

CONTINUE TO THE NEXT PAGE

The estimated combined density of the Method C and the oversize particles is 129.0 pcf, and the combined water content is theoretically 13.8 percent. These estimated values could then be used as target values for a fill constructed using the oversize particles with the Method C test specimen soil.

D. Matching Questions

1. F	5. C
2. G	6. D
3. A	7. E
4. B	

START THE TAPE WHEN YOU HAVE FINISHED

APPENDIX

SCS Logo ENG - SOIL MECHANICS TRAINING SERIES--
BASIC SOIL PROPERTIES
MODULE 5 - COMPACTION
PART C
1 COMPACTION OF GRAVELLY SOILS

-

Part C of Module 5 covers the compaction test procedures used for soils that have more than twelve percent fines and contain less than 80% fines. It also covers procedures for obtaining corrected values for water content and dry unit weight when soils that have more than five percent oversize particles excluded from the test specimen are tested by
2 methods of Part B of the Module.

-

At the completion of Part C, you will be able to meet the following objectives:

1. State which ASTM Compaction test method is applicable to
3 soils with varying gravel contents.

-

2. Explain conceptually the difference in the three test
4 methods for performing compaction tests.

-

3. Define each term in the rock correction equations.
5 Use the equations to solve simple problems.

-

ACTIVITY 1 These objectives are shown in Activity 1, Part C, of your
6 Study Guide. Stop the tape before continuing.

-

Three methods are used in performing compaction tests using either standard or modified energies. These are called Method A, Method B, and Method C.

In Part B of Module 5 you learned that soils that have 80 percent or more fines are tested by sieving the sample through the number four sieve before testing. This procedure is referred to as Method A in ASTM test procedures D 698 and D 1557.

If samples tested by Method A have more than five percent gravel content, correction equations are used to determine the theoretical maximum dry density and optimum water content
7 for the total sample.

To predict the engineering behavior of soils that have
ACTIVITY 2 less than 80 percent fines, other standard compaction test procedures must be used. A general discussion on the importance of using these other test methods in earth fill design is given in Part C, Activity 2. Stop the tape and review that Activity before proceeding.

8

Two compaction test methods are used when samples contain less than 80 percent fines. However, standard methods are not available for performing compaction tests when samples contain more than 30 percent by dry weight of particles
9 larger than the three-fourths inch sieve. (70% or less is finer than the three-fourths inch sieve).

Method B is used when a sample has less than 80 percent fines, and it has 80 percent or more finer than the
10 three-eighths inch sieve.

Method C is used when samples have less than 80 percent fines
and less than 80 percent finer than the three-eighths inch
sieve. Remember, standard procedures are not available if
70 percent or less of the sample is finer than the
11 three-fourths inch sieve.

Part B, Activity 3, of your Study Guide contains a flow
ACTIVITY 3 chart with the criteria for selection of the appropriate
compaction test method. Activity 3 also gives review
problems. Stop the tape and complete Activity 3 before
12 continuing.

Method B test procedures will be discussed first. Soils are prepared for method B tests by sieving the sample through a three-eighths inch sieve. The soil may be air-dried before sieving if its properties are not significantly changed by air-drying.

If the sample has over five percent but less than twenty
percent of gravel larger than the three-eighths inch sieve,
test results should be corrected for oversize content using
procedures discussed later in this Module. If the sample
contains five percent or less larger than the three-eighths
13 inch sieve, no corrections are necessary.

Method B uses the same size mold and the same energy
application as used in the Method A tests covered in Part B
of the Module. Method B tests may be performed using either
of the two standardized energies, Standard (ASTM 698), or
14 Modified (ASTM D 1557) energies.

After preparing a series of four to five specimens at
successively higher water contents, values are obtained for
wet unit weight, water content, and dry unit weight after
compaction of each specimen, just as you learned for Method
15 A tests in Part B of this Module.

The data is plotted the same way as you learned for Method A tests. Values for maximum dry unit weight and optimum water content are obtained from the curve and reported as test
16 results.

Values for dry unit weight on tests performed using Method B will be higher than tests performed using Method A if the same soils are tested. Method B includes gravel size particles that are generally more dense than a corresponding
17 volume of minus number four material.

Part C, Activity 4 has a summary of procedures for performing
ACTIVITY 4 compaction tests by Method B. The activity shows example data for two samples tested using both Method A and B. Stop
18 the tape and complete the Activity, before continuing.

Soils to be tested using Method C procedures are first sieved through a three-fourths inch sieve. Remember that samples that have more than 30 percent larger than the three-fourths inch sieve are not tested with standard compaction test procedures.

If the sample contains between six percent and 30 percent larger than the three-fourths inch sieve, the maximum dry unit weight and optimum water content obtained using Method C may be corrected for the oversize particles using the procedures discussed later on in this Part of the Module. If the sample contains five percent or less larger than the three-fourths inch sieve, no corrections are necessary.
19 Corrected values represent the total sample.

A larger mold, six inches in diameter, is used for the Method C test procedure. This is necessary because of the larger size particles included in the sample tested. The mold has a volume of about two and one-fourth times the volume of the
20 mold used for Method A and B tests.

To achieve the same compactive energy per volume of soil, the hammer must be dropped a larger number of times per lift. Method C uses 56 blows of the hammer per lift as compared to the 25 blows per lift used for Methods A and B using both
21 Standard or Modified energies.

The size of particles included in the test, the mold size, and the number of blows per lift are the major differences in the test procedures in comparing Method C tests to Methods A
22 and B.

ACTIVITY 5 Part C, Activity 5 in your Study Guide summarizes test procedures and test equipment used for Method C tests and shows examples for soils tested using both Method A and Method C. The soils in the example are the same except for gravel included in the two tests. Stop and study that
23 Activity now.

In summary, three methods are used in performing compaction tests using either standard or modified energies. These
24 methods are called Method A, Method B, and Method C.

Selection of the method to use is based on the gravel content of the sample being tested.

Method A tests have no gravel in the test specimen. Method B tests have less than 80 percent fines and 80 percent or more is finer than the three-eighths inch sieve. Method C tests have less than 80 percent and less than 80 percent is finer
25 than a three eighths inch sieve.

Standardized methods are not available for soils that have more than 30 percent of particles larger than the
26 three-fourths inch sieve.

-

The mold size used and numbers of blows per lift are variables in the three test methods, together with the size
27 of particles used in the test.

-

Activity 6 summarizes the differences in the three test methods. Stop the tape and study the Activity before
28 continuing.

-

The use of the rock correction equations will now be discussed. These equations are useful when a soil is composed of a mixture of soil and gravel.

Because hard gravel size particles cannot be compacted, the only densification that can result in a soil-gravel mixture is due to rearrangement of the gravel particles and compaction of the finer particles in the sample. The portion of a soil-gravel mixture in the test specimen that is finer than the specified sieve used is often referred to as the
29 matrix in the sample.

-

Use of the rock correction equations enables one to separate the unit weight and water content of the matrix in a sample from that of the gravel excluded from the matrix in the sample.

The equations are useful both in design and quality control during construction of earth fills constructed with gravelly
30 soils.

-

Slide with Rock `orrection Equation 31	This theoretical equation calculates the combined dry unit weight of a soil-gravel mixture. It is quite accurate for oversize gravel contents less than about forty percent.
	-
Highlight term WRS in Equation 32	Let's examine the definition of each term in the equation. The term W-sub-RS is the combined dry unit weight of the compacted soil and rock, or gravel.
	-
Highlight term WS in Equation 33	The term W-sub-S is the dry unit weight of the test fraction. The test fraction may be the portion of the sample finer than the number four sieve in the case of Method A tests, or the portion of the sample finer than the three-eighths inch sieve in the case of Method B tests, or the portion of the sample finer than the three-fourths inch sieve in the case of Method C tests.
	-
lighlight term WR in Equation 34	The term W-sub-R is the specific gravity of the oversize particles. This value is obtained from a laboratory test. This term is also abbreviated as G-sub-m, the bulk surface dry specific gravity of the oversize particles. This value should be in the same units used to express dry unit weight, either pounds per cubic foot or kilograms per cubic meter. Remember that specific gravity is the ratio of the unit weight of a substance to that of water. To convert to pounds per cubic foot, multiply by 62.4. To convert to kilograms per cubic meter, multiply by 1000.
	-
Highlight term P in Equation 35	P is the percentage of oversize material, or the percentage of particles not included in the test. It is expressed as a decimal. Again, for Method A tests, the P would be the percentage of particles larger than the number 4 sieve. For Method B, it would be the percentage larger than the three eights inch sieve. And, for Method C tests, it is the percentage larger than the three-fourths inch sieve.
	-

36 If you know any three of the terms in this equation, you may solve for the remaining unknown term.

-

Activity 7

37 Part C, Activity 7 in your Study Guide contains more detail on the use of this equation and has examples and problems on its use. Stop the tape and complete that Activity before continuing.

-

w_{RS} (%) = (w_S (%) * (1-p) + w_R (%) * p)/100

38 This equation is used to calculate the water content of a mixture of a test matrix and oversize particles.

-

Highlight term w_{RS} in Equation

39 The terms are defined as follows:
w-sub-RS is the water content of the combined test fraction and oversize particles. The water content is expressed as a percentage.

-

Highlight term W_S

40 w-sub-S is the water content of the test matrix. It is also expressed as a percentage. Often, calculations will be made using optimum water content from the compaction test for this value.

-

Highlight term w_R in equation

41 w-sub-R is the water content, or percent absorption, of the oversize material in the sample. Percent absorption values are obtained in the laboratory bulk specific gravity test for gravels.

-

42 p is the percent of oversize particles in the sample tested. It is expressed as a decimal in the equation.

-

Activity 8 Activity 8 has examples and problems on the use of the water content correction equations. Stop the tape and complete
43 that Activity before continuing.

Let's review the objectives of Part C of the Module. Objective 1 was to state which of the three ASTM test methods is applicable depending on the gravel content of the soil
44 being tested.

Objective 2 was to explain the differences in the test
45 methods used in performing compaction tests.

Objective 3 was to define each term in the rock correction
46 equations for density and water content, and to use the rock correction equations to solve simple problems.

Activity 9 To test your completion of the objectives of Part C, complete
47 Activity 9 in your Study Guide.

You are now ready to proceed to Part D of this Module covering test procedures for soils with less than twelve
48 percent fines.

United States
Department of
Agriculture

Soil
Conservation
Service

Soil Mechanics Training Series

Basic Soil Properties

Module 5 - Compaction

Part D - Compaction of Clean, Coarse-grained Soils

Study Guide

ENG-SOIL MECHANICS TRAINING SERIES--

BASIC SOIL PROPERTIES

MODULE 5 - COMPACTION

PART D

COMPACTION OF CLEAN, COARSE-GRAINED SOILS

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--
BASIC SOIL PROPERTIES
MODULE 5 - COMPACTION
PART D
COMPACTION OF CLEAN, COARSE-GRAINED SOILS

INTRODUCTION

This is Part D of Module 5 - Compaction of Clean, Coarse-grained Soils 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 D has three 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 D 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

At the completion of Part D, you will be able to:

1. From a list of terms, define the terms associated with index density and relative density.

2. Identify the equipment and procedures used for performing index density tests in the laboratory and field.

3. Estimate values for index densities based on soil classification and gradation data.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 2 - INTRODUCTION

Acceptable engineering characteristics are attained at different dry unit weights for different compacted kinds of soil. Although an SP soil might be well compacted and relatively dense at a dry unit weight of 100 pcf, this might represent loose fill material of a GW soil. For this reason, fill placement must be specified in terms of a reference density test when kinds of soil are variable on a site.

As you learned in previous parts of this Module, compaction tests are quite useful in control and specification of densities in soil that has more than 12 percent fines. Performing compaction tests is difficult on soil that has less than about 12 percent fines. The low fines content of the soil results in a rather free-draining character. Water is not readily retained in the pores. When this kind of soil is compacted in a compaction test mold, water in the soil may drain out the bottom of the sample. Obtaining more than 1 or 2 specimens is difficult with differing water contents from which a compaction curve could be plotted. Even though a complete curve may not be developed, however, a value of dry unit weight resulting from the application of standard compactive energy may be of interest. This is especially true for soil that has between 5 percent and 12 percent fines content.

Tests other than compaction tests are used for assessing the compaction characteristics of these kinds of soils. The specific test procedures are covered later in the module.

Tests used for clean, coarse-grained soil determine values for minimum and maximum index densities for the soils. Practical design densities usually are somewhere between these extreme values. These tests may also form the basis for field quality control.

You may want to review Activity 6 of Part A of this Module that covers the general compaction characteristics of these soil groups.

The Unified Soil Classification System classifications to which these concepts apply are:

GRAVELS - GP GP-GM GP-GC GW GW-GM GW-GC

SANDS - SP SP-SM SP-SC SW SW-SM SW-SC

These soils may be naturally occurring soils in a borrow area, or they may be filters or drain system materials.

Note that density is often used interchangeably with unit weight in these discussions. You should recall from other Parts of this Module that density is actually an expression of the mass of an object per unit volume whereas unit weight is an expression of the weight of an object per unit volume. The weight of an object is equal to its mass times the gravity constant. Because the gravity constant varies slightly over the earth's surface, there is a minor difference in the two values, but for practical purposes, the terms may be used interchangeably.

START THE PLAYER WHEN YOU HAVE FINISHED

ACTIVITY 3 - MINIMUM INDEX DENSITY TEST

One of the tests used to evaluate compaction characteristics of relatively clean coarse-grained soil is the minimum index density test. Detailed test methods are contained in ASTM Test Method D 4254. This discussion is a summary of important points in the procedure, but you should refer to the ASTM standard for detail adequate to perform the test.

Minimum index density is defined as the reference dry density of a soil in the loosest state of compactness at which it can be placed using a standard laboratory procedure that prevents bulking and minimizes particle segregation. From the definition, the value of minimum index density should not be regarded as an absolute value of the minimum density to which a particular soil could occur. If a soil were deposited in a manner such that bulking of the soil and particle segregation could occur, then a lower value of density might result. Bulking is the creation of a loose structure in a sand or gravel caused by capillary stresses in the moist material. It results in a loose structure. Segregation is the separation of coarser fragments from finer fragments in a sample caused by dropping the sample from too great a height during placement.

Soil for a minimum index density test is first oven dried at 110 degrees Centigrade (± 5 degrees) and then processed to remove any weakly cemented aggregates. The amount of sample needed to perform the test depends on the maximum particle size in the sample. About 75 pounds of sample are required for soil that has maximum particle sizes larger than the 3/4 inch sieve; 25 pounds of sample are needed for soil that has a maximum particle size smaller than the 3/4 inch sieve. Only the portion of a soil sample finer than 3 inches is used in these test methods.

A representative sample must be used for performing the test. Representative samples are usually obtained using sample splitters or the technique of quartering.

CONTINUE TO THE NEXT PAGE

ACTIVITY 3 - Continued

The minimum index density test is performed by carefully pouring the soil into a cylindrical mold of known volume. The soil is allowed to drop only from a specified height, using specified pouring devices and procedures. The size of mold and the type of pouring device are selected based on the maximum particle size in the soil, according to the following table:

Maximum particle size	Required size of sample (pounds)	Placement device used in minimum density test	Nominal size of mold (volume - cubic foot)
3"	75	Shovel or extra large scoop	0.5
1-1/2"	75	Scoop	0.5
3/4"	25	Scoop	0.1
3/8"	25	Pouring device with 1" diameter	0.1
#4 sieve	25	Pouring device with 1/2" diameter spout	0.1

The mold is filled by pouring the prepared sample carefully into the mold with the required pouring device using a spiralling movement of the device over the surface of the sample. The free fall of the soil is kept to a maximum of about 1/2 inch or just high enough to maintain continuous flow of the sample without the spout contacting the already deposited soil.

The mold is overfilled slightly (1/2" to 1" above the top of the mold). The excess soil is then carefully screed off with a straightedge to avoid any vibration or jarring of the mold. Do not jar the mold while pouring the sample into the mold or when screeding off the excess soil, because any jarring of the mold will cause an increase in the density of the soil.

Next, the weight of the mold and soil is determined. The volume of the mold and its weight should have been determined previously. Knowing the weight of soil and volume of the mold, the density of the soil at its minimum index state may be determined.

The test is usually repeated until several trials are obtained with results within 1 percent of one another to insure accuracy.

CONTINUE TO THE NEXT PAGE

ACTIVITY 3 - Continued

Example

A soil classifies as an SP soil. It has 100 percent finer than the #4 sieve. The minimum density test is performed using a mold that has a volume of 0.10034 cubic foot and a pouring device that has a spout having a diameter of 1/2 inch. The wei of the mold and soil is 16.96 pounds; the weight of the mold alone is 8.14 pounds. The minimum index density is calculated as follows:

$$\text{Minimum Index Density} = \frac{(\text{Weight of Soil + Mold})-(\text{Weight of Mold})}{\text{Volume of Mold}}$$

$$= \frac{16.96-8.14}{0.10034}$$

= 87.9 pounds per cubic foot

Problem:

Given the gradation of the following soils, determine the mold size and pouring device to use for a minimum index density test on each soil. (The maximum particle size is the smallest sieve size that 100 percent of the sample passes.)

Soil No.	#200	Percent finer #4	3/8"	1/2"	3/4"	1-1/2"	3"	Mold size and pouring device
1	8	98	100	100	100	100	100	
2	3	52	64	72	88	92	100	
3	4	72	79	89	100	100	100	

WHEN YOU HAVE COMPLETED THE ACTIVITY, CHECK YOUR ANSWERS ON THE FOLLOWING PAGE

ACTIVITY 3 - Solution

Soil 1 - The sample has a maximum particle size of 3/8 inch. At least 25 pounds of oven-dried sample is required for the test. A mold that has a volume of about 0.1 cubic foot should be used with a pouring device with a spout having a 1 inch diameter.

Soil 2 - The sample has a maximum particle size of 3 inches. At least 75 pounds of oven-dried sample is required for the test. A mold that has a volume of about 0.5 cubic foot should be used with a extra large scoop or shovel for a pouring device.

Soil 3 - The sample has a maximum particle size of 3/4 inch. At least 25 pounds of oven-dried sample is required for the test. A mold that has a volume of about 0.1 cubic foot should be used with a scoop for a pouring device.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 4 - MAXIMUM INDEX DENSITY TEST

The second test to evaluate compaction characteristics of relatively clean, coarse-grained soils is the maximum index density test. Detailed test methods are contained in ASTM Test Method D 4253. This discussion is a summary of the important points in the procedure, but you should refer to the ASTM standard for detail adequate for actually performing the test.

Maximum index density is defined as the reference dry density of a soil in the densest state of compactness that can be attained using a standard laboratory procedure that minimizes particle segregation and breakdown. From the definition, the value of maximum index density should not be regarded as an absolute value of the maximum density at which a particular soil could occur. If a soil were densified by other means than the test procedure, higher densities could be attainable.

This test may be performed on a sample of soil which was used for the minimum index test, or a separate specimen may be prepared for this test. A sample should be used that will result in a value of minimum index density within the 1 percent tolerance mentioned for that procedure. The requirements for sample size and mold volume are the same as those for the minimum index density test and are not repeated here.

Several test methods are used for performing the maximum index density test. The differences in the methods involve whether the sample is vibrated in a wet or dry state, and what type of vibrating table is used, as detailed below.

The test is performed by placing either oven-dried or wet soil in a mold, applying a surcharge weight that exerts a surface pressure of 2 pounds per square inch on the soil, and then vertically vibrating the mold, soil, and surcharge. An electromagnetic, eccentric, or cam-driven vibrating table operating at about 60 Hertz (cycles per second) for 8 minutes is used to vibrate the sample and apparatus. The maximum index density is obtained by dividing the oven-dried weight of the densified soil by its densified volume. The densified volume of the sample is obtained by measurements of the vibrated height of the sample times the area of the mold.

The most common method for performing the test is using oven-dried soil and an electromagnetic vibrating table. Both the dry and wet methods should be used on a new job, because occasionally the wet method will result in significantly higher values of maximum index density than the dry method. On soil that has between 5 percent and 12 percent fines, impact compaction tests (ASTM D 698 or D 1557) may be useful in evaluating what is an appropriate value of maximum index density.

Some soil may experience significant degradation or breakdown of sand and gravel particles during the test. This may be evaluated by performing a gradation analysis before and after performing the maximum index density test.

CONTINUE TO NEXT PAGE

ACTIVITY 4 - Continued

Example

The sample used in the example for Activity 3 was subjected to a maximum index density test. The densified volume of the sample was determined to be 0.08345 cubic foot. What is the maximum index density of the sample?

Solution

The maximum index dry density is equal to the weight of dry soil in the mold divided by the vibrated volume of the sample. The soil in Activity 3 had a dry weight of 16.96-8.14, or 8.82 pounds. This weight, divided by 0.08645 cubic foot is 105.7 pounds per cubic foot, the maximum index density for the sample.

CONTINUE TO THE NEXT PAGE

ACTIVITY 4 - Continued

Problem

The same soil was evaluated for maximum index density by using the wet sample preparation method. Using the same mold, which has a volume of 0.10034 cubic feet and a weight of 8.14 pounds, the mold was carefully filled with wet soil while vibrating the mold. After filling, the surcharge weight is placed on the sample and the sample vibrated additionally. The vibrated volume of the sample is determined to be 0.09243 cubic foot. The wet weight of the soil and mold is 18.48 pounds, and the measured water content of the sample is determined to be 6.2 percent. What is the maximum index density of the sample?

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

ACTIVITY 4 - Problem Solution

The following information is given:

Weight of mold + wet soil = 18.48 pounds
Weight of mold = 8.14 pounds
Volume of mold = 0.10034 cubic foot
Water content of soil = 6.2%
Vibrated volume of soil = 0.09243 cubic foot

The weight of wet soil = 18.48-8.14
= 10.34 pounds

Using the formula Dry Weight = Wet Weight/(1+w(%)/100)
= 10.34 pounds/(1+6.2%/100)
= 10.34/1.062
= 9.736 pounds

The maximum index density is the weight of dry soil divided by the vibrated volume of the soil = 9.736 pounds/0.09243 cubic foot
= 105.3 pounds per cubic foot

This indicates there was little difference in the values of maximum index density between the dry and wet methods. Subsequent testing on similar soils from this site may use the dry method.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 5 - RELATIVE DENSITY

Results of the minimum and maximum index density tests are used in several ways by designers and construction inspection personnel in projects where clean, coarse-grained soil is compacted in a fill. The kind of soil may form the entire fill in some projects, and in other situations, the clean coarse-grained material may be a filter or drain section in an embankment or surrounding a concrete structure.

In any case, these tests are performed for the same reasons that the compaction test is performed on soil that has more than 12 percent fines. If laboratory tests for shear strength, consolidation, or permeability are desired, a value for placement dry density must be assumed so that the tests may be performed at that density. If satisfactory properties are obtained at these densities, then the project may be designed and placement of the soil specified at comparable densities to ensure the fill is constructed to a degree of compactness similar to that tested in the laboratory. These concepts are summarized in the flow chart on Figure 5.1, p. 20. Review the information before continuing.

Samples of proposed fill material are obtained usually in the site investigation of a project. The number of samples needed is a function of the yardage of soil represented and the variability of the deposits. The size of sample needed depends on the maximum particle size of the sample. Recall that about 75 pounds of sample are needed for tests on soil that has larger particles, and sample sizes of 25 pounds are adequate for samples that have no large gravels.

After performing minimum and maximum index density tests, a designer must decide at what intermediate density he wishes to assume the fill should be compacted. One approach is to assume the soil is placed at some arbitrary percent of the maximum index density, such as 90 or 95 percent of maximum index density.

A more common assumption is based on the concept of relative density. Relative density is defined as the ratio, expressed as a percentage, of the difference between the maximum index void ratio and a given value of void ratio; to the difference between its maximum and minimum index void ratios.

In equation form, relative density is defined as:

$$D_d\ (\%) = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$$

CONTINUE TO THE NEXT PAGE

ACTIVITY 5 - Continued

where,

D_d = relative density, expressed as a percentage

e_{max} = maximum index void ratio. This value is calculated from the minimum index density using the formula:

$$e_{max} = \frac{\text{Specific gravity x 62.425}}{\text{Minimum index density}} - 1$$

e_{min} = minimum index void ratio. This value is calculated from the maximum index density using the formula.

$$e_{min} = \frac{\text{Specific gravity x 62.425}}{\text{Maximum index density}} - 1$$

e = void ratio at which relative density is being calculated. This value is obtained from a measurement of the soil's in-place dry density from the equation:

$$e = \frac{\text{Specific gravity x 62.4}}{\text{Dry Unit Weight (pcf)}} - 1.0$$

CONTINUE TO NEXT PAGE

Note

The equations for calculating e_{max} and e_{min} assume that the maximum and minimum index densities are expressed in units of pounds per cubic foot. If units of kilograms per cubic meter are used for measurement of maximum and minimum index densities, then the constant 62.4 in the equation should be changed to 1000, which is the unit weight of water in the metric system.

An alternative formula expressing relative density in terms of density rather than void ratio is shown below:

$$D_d\ (\%) = \frac{D_{max}\ (D - D_{min})}{D\ (D_{max} - D_{min})} \times 100 \quad \text{or} \quad \frac{1 - \frac{D_{min}}{D}}{1 - \frac{D_{min}}{D_{max}}} \times 100$$

where,

D_d (%) = relative density, expressed as a percentage

D_{max} = maximum index density, pcf or Kgm

D_{min} = minimum index density, pcf or Kgm

D = placement density,pcf or Kgm

Common values for relative density assumed in preliminary designs may range from 50 to 80 percent. After assumming a value for relative density, the above equations are used to calculate what the corresponding value of placement density is, as shown with the following example:

Example

A minimum and maximum index density test are performed on a sample of SP soil. Values obtained are 89.5 pounds per cubic foot and 108.5 pounds per cubic foot, respectively. What density corresponds to a relative density value of 70%?

Solution

The equation for Relative Density may be arranged as follows:

$$D = \frac{D_{min}}{1 - \frac{D_d(\%) \times (D_{max} - D_{min})}{100 \times D_{max}}} \quad \text{or} \quad \frac{D_{max}\ D_{min}}{D_{max} - \frac{D_d(\%)}{100}\ (D_{max} - D_{min})}$$

CONTINUE TO NEXT PAGE

ACTIVITY 5 - Continued

Substituting given values into this equation:

$$D = \frac{89.5}{1 - \frac{70 \times (108.5-89.5)}{100 \times 108.5}}$$

$$D = \frac{89.5}{1 - \frac{70 \times (19)}{10,850}}$$

$$= \frac{89.5}{1 - 0.12258}$$

= 102.0 pounds per cubic foot

Problem

A soil's minimum index density is 94.5 pounds per cubic foot and its maximum index density is 111.5 pounds per cubic foot. The soil has a specific gravity of 2.66. Calculate the maximum and minimum void ratios for the sample, and determine what the relative density of a compacted fill of this soil would be if an in-place density test of the fill measured a dry unit weight of 107.6 pounds per cubic foot.

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

ACTIVITY 5 - Worksheet

ACTIVITY 5 - Problem Solution

The following information is given:

D_{max} = 111.5 pounds per cubic foot
D_{min} = 94.5 pounds per cubic foot
G_s = 2.66

1. Calculate the maximum void ratio for the sample using the equation:

$$e_{max} = \frac{\text{Specific gravity} \times 62.425}{\text{Minimum index density}} - 1$$

$$= \frac{2.66 \times 62.425}{94.5} - 1$$

$$= 1.7571 - 1$$

$$= 0.7571$$

2. Calculate the minimum void ratio for the sample using the equation:

$$e_{min} = \frac{\text{Specific gravity} \times 62.425}{\text{Maximum index density}} - 1$$

$$= \frac{2.66 \times 62.425}{111.5} - 1$$

$$= 1.4892 - 1$$

$$= 0.4892$$

3. Calculate the void ratio of the soil in the fill using the equation

$$e = \frac{\text{Specific gravity} \times 62.425}{\text{In place density}} - 1$$

$$= \frac{2.66 \times 62.425}{107.6} - 1$$

$$= 1.5432 - 1$$

$$= 0.5432$$

CONTINUE TO NEXT PAGE

ACTIVITY 5 - Problem Solution Continued

4. Calculate the value for relative density using the equation:

$$D_d\ (\%) = \frac{e_{max} - e}{e_{max} - e_{min}} *100$$

$$= \frac{0.7571 - 0.5432}{0.7571 - 0.4892} *100$$

$$= \frac{0.2139}{0.2679} \times 100$$

$$= 79.8\%$$

This would represent very well compacted soil in all likelihood.

START THE TAPE WHEN YOU HAVE FINISHED

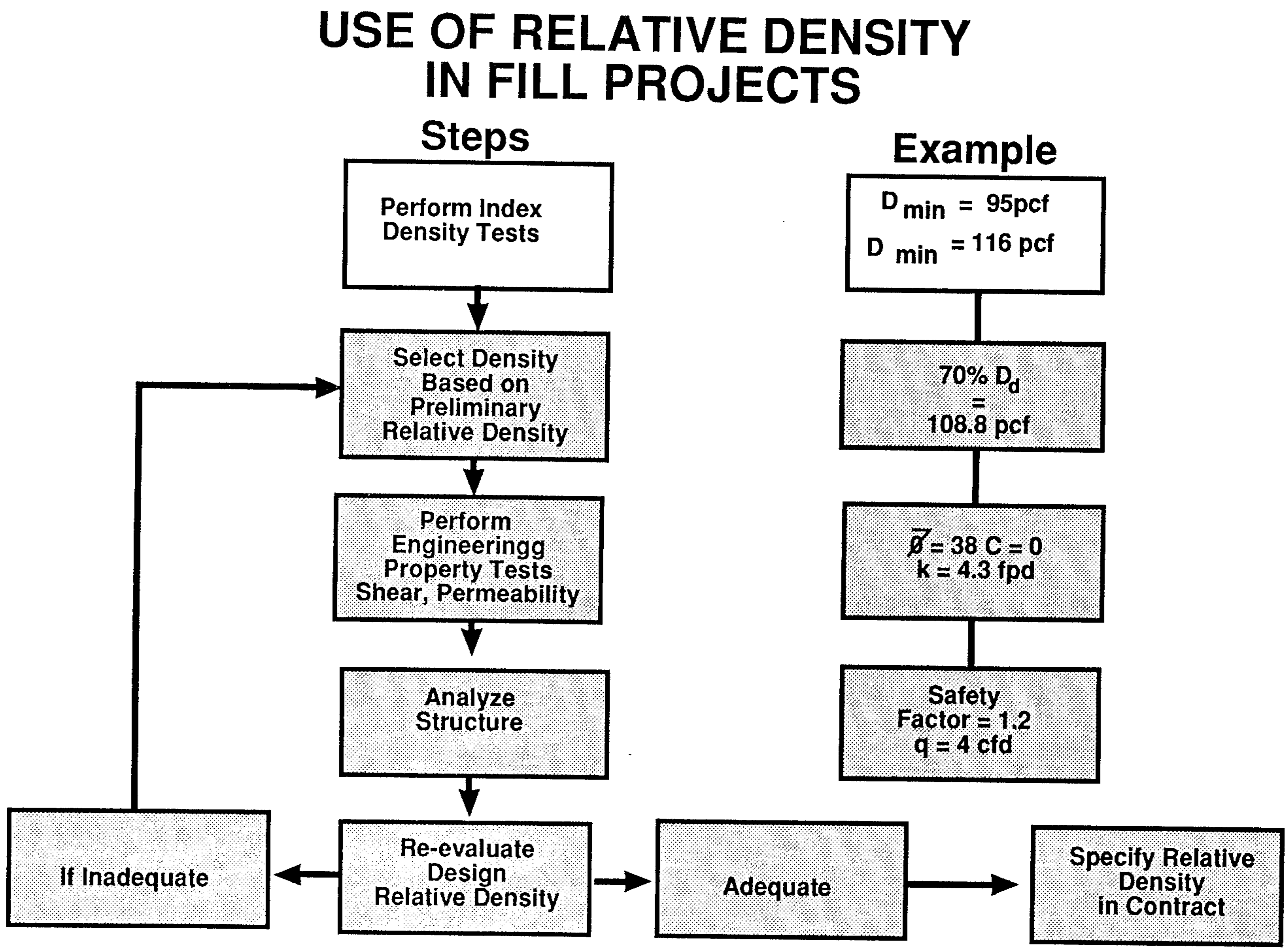

USE OF RELATIVE DENSITY
IN FILL PROJECTS
Steps
Perform Index Density Tests
Select Density Based on Preliminary Relative Density
Perform Engineeringg Property Tests Shear, Permeability
Analyze Structure
Re-evaluate Design Relative Density
If Inadequate
Adequate
Specify Relative Density in Contract
Example
D min = 95pcf
D min = 116 pcf
70% Dd = 108.8 pcf
Ø = 38 C = 0
k = 4.3 fpd
Safety Factor = 1.2
q = 4 cfd

Figure 5.1

ACTIVITY 6 - ESTIMATING INDEX DENSITY VALUES

To obtain values for minimum and maximum index densities is frequently difficult particularly in a construction project that has no field laboratory. Testing may not be justified for smaller projects. Empirical estimates of values of minimum and maximum index densities may be useful in these cases. This Activity presents two methods for estimating relative density parameters.

Method 1

The first method is one developed by the U.S. Army Corps of Engineers. Values of minimum and maximum index densities are estimated based on the percent finer than the number 16 sieve in a soil. The equations are based on correlations from a large number of tests. The equations do not consider other factors such as angularity of particles, whether the soil is well-graded or poorly graded, or what differences might occur because of specific gravity values. As you would with any correlation, you should know the limitations and lack of precision of such estimates. However, for a preliminary estimate, or where no other means is available for obtaining a reasonable estimate, the equations are useful.

Estimates for minimum and maximum index densities are given by the equations:

$$\text{Minimum Index Density} = 125.5 - 0.36 \times P$$

$$\text{Maximum Index Density} = 132.9 - 0.27 \times P$$

where,

Minimum and Maximum Index Densities are expressed in pounds per cubic foot, and

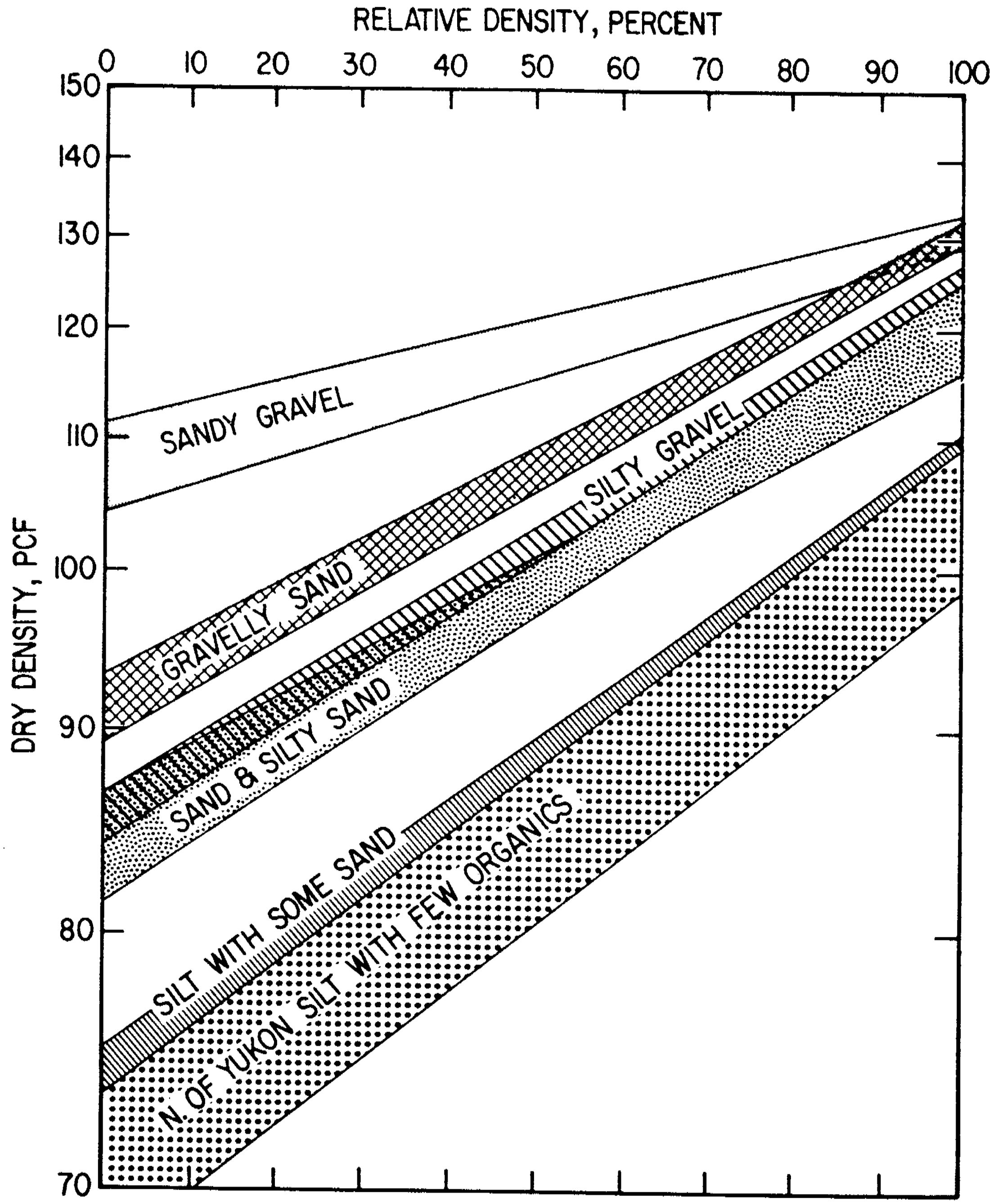
P = the percent of the sample finer than the Number 16 sieve

These equations are taken from the Corps of Engineers Engineering Manual EM-1110-2-1911, p. 5-34. They should not be used for gravelly soils.

Method 2

Another empirical tool for evaluating relative density is shown on Figure 6.1. This chart is taken from an article of the American Society of Civil Engineers titled Liquefaction Problems in Geotechnical Engineering, 1976, page 164, authored by N. C. Donovan and S. Singh. Relative density is read from the chart by entering the chart with a value for a soil's dry unit weight and soil type. The chart may also be used to estimate a value for dry unit weight if you know the relative density and kind of soil. This chart was developed in conjunction with the Alaska pipeline design. The same precautions on the use of such a correlation as disscussed previously should be regarded when using such a chart. Other important factors are not included in the chart, and individual variations may be large.

CONTINUE TO NEXT PAGE



Reference: Donovan, N.C. and S. Singh, "Liquefaction Criteria for the Trans-Alaska Pipeline", Liquefaction Problems in Geotechnical Engineering, A.S.C.E., 1976, p. 164.

RELATIONSHIP BETWEEN DRY DENSITY AND RELATIVE DENSITY FOR SOILS ALONG PIPELINE ROUTE

Figure 6.1

Example Problem

A soil has 79 percent finer than the #16 sieve. The soil is a well graded sand with no gravel. An in-place density test was made in a fill constructed of the soil, and a measured value of 106.0 pounds per cubic foot was reported as the dry unit weight of the compacted fill. What is the relative density of the fill? Estimate by both methods.

Method 1

Minimum Index Density = 125.5 - 0.36 x P
= 125.5 - 0.36 x 79
= 125.5 - 28.44
= 97.06 pounds per cubic foot

Maximum Index Density = 132.9 - 0.27 x P
= 132.9 - 0.27 x 79
= 132.9 - 21.33
= 111.57 pounds per cubic foot

Using the value given of 106.0 pcf for in-place density, D:

$$D_d\ (\%) = \frac{D_{max}\ (D - D_{min})}{D\ (D_{max} - D_{min})} \times 100$$

$$= \frac{111.57\ (106.0 - 97.06)}{106.0\ (111.57 - 97.06)} \times 100$$

$$= \frac{997.44}{1{,}538.06} \times 100$$

$$= 65\%$$

Method 2

Entering Figure 6.1 with an in-place dry unit weight of 106.0 pounds per cubic foot, read horizontally to the band for sand and silty sand. Read upwards to the relative density scale, and detemine that the in-place soil has a relative density of between 62 percent and 72 percent or an average of about 67 percent. This agrees closely with the estimate of the Corps of Engineers Method.

CONTINUE TO THE NEXT PAGE

Problem

ASTM standard gradation C-33 is often specified for a fine filter or drain material. This gradation is a standard gradation used in manufacture of concrete. On a hypothetical construction project, it is considered desirable to place this drain material at a relative density of 70 percent. The standard gradation for this filter is shown on Figure 6.2. Estimate by both methods what a desirable range in the value of compacted density would be for this material with the given information. You should obtain two estimates; one estimate for the finest gradation curve shown and one for the coarsest gradation curve shown on Figure 6.2. The equations used for calculating density from known values of relative density and index densities is shown on page 15. Note that this problem soil would correspond to the sand/silty sand band on Figure 6.1.

AFTER COMPLETING THE ACTIVITY, CHECK THE SOLUTION ON PAGE 26

U.S. Department of Agriculture
Soil Conservation Service

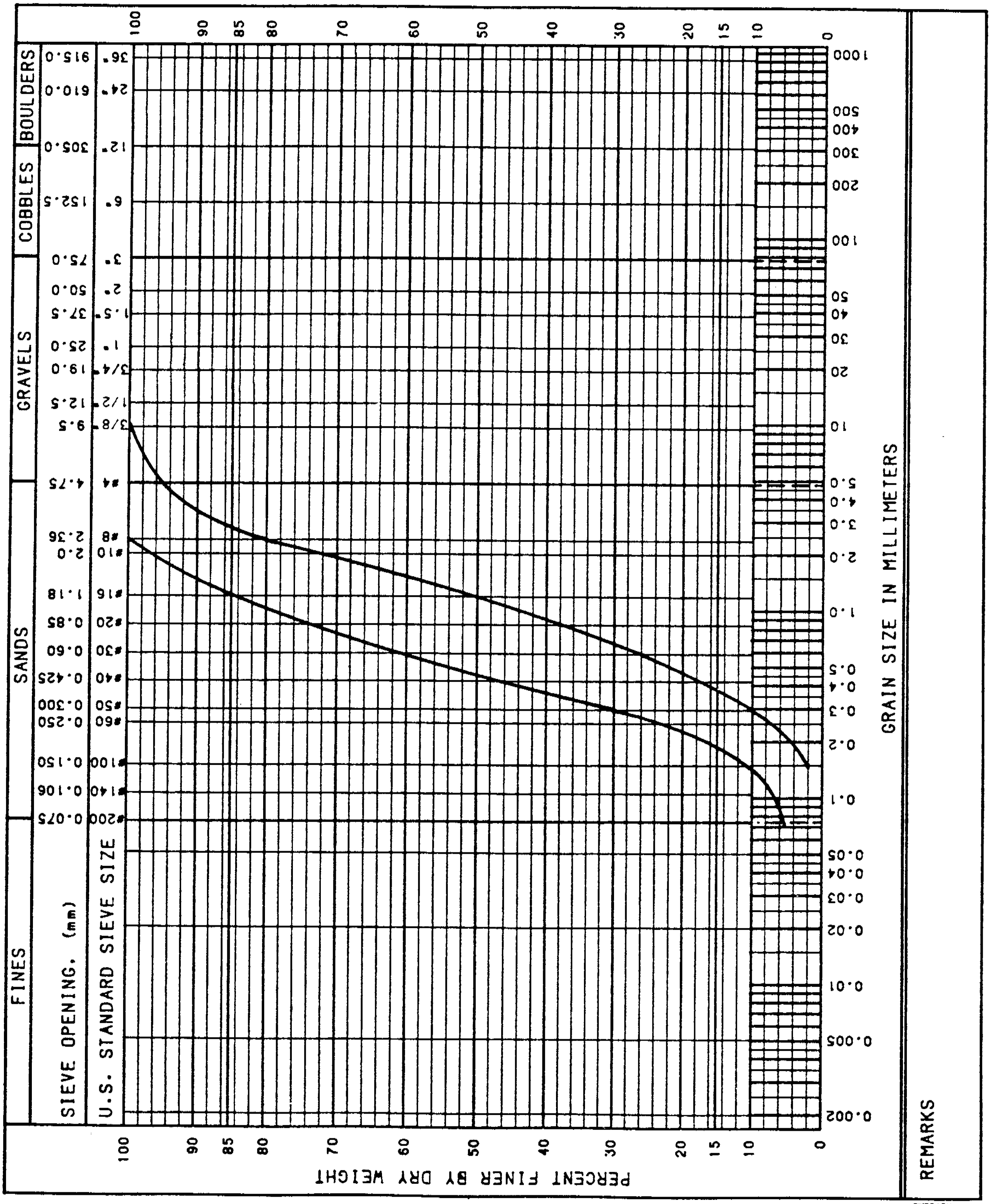
SCS-ENG-130
2-85

GRAIN SIZE ANALYSIS FOR

ACTIVITY 6 - Figure 6.2
(Specify)

Project and state PROBLEM

Designed at ____ By ____ Date ____



ACTIVITY 6 - Solution

Using the given gradation curve, the range of permissible materials has a percent finer than the #16 sieve of between 50 and 85 percent.

Method A (Corps of Engineers)

Determine minimum and maximum values of index densities for the lower value of percent finer than the #16 sieve.

Minimum Index Density = 125.5 - 0.36 x P
= 125.5 - 0.36 x 50
= 107.5 pounds per cubic foot

Maximum Index Density = 132.9 - 0.27 x P
= 132.9 - 0.27 x 50
= 119.4 pounds per cubic foot

The density corresponding to 70 percent relative density may be calculated from the equation.

$$D = \frac{D_{min}}{1 - \frac{D_d(\%) \times (D_{max} - D_{min})}{100 \times D_{max}}}$$

$$D = \frac{107.5}{1 - \frac{70 \times (119.4-107.5)}{100 \times 119.4}}$$

= 115.6 pounds per cubic foot

Using the same procedure for the maximum shown value of percent finer than the #16 sieve of 85, then

Minimum Index Density = 125.5 - 0.36 x P
= 125.5 - 0.36 x 85
= 94.9 pounds per cubic foot

Maximum Index Density = 132.9 - 0.27 x P
= 132.9 - 0.27 x 85
= 109.95 pounds per cubic foot

CONTINUE TO NEXT PAGE

ACTIVITY 6 - Solution Continued

$$D = \frac{D_{min}}{1 - \frac{D_d(\%) \times (D_{max} - D_{min})}{100 \times D_{max}}}$$

$$D = \frac{94.9}{1 - \frac{70 \times (109.95 - 94.9)}{100 \times 109.95}}$$

$$= 105.0 \text{ pounds per cubic foot}$$

The range of estimated dry densities corresponding to 70 percent relative density by this method is then from 105.0 to 115.6 pounds per cubic foot.

Using Method 2, the chart should be read from a relative density value of 70 percent at the top of the chart downwards to the band shown for sand and silty sand, then read horizontally to the dry density scale - A range of dry densities of from about 104.0 to 109.0 pounds per cubic foot. This shows good agreement between the two methods for estimating.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 7 - EXAMPLES OF EQUIPMENT SPECIFICATIONS

On some projects, to perform index density tests may be impractical in the design and construction of a fill project where relatively clean, coarse-grained soil is used. Performing field density tests in this kind of soil is also difficult, especially when the soil contains significant gravel content. In these cases, to specify the type of equipment and mode of operation may be preferable to control the placement of the soil. These specifications should be based on previous favorable experience with placement of similar soil.

SCS specifications often include a paragraph requiring that these soil types be thoroughly wet during compaction to reduce the bulking tendencies of moist sands, and ensure good compaction.

Examples of this type of specification are shown below. The first specification shown is one used for placement of drain fill. These materials are clean sands and gravels.

Example specification 1. Fill shall be placed uniformly in layers not more than 12 inches deep before compaction. The material shall be placed in a manner to avoid segration of particles sizes. Each layer shall be compacted by at least 2 passes, over the entire surface, of a steel-drum vibrating roller weighing not less than 5 tons and exerting a vertical vibrating force of not less than 20,000 pounds at least 1,200 times per minute.

Example specification 2. Fill shall be placed uniformly in layers not more than 12 inches deep before compaction. The material shall be placed in a manner to avoid segregation of particle sizes. Each layer shall be compacted by at least 2 passes, over the entire surface, of a pneumatic-tired roller exerting a pressure of not less than 75 pounds per square inch. A pass is defined as at least one complete coverage of the roller wheel, tire or drum over the entire surface of the layer.

Example specification 3. Fill shall be placed uniformly in layers not more than 12 inches deep before compaction. The material shall be placed in a manner to avoid segregation of particle sizes. Each layer shall be compacted by at least 4 passes, over the entire surface, of the track of a crawler-type tractor weighing not less than 20 tons.

START THE TAPE WHEN YOU HAVE FINISHED

ACTIVITY 8 - TEST OF OBJECTIVES

To test your understanding of the material in Part D of this Module and to see whether the objectives have been met, complete the following questions:

Match the term on the left with the appropriate definition on the right:

1. Minimum void ratio _____
2. Surcharge weight _____
3. 60 Hertz _____
4. Relative density _____
5. 0.1 cubic foot mold _____
6. Unified Soil Classifications for which minimum and maximum index density tests do not apply _____
7. Unified Soil Classifications for which minimum and maximum index density tests apply _____
8. Most efficient method of compacting clean, coarse-grained soils _____
9. Method of Maximum Index Density Test likely to result in highest values _____
10. ASTM Test Method Designations for Minimum and Maximum Index Density Tests _____
11. Maximum void ratio _____
12. 0.5 cubic foot mold _____

A. CH, ML, SC, GC

B. Mold size for samples with maximum particles sizes less than 3/4"

C. Void ratio corresponding to maximum index density

D. D 4254 and D 4253

E. Frequenty of vibration of table on maximum index test

F. Exerts pressure of 2 pounds per square inch

G. Mold size for samples with particles larger than 3/4"

H. Void ratio corresponding to minimum index density

I. GP, SP, GP-GM, SP-SM

J. Vibratory

K. $\frac{e_{max} - e}{e - e_{min}} \times 100$

L. Wet method

CONTINUE TO NEXT PAGE

ACTIVITY 8 - Continued

The soil with gradation shown on Figure. 8.1 will be the primary fill material for a building foundation. Preliminary design estimates are that the soil should be placed at a relative density of 80 percent.

1. What size mold and type of pouring device should be used for the minimum and maximum index density tests?

2. Give an estimate of the minimum and maximum index densities for the sample, and state what value of dry density corresponds to 80 percent relative density based on these estimates.

WHEN YOU HAVE COMPLETED THE TEST, CHECK YOUR ANSWERS ON THE PAGE 34

U.S. Department of Agriculture
Soil Conservation Service

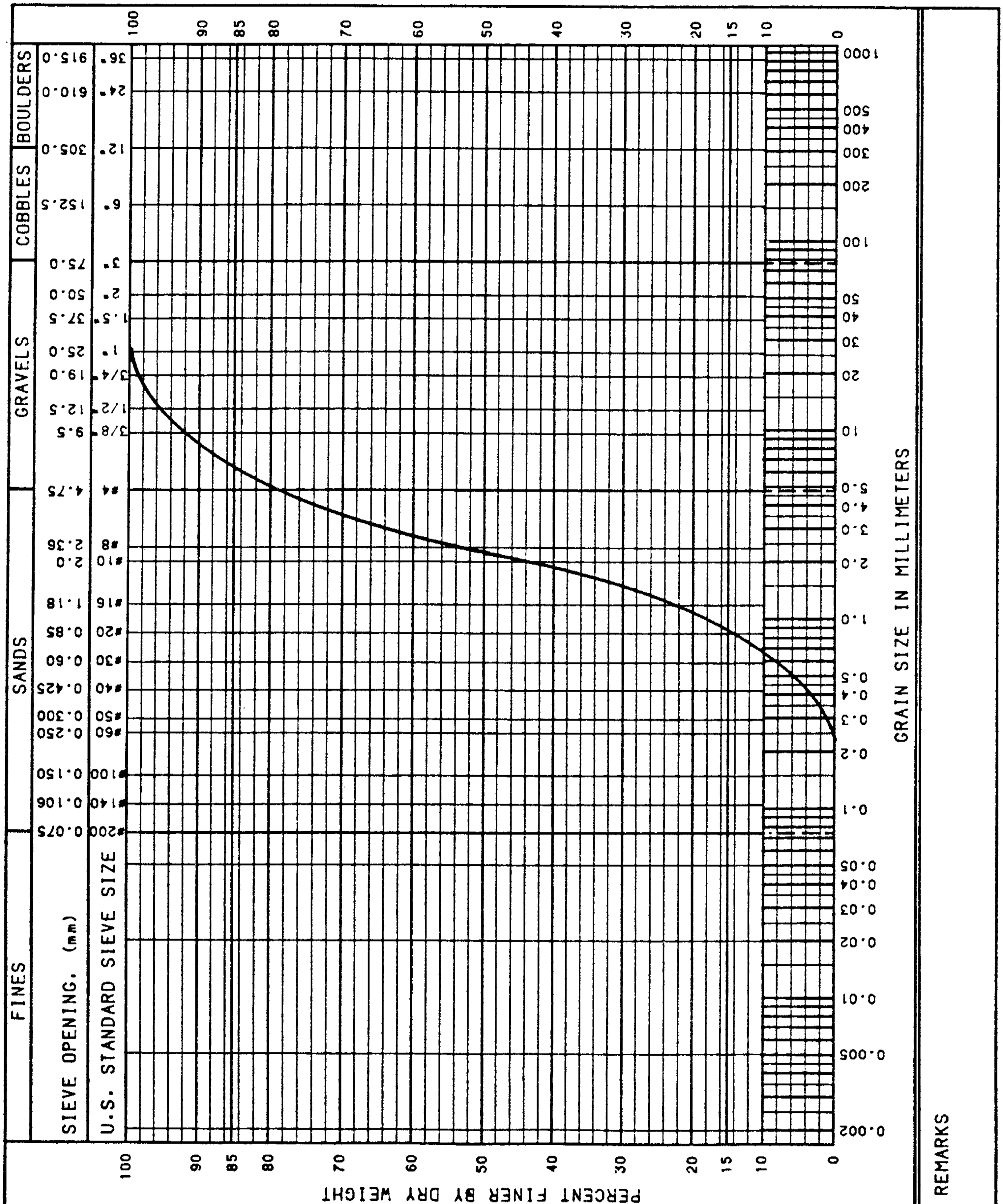
SCS-ENG-130
2-85

GRAIN SIZE ANALYSIS FOR

ACTIVITY 8 - Figure 8.1
(Specify)

Project and state PROBLEM

Designed at ________ By ________ Date ________



ACTIVITY 8 - PROBLEM SOLUTIONS

Matching questions:

1.	C	7.	I
2.	F	8.	J
3.	E	9.	L
4.	K	10.	D
5.	B	11.	H
6.	A	12.	G

Answers for given soil gradation:

1. The soil has a maximum particle size of 1". The table in Activity 3 shows that a 75 pound sample is required, using a scoop fill a mold with a volume of 0.5 cubic foot.

2. Using the Corps of Engineers equation for estimating minimum and maximum index densities, with a percent finer than the #16 sieve read, from the gradation curve of 22 percent, as follows:

Minimum Index Density = 125.5 - 0.36 x P
= 125.5 - 0.36 x 22
= 117.6 pounds per cubic foot

Maximum Index Density = 132.9 - 0.27 x P
= 132.9 - 0.27 x 22
= 127.0 pounds per cubic foot

ACTIVITY 8 - Continued

Substitute known values in the following equation from Activity 6:

$$D = \frac{D_{min}}{1 - \frac{D_d(\%) \times (D_{max} - D_{min})}{100 \times D_{max}}}$$

$$D = \frac{117.6}{1 - \frac{80 \times (127.0-117.6)}{100 \times 127.0}}$$

$$D = \frac{117.6}{1 - 0.0592}$$

D = 125 pcf

Using the chart shown in Activity 6, with the kind of soil being a slightly gravelly, clean sand, entering the chart with a relative density value of 80 percent, read an in-place density of 120.0 pcf.

THIS COMPLETES ACTIVITY 8 AND COMPLETES PART D OF THE MODULE
YOU SHOULD NOW CONTINUE WITH PART E OF THE MODULE

APPENDIX

SCS Logo

ENG-SOIL MECHANICS TRAINING SERIES--
BASIC SOIL PROPERTIES
1 MODULE 5 - COMPACTION
PART D
COMPACTION OF CLEAN, COARSE-GRAINED SOILS

-

Part D of Module 5 covers the laboratory and field tests used to control placement of relatively clean, coarse-grained
2 soils in a compacted fill.

-

At the completion of Part D you will be able to:

1. From a list, define the terms associated with
3 index density and relative density.

-

2. Identify the equipment and procedures used for performing
4 index density tests in the laboratory and field.

-

3. Estimate values for index densities based on soil
5 classification and gradation data.

-

ACTIVITY 1

These objectives are listed in Activity 1, Part D, of your Study Guide. Stop the tape and review the Activity before
6 continuing.

-

You should recall from Part A of this Module that compaction tests are not recommended for coarse-grained soils that have less than about 12 percent of the sample finer than the number 200 sieve, or for soils that have more than 30 percent
7 by weight of particles larger than three-fourths inch.

-

Because soils that have less than 12 percent fines have a limited water holding capability, performing compaction tests are difficult on these soils. In a compaction test on this kind of soil, the curve obtained will likely be quite flat, and not useful for determining maximum dry unit weight or optimum water content values.

The Unified Soil Groups shown are those that have less than
8 12 percent fines.

-

Performing one compaction trial at some arbitrary water content may occasionally be useful to compare values of dry unit weight obtained with other procedures mentioned in this
9 Part of the Module.

-

Soils that have more than 30 percent of particles larger than the three-fourths inch sieve are also difficult to test. Large gravel particles interfere with the compaction procedure in the small standard size molds used. Compaction test methods for these very gravelly soils are in development
10 but have not yet been standardized.

-

Alternative laboratory tests are used to obtain reference densities for relatively clean, coarse-grained soils. The tests are called the maximum index densities and minimum index density tests. The ASTM designations are D 4253 and D
11 4254, respectively. These will be covered in detail.

-

Let's review some of the main points on compacting these soils that were covered in Part A of this module.

The most effective means of compacting or densifying these
12 soils is vibration.

-

These soils may be most effectively compacted at low or very high water contents. Flooding is often used to ensure good
13 compaction and prevent bulking.

-

These soils may be placed and compacted in thicker lifts in
14 the field than soils that have higher fines contents.

-

The reasons for compacting these soils are to improve the engineering properties, increase shear strength, and decrease compressibility. Although permeability may be reduced, these soils have relatively high permeabilities due
15 to their low fines content.

-

When relatively clean coarse-grained soils are used in a fill, a designer must base the design on engineering parameters obtained from laboratory tests or correlations. To perform laboratory tests or to use correlations available, one must know at what density the soils will be placed in the fill.

By performing a maximum index density test and a minimum index density test on the soils, the designer may select a design density somewhere between these two test densities. Engineering property tests or correlations may then be based on this design density. Note that density is used interchangeably with the term unit weight in these
16 discussions.

-

ACTIVITY 2 Activity 2 summarizes the main points discussed in this
17 introduction. Stop the tape and review the Activity before continuing.

-

The minimum index density test will be discussed first. Detailed test procedures are given in ASTM D 4254. You should realize that it is outside the scope of this Module to give enough detail for actually performing the tests. You
18 should refer to the ASTM standards for this detail.

-

The minimum index density is defined as the reference dry density of a soil in the loosest state of compactness at which it can be placed using a standard laboratory procedure
19 that prevents bulking and minimizes particle segregation.

-

Bulking is the creation of a loose structure in a sand or gravel caused by capillary stresses in the moist material. Proper preparation of the samples for the test will minimize
20 this problem.

-

Segregation is the separation of coarser fragments from finer fragments in a sample caused by dropping the sample from too great a height during placement. Use of proper
21 procedures and equipment will minimize this problem.

-

Different sizes of test equipment and test procedures are used depending on the maximum particle size of the sample to be tested. Soils that have a maximum particle size of 3/4 inch are tested in a small mold and soils that have larger
22 gravels are tested in a larger mold.

-

Photo The minimum index test procedure involves placing a prepared sample carefully by prescribed procedures into a mold of known volume. The test procedures are designed to attain the loosest state of density possible for that gradation of soil. However, an absolute minimum density is not implied, because
23 other methods could result in slightly lower density.

-

The most common method of performing the test is to use a
Photo pouring device such as the one shown. The mold is filled with the soil slowly and with a minimum of disturbance of the soil as it is poured into the mold. Care is taken not to drop the soil from any height that would cause higher
24 densities and cause segregation.

-

After carefully filling the mold, the surface of the soil is screeded with a straight edge so that the resulting soil
Photo volume will be precisely known. By weighing the mold that has the soil in it, and knowing the volume of the mold from prior calibrations, one may calculate the density or dry unit
25 weight of the soil in a minimum index density state.

-

The size of mold and the pouring device used depends on the gradation of the sample being tested. A one-tenth cubic foot mold is used for sands, and a one-half cubic foot mold is used for samples that have gravel. Oven-dry soil is used to eliminate any bulking that might be caused by moisture in
26 the sample.

-

ACTIVITY 3 Activity 3, Part D, of your Study Guide has more detailed descriptions of the minimum index density test procedures and has examples and problems. Stop the tape and complete the
27 Activity.

-

The maximum index density test is performed by procedures
28 listed in ASTM D 4253.

-

The maximum index density is defined as the reference dry density of a soil in the densest state of compactness that can be attained using a standard laboratory procedure
29 that minimizes particle segregation and breakdown.

-

The maximum index density test may be performed on either oven-dried or wet soil. The soil is placed in the same mold
Photo as used in the minimum index density test. The soil is placed carefully in the mold to minimize segregation. Often, the sample used for the minimum index density test is used to
30 perform this test procedure, if oven-dry soil is being tested.

-

A surcharge weight is then placed on the surface of the soil in the mold. The weight applies a pressure of 2 pounds per square inch. A sleeve holds the surcharge in alignment.

31

-

The sample and apparatus are then bolted to a vibratory table that has the capability of vibrating at 50 to 60 Hertz. The sample is then vibrated for eight to ten minutes. Hertz
32 units are cycles per second.

-

The vibration of the table and the presence of the surcharge weight densifies the sample. The final density is termed the maximum index density. By carefully measuring the height of the vibrated sample after removing the surcharge weight, and knowing the weight of sample with which the test was started and the volume of the mold, a value of maximum index density
33 may be calculated.

-

Care must be exercised in interpreting results of tests on samples that may experience breakdown of particles during the test because this will result in an increase in density.

Repeatability of results depends on careful calibration of equipment and strict adherence to test procedures.

Test results should always state (1) the maximum size of particles in the soil tested, (2) whether the sample tested
34 was oven-dry or wet, and (3) what size of mold was used for the test.

ACTIVITY 4 Activity 4 has details on procedures for performing the maximum index density test. Stop the tape and complete
35 the Activity.

A designer may select a preliminary design density based upon the results of these two tests. Usually, a density is selected somewhere between the minimum and maximum index test values. Two ways are used to specify these design densities, as follows:

1. A design density may be expressed as some percentage of the maximum index density, such as 90 percent of maximum index density.

2. A relative density may be specified. Relative density is
36 defined as follows:

$$D_r\ (\%) = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$$

Relative density is the ratio, expressed as a percentage, of the difference between the maximum index void ratio and any given void ratio to the difference between its maximum and minimum index void ratios, by the equation shown. Recall from Module 4 that void ratio is calculated from the specific
37 gravity and the dry density of a sample.

$$D_r\ (\%) = \frac{D_{max}\ (D-D_{min})}{D(D_{max}-D_{min})} \times 100$$

Because density is directly related to void ratio, an alternative equation may be derived. This equation shows relative density in terms of a given density and the minimum and maximum index densities, rather than in terms of void ratios. Typical values for relative density selected for preliminary design are from 50 to 80 percent relative
38 density.

ACTIVITY 5

Activity 5, Part D, of your Study Guide reviews relative terminology and has examples and problems on relative density calculations. Stop the tape and complete that Activity.

39

-

Clean and dual classified coarse-grained soils are somewhat rare in nature. Beach sands and some desert soils are examples of clean coarse-grained soils. Consequently, few fills containing large quantities of clean or dual classifications of coarse-grained soils are constructed. Relative density most frequently applies to the placement and control of the density of drain and filter materials. These materials have usually been processed and washed to remove

40 most of the fines.

-

ESTIMATES OF MINIMUM AND MAXIMUM INDEX DENSITIES

Correlations have been developed from a large number of tests that can be used to obtain an estimate of minimum and maximum index densities. The correlations are based on gradation of soils. The correlations shown are based on the percent of the sample finer than the number 16 size sieve.

41 They were developed by the U.S. Army Corps of Engineers.

-

Correlations should be used with caution because they do not consider important variables such as specific gravity of the particles and shape of the particles. Samples of the same gradation but with differing angularity of particles will have significantly differing values of reference densities.

Correlations may be useful for preliminary estimates of relative density values, and for cases where extensive

42 laboratory testing is not justified.

-

ACTIVITY 6

Activity 6, of your Study Guide covers correlations for estimating values of index densities for clean coarse-grained

43 soils. Stop the tape and complete the Activity.

-

Relative density and index density tests are used as follows in the design of an earth fill:

First, index density tests are performed on representative

44 soils to be used in the fill.

-

Then, a design relative density is arbitrarily selected.
45 Often, 70 percent relative density is assumed.

-

Engineering property tests such as shear strength and
46 permeability tests are then performed at a dry density
corresponding to the preliminary design density. The flow
charts shows parameters that might be obtained in tests on a
soil.

-

Using engineering test values obtained, the structure is
47 analyzed for stability or seepage problems.

-

If the resulting design is judged inadequate, other design
densities may be assumed and the process repeated until an
acceptable fill is indicated. If the design is adequate, the
relative density assumed will be used to write construction
48 specifications.

-

After a design is based on a relative density value, then
construction specifications may be written requiring the
coarse-grained soils to be placed at the required reference
densities. Just as with compaction, using a reference
density rather than some single value of density is
preferable when materials are expected to be variable. Field
49 tests must be performed if different soils are encountered.

-

These index density tests are difficult to perform in the
field. Consequently, using relative density specifications
for earth fill quality control is unusual in the Soil
Conservation Service. A more common approach is to specify
an acceptable density value based on laboratory tests or
correlations, or to specify the equipment type, lift
thickness, and minimum number of passes of the equipment,
50 based on previous favorable experience.

-

Usually, specifications also require thorough wetting of
clean fine sands to prevent bulking and ensure good
51 compaction. Filters and drains may be composed of these soil
types.

-

ACTIVITY 7

52 Examples of construction specifications for placing coarse-grained soils with less than 12 percent fines are shown in Activity 7, of your Study Guide. Stop the tape and review the Activity.

-

53 Let's review the objectives of Part D. Objective 1 was to define the terms associated with index density and relative density.

-

54 Objective 2 was to identify the equipment and procedures used for performing index density tests in the laboratory and field.

-

55 Objective 3 was to estimate values for index densities based on soil classification and gradation data.

-

ACTIVITY 8

56 Activity 8, Part D, tests your completion of these objectives. Stop the tape and complete the Activity.

-

57 That completes Part D of Module 5. You are now ready to proceed to Part E.

United States
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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--
BASIC SOIL PROPERTIES
MODULE 5 - COMPACTION
PART E
EVALUATION OF COMPACTION DATA AND SPECIFICATIONS

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.

<u>Example 1</u>: 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 <u>not</u> 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/ft³, 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/ft³, 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/ft³, 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

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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
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 ______"

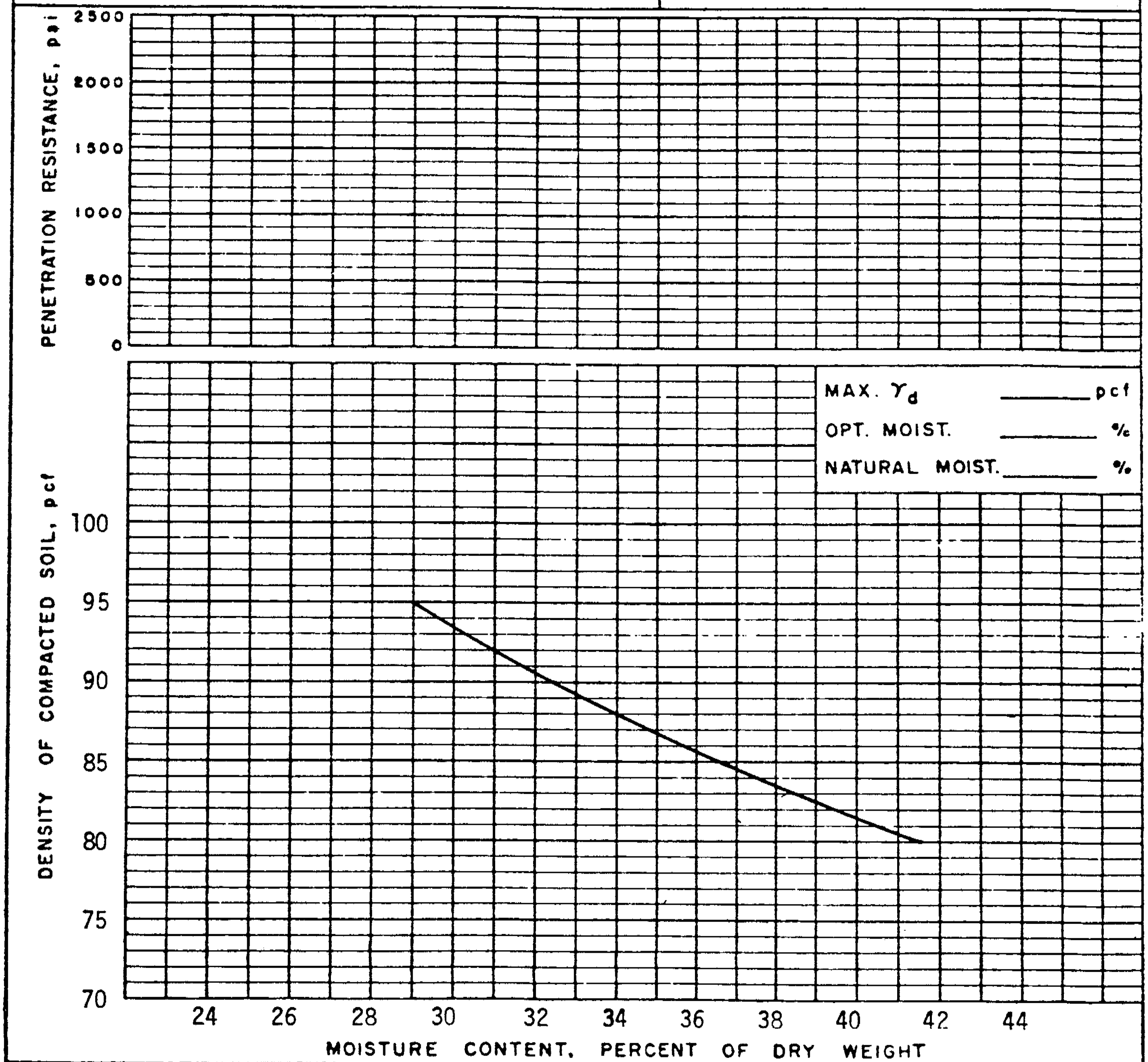
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.72 / PLUS NO. 4 ______

CURVE NO. ______ OF ______

STD. (ASTM D-698) ☐; METHOD ______

MOD. (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)



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 ______"

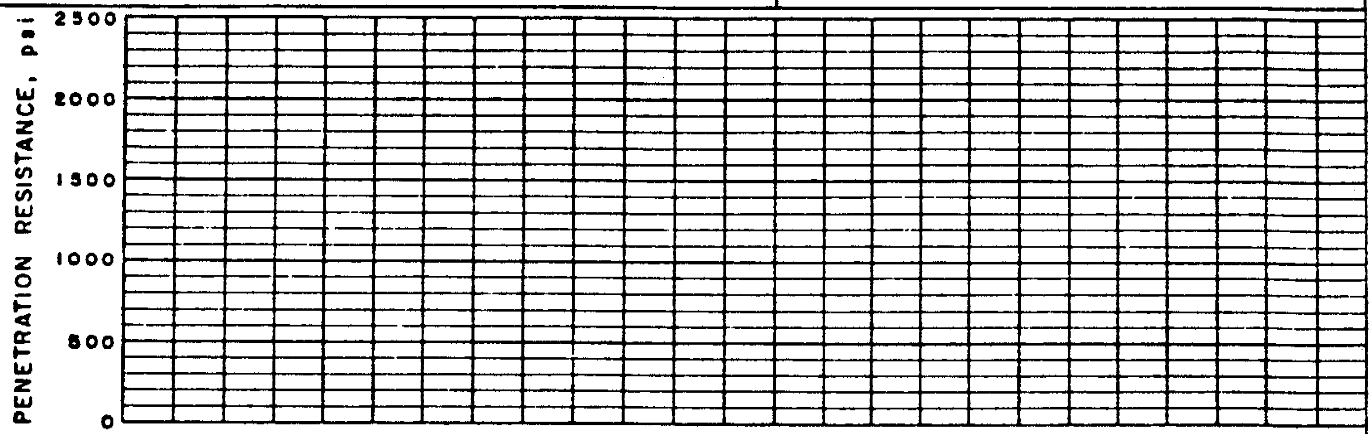
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 ______ ; PLUS NO. 4 ______

CURVE NO. ______ OF ______

STD. (ASTM D-698) ☐; METHOD ______

MOD. (ASTM D-1557) ☐; METHOD ______

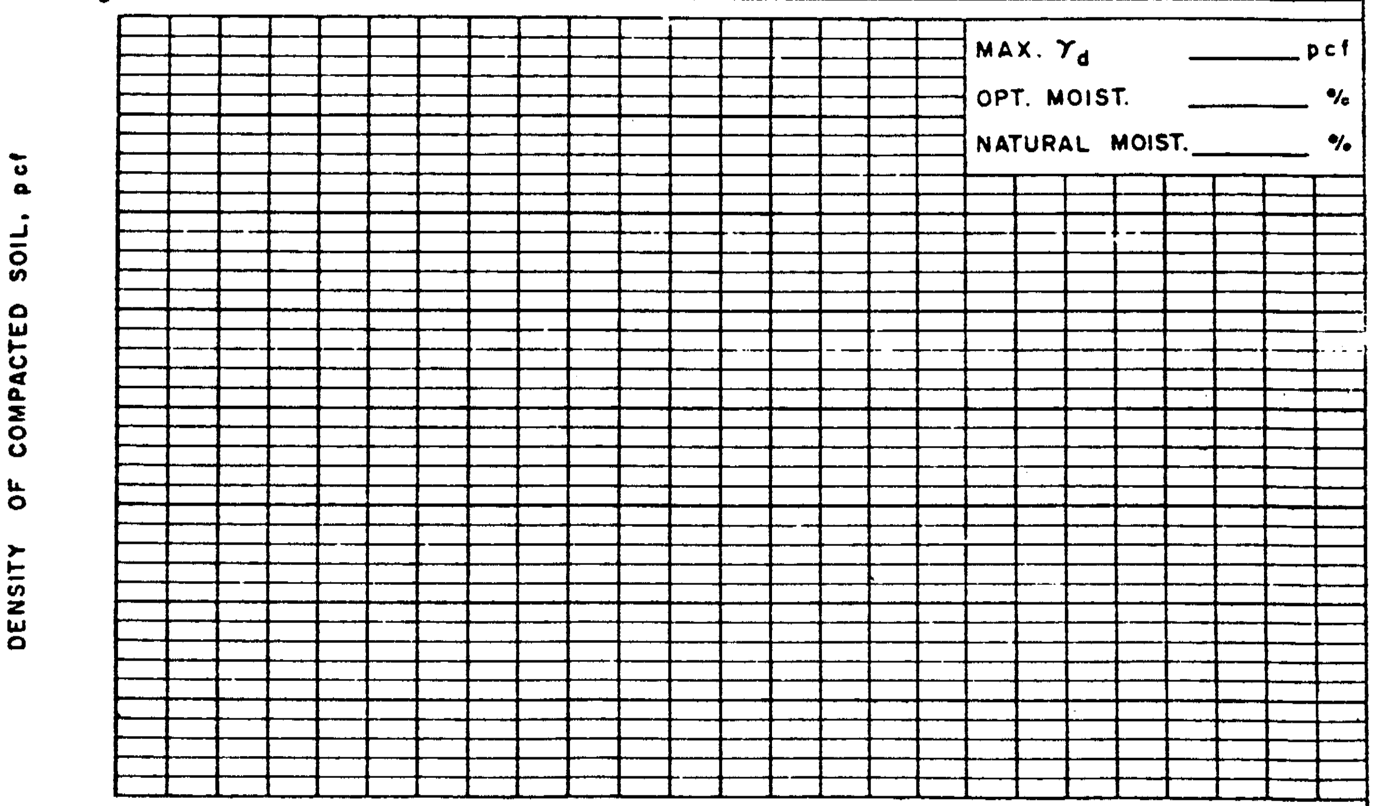
OTHER TEST ☐ (SEE REMARKS)



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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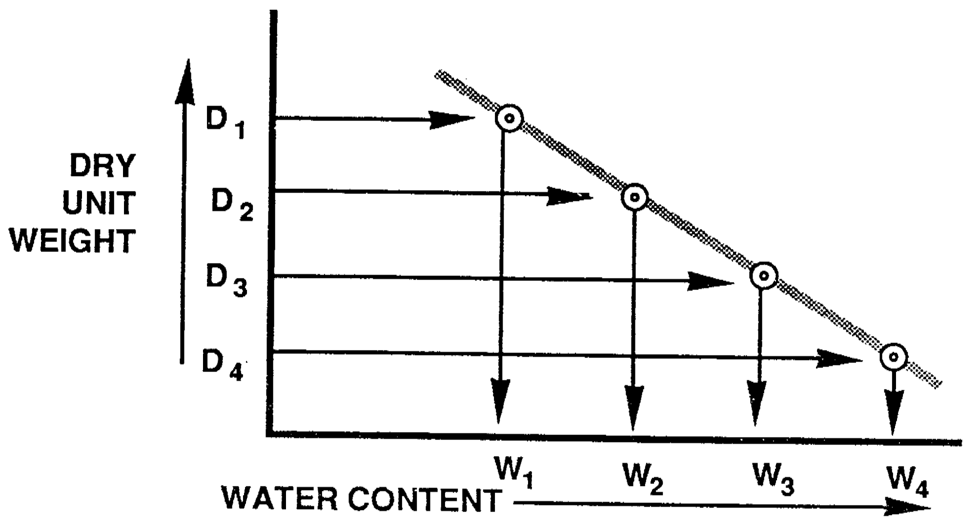

ASSUMED DENSITY	SATURATED WATER CONTENT
D_1	W_1
D_2	W_2
D_3	W_3
D_4	W_4

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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FILE CODE ENG-22

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 ______ "

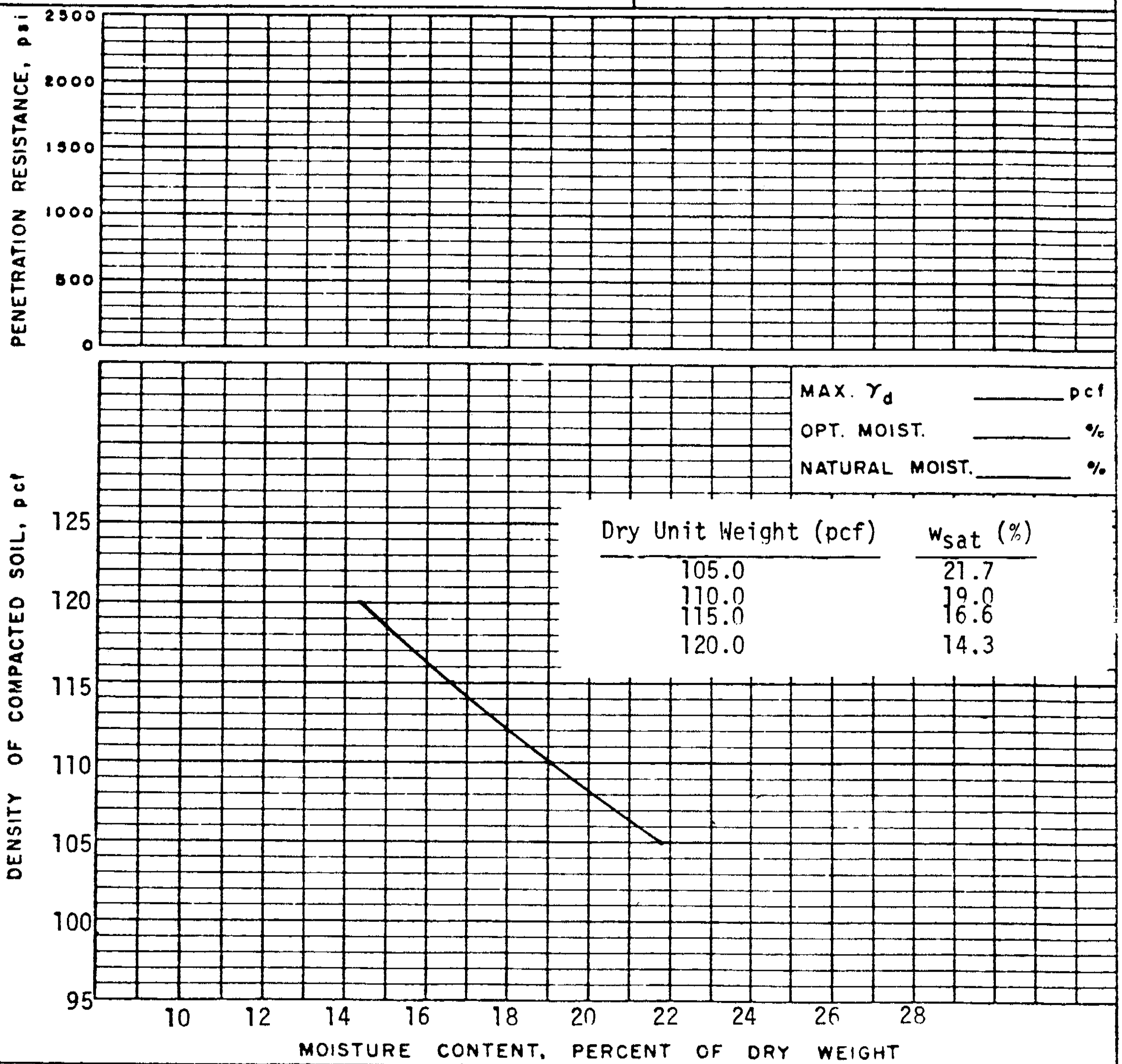
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.65 ; PLUS NO. 4 ______

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}

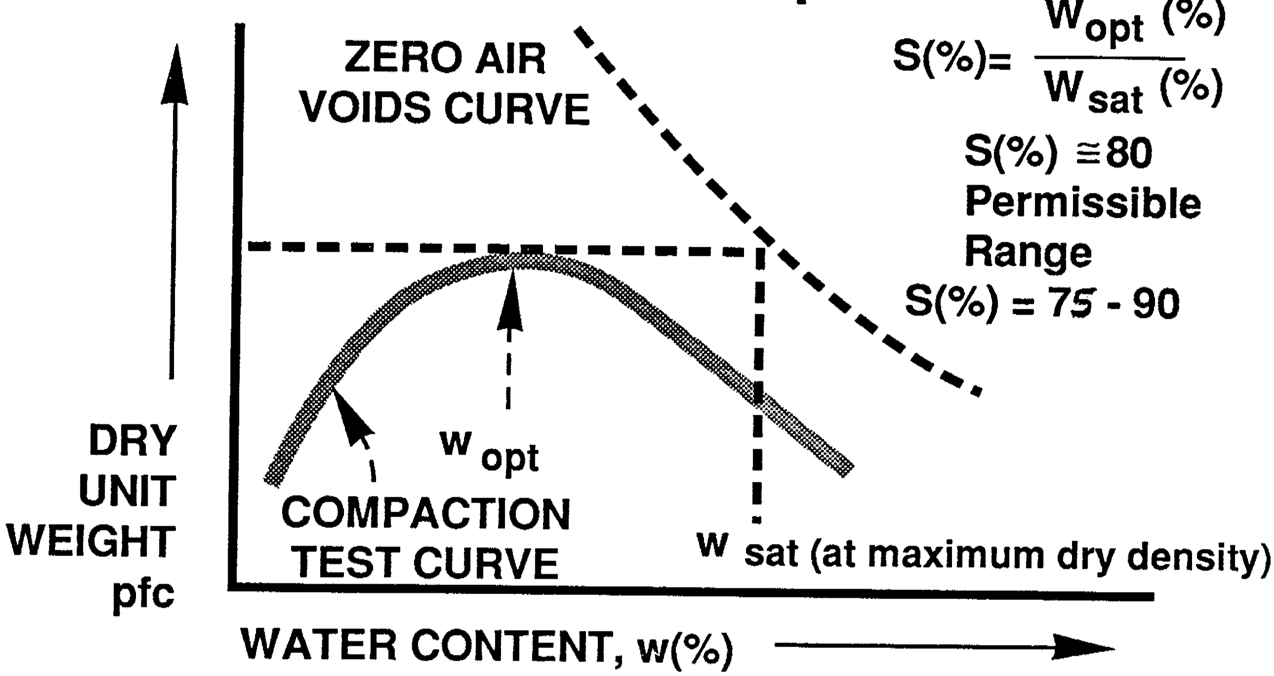

Fig. 6.1

CHECK COMPACTION CURVE "WET" SIDE

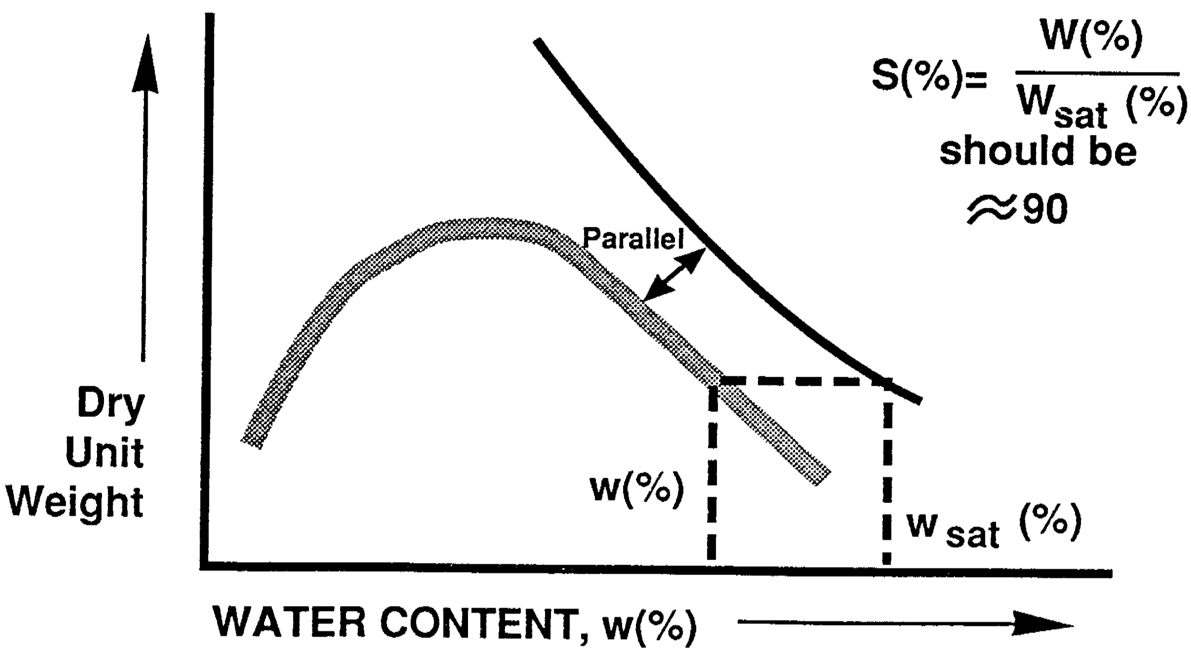

Fig. 6.2

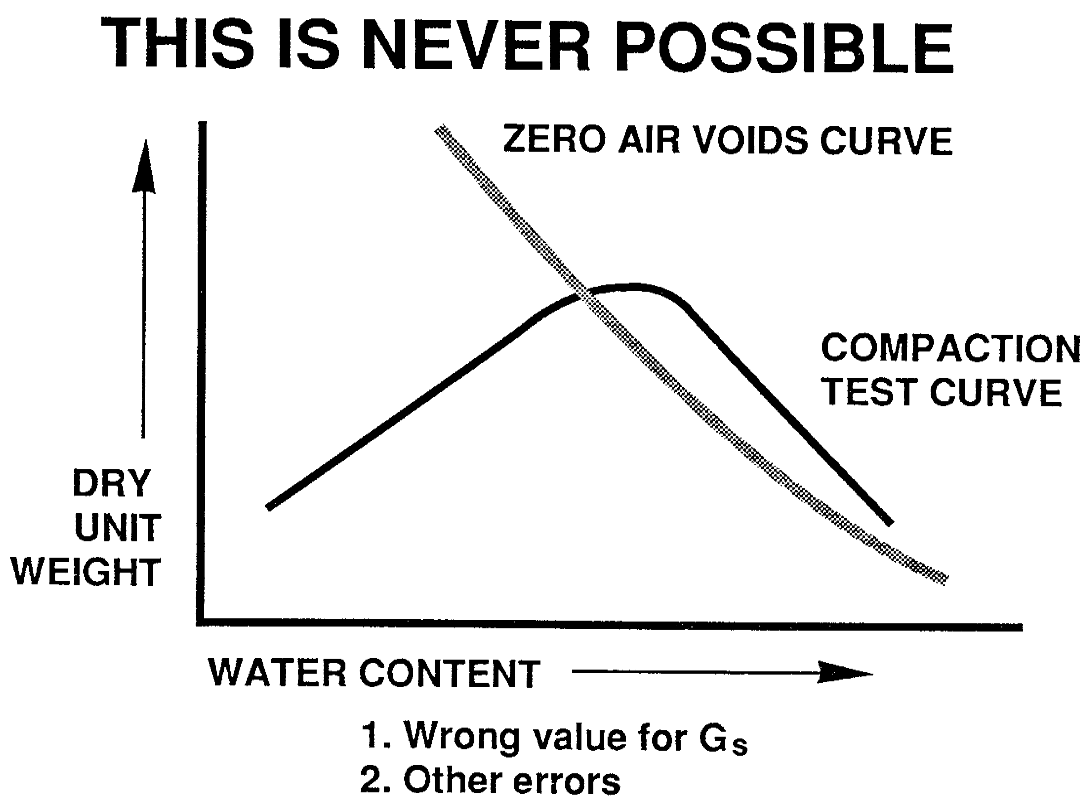

Figure 6.3--Ilustration of Compaction Curve Intersecting Zero Air Voids Curve.

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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 ______ "

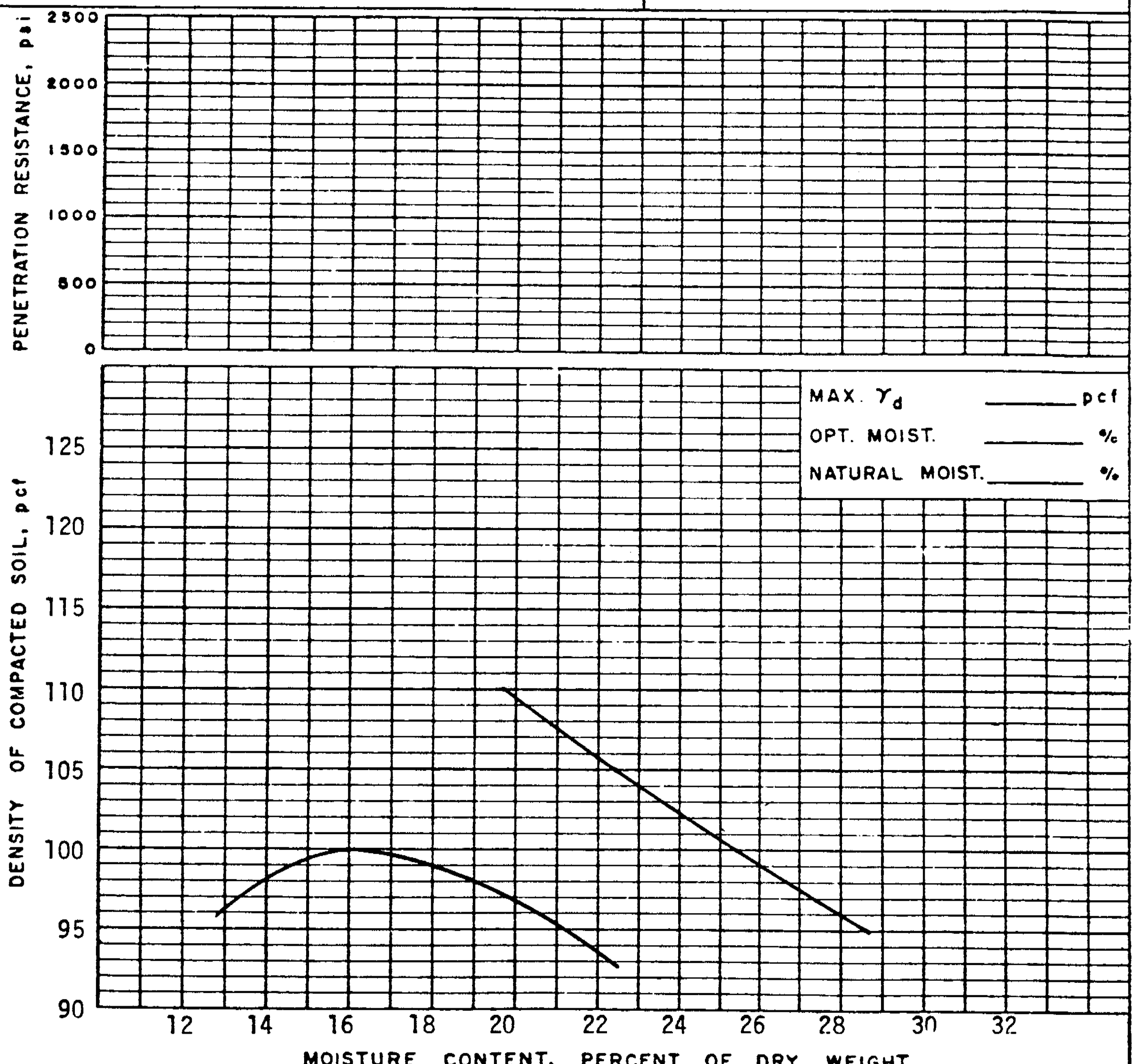
SPECIFIC GRAVITY (G_s) MINUS NO. 4 ______ / PLUS NO. 4 ______

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 ______"

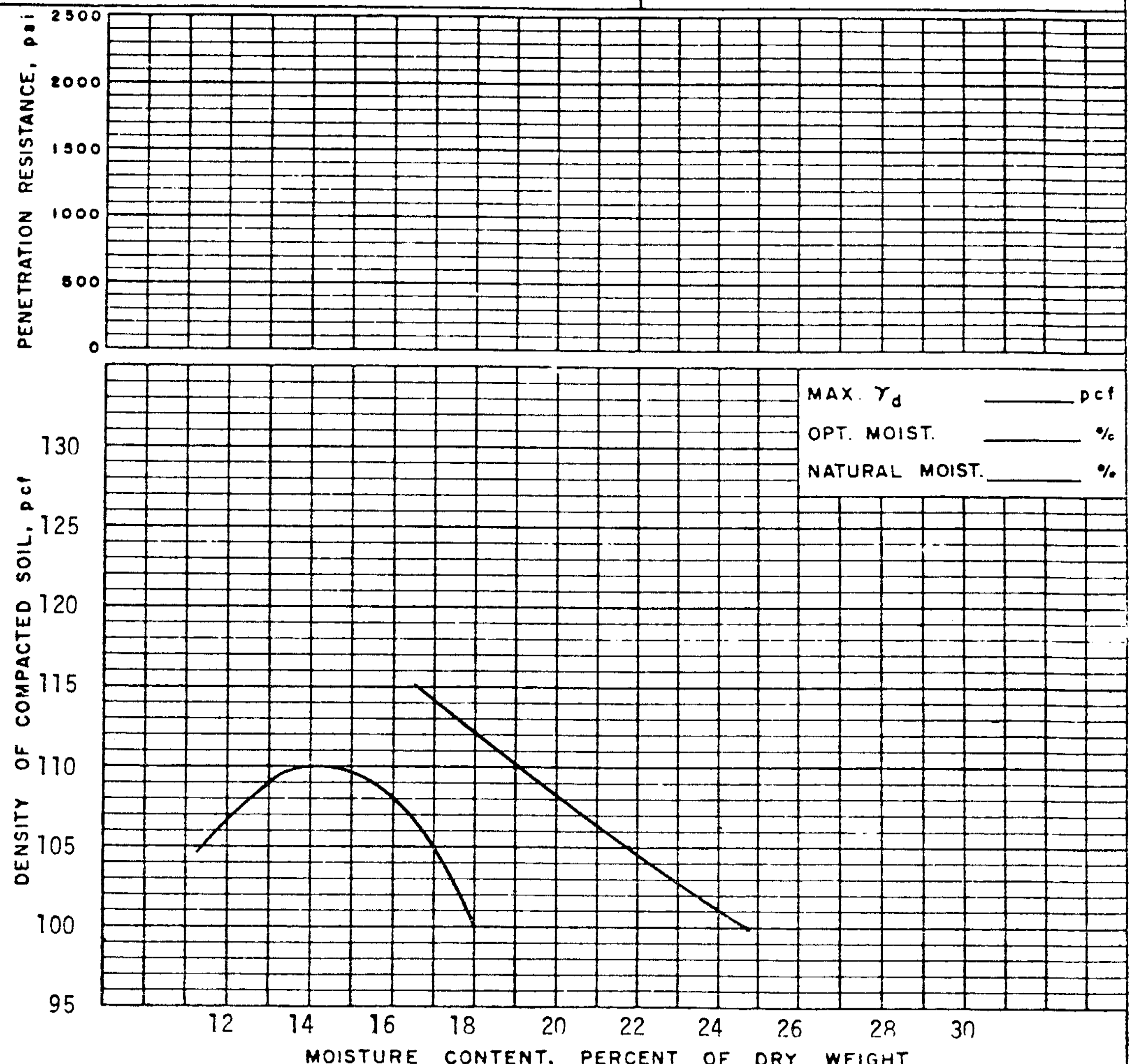
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 ______ / PLUS NO. 4 ______

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 ______ "

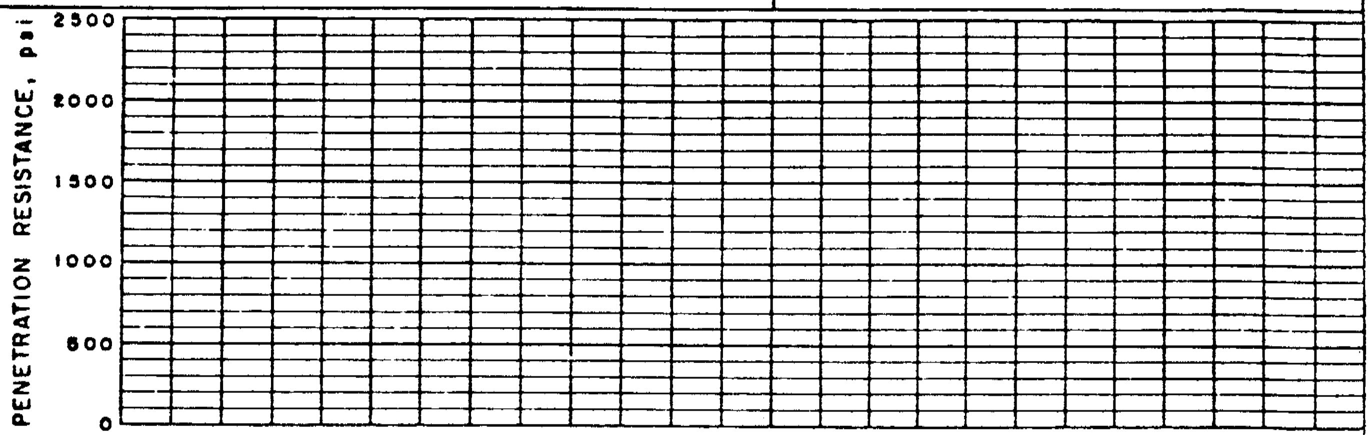
SPECIFIC GRAVITY (G_s) MINUS NO. 4 ______ PLUS NO. 4 ______

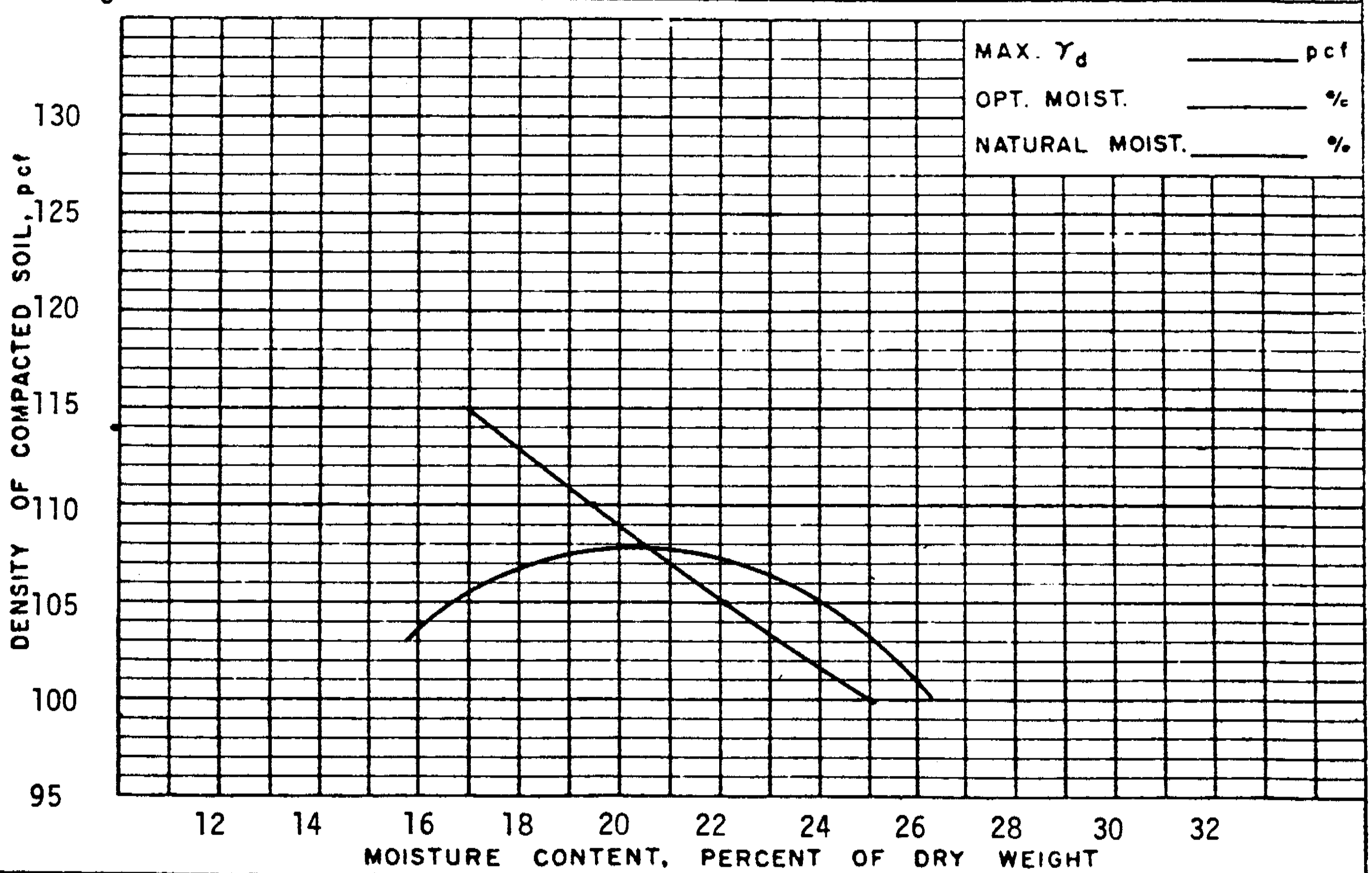
CURVE NO. ______ OF ______

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 "

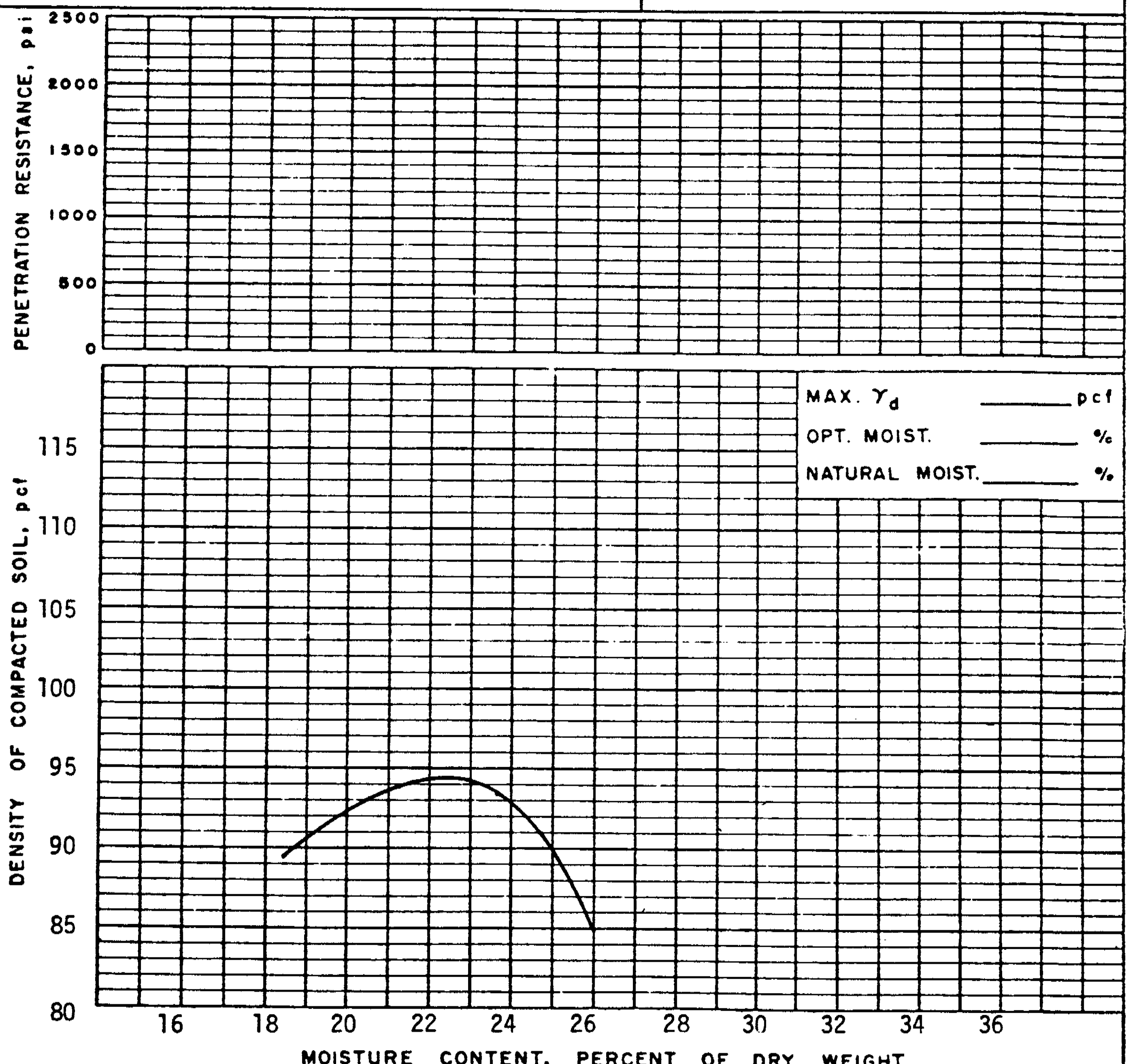
SPECIFIC GRAVITY (G_s) MINUS NO. 4 2.80 ; PLUS NO. 4 ______

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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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 "

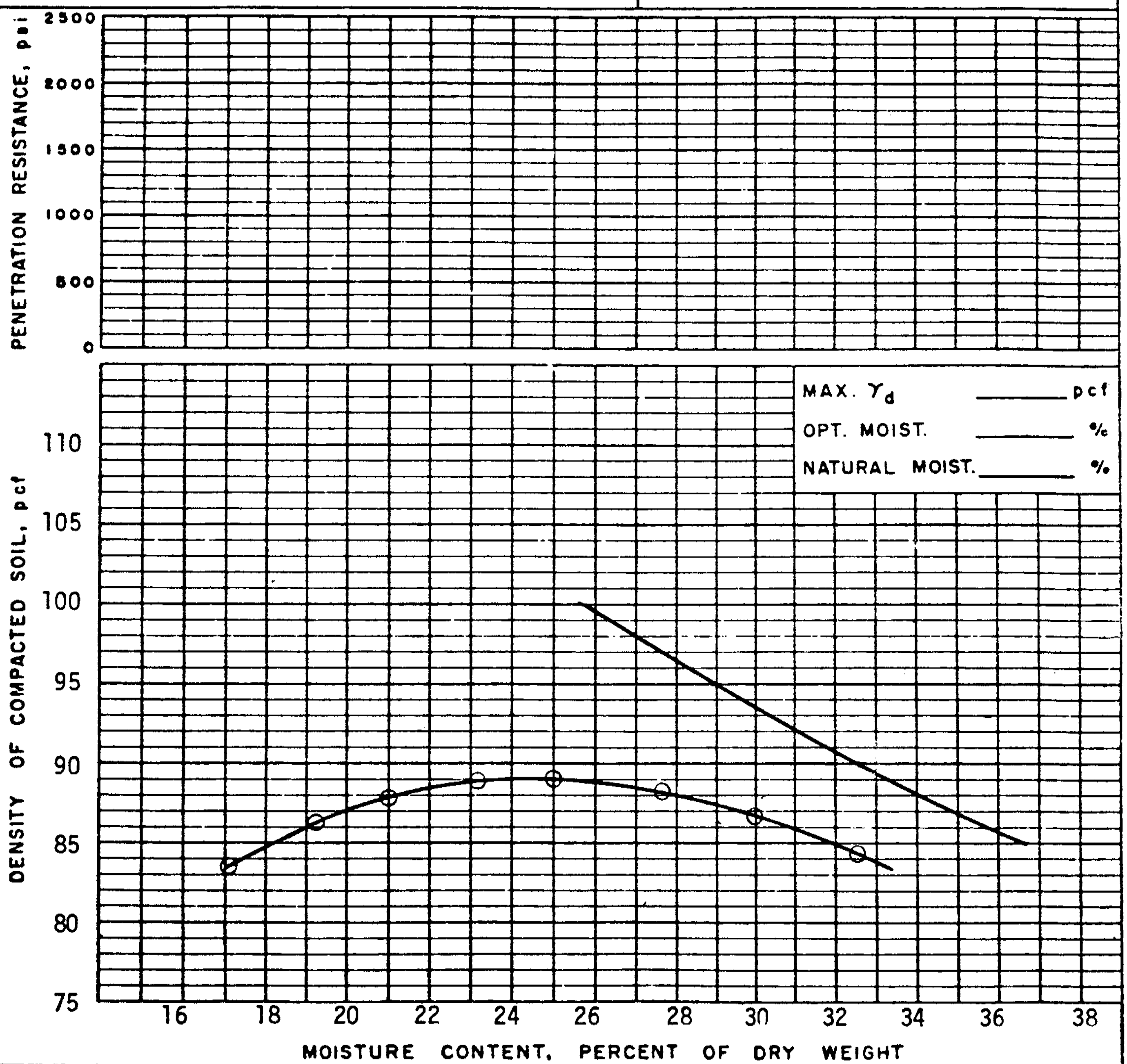
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.72 ; PLUS NO. 4 ______

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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ACTIVITY 7 - PART E

LABORATORY NO ______

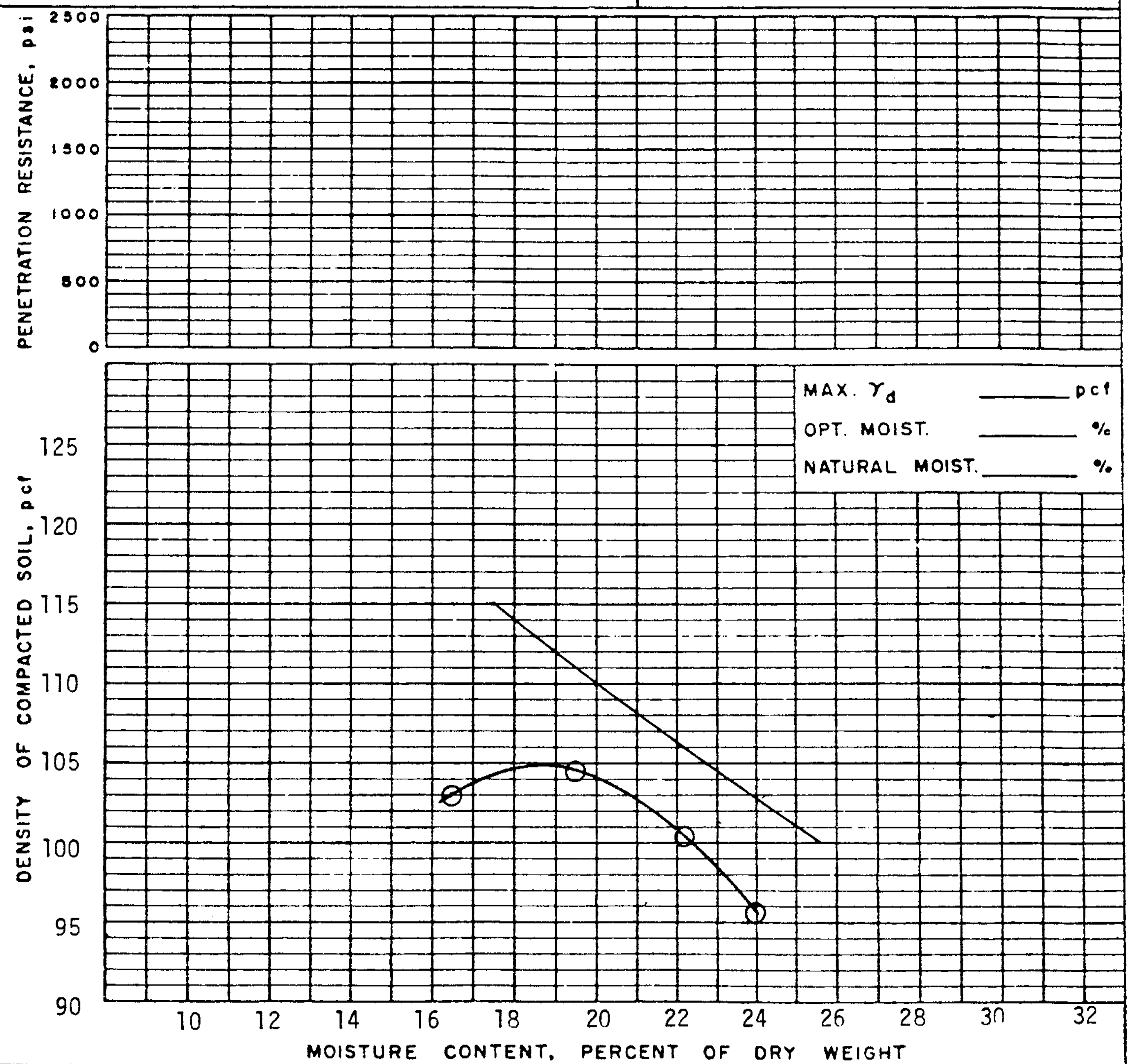
MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	COMPACTION AND PENETRATION RESISTANCE

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	MOD. (ASTM D-1557) ☐; METHOD ______
SPECIFIC GRAVITY (G_s) PLUS NO. 4 ______	OTHER TEST ☐ (SEE REMARKS)



REMARKS

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

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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 7.3 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 "

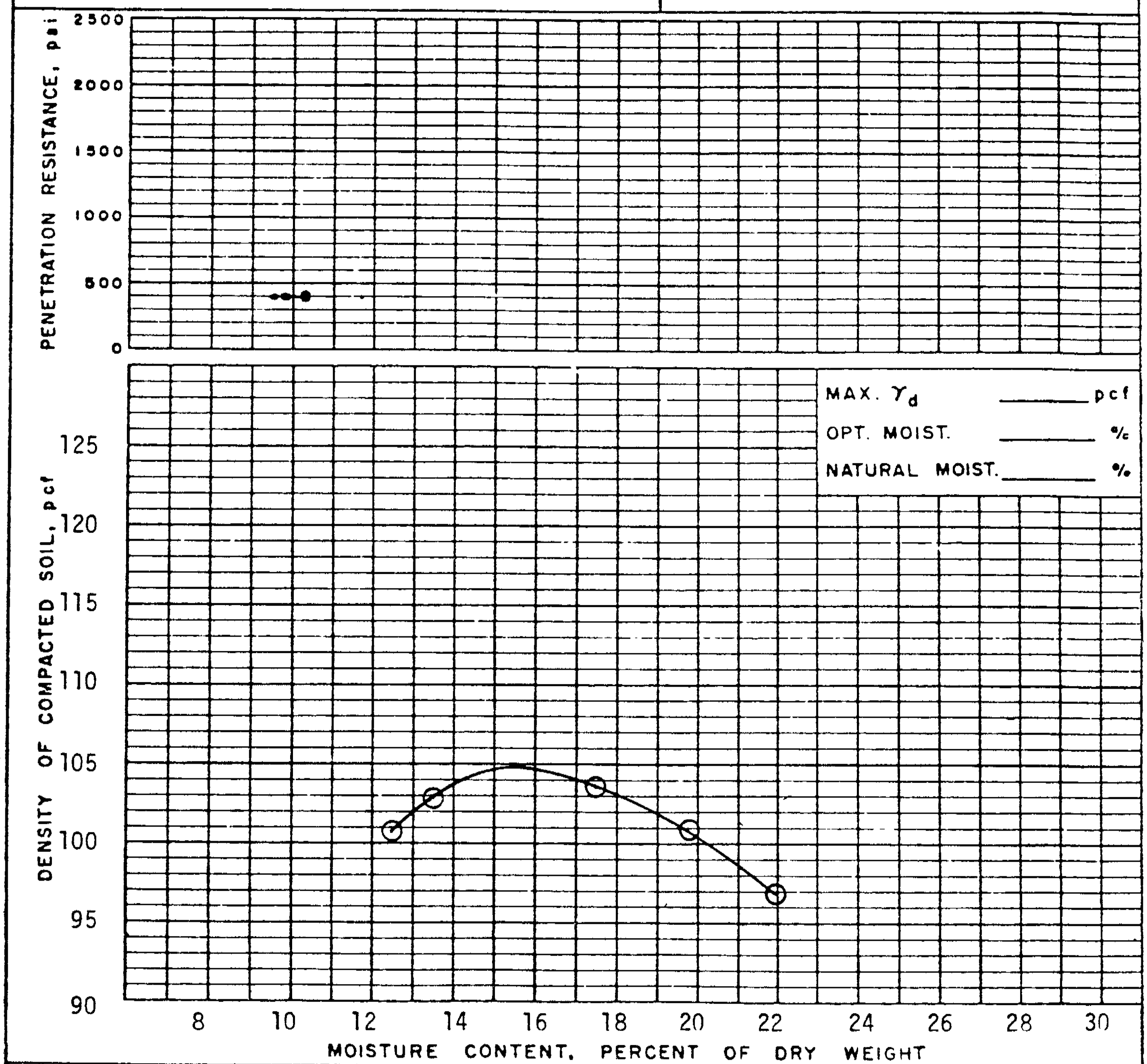
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.77 ; PLUS NO. 4 ______ }

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)

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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

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FILE CODE ENG-22

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 "

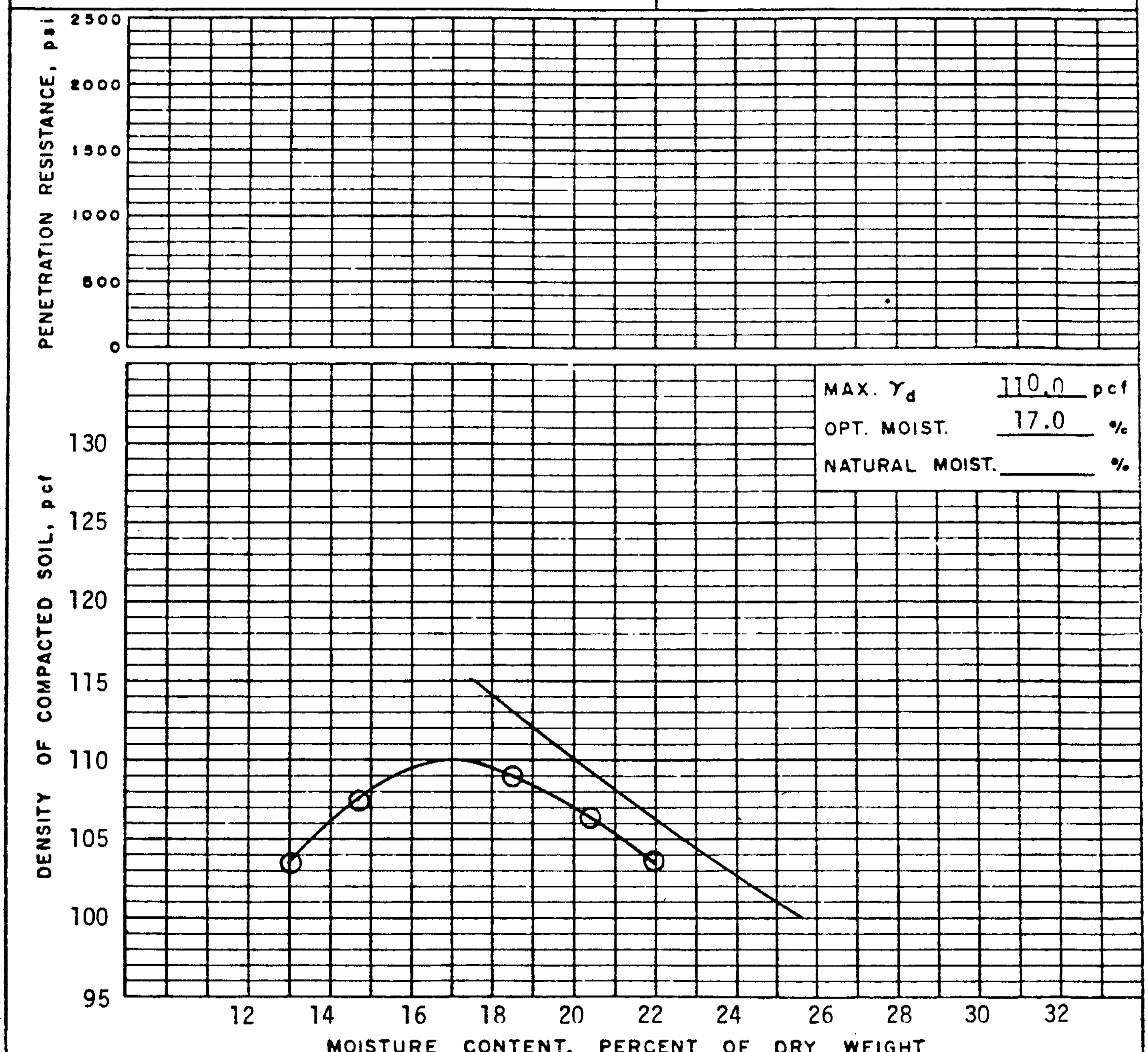
SPECIFIC GRAVITY (G_s) { MINUS NO. 4 2.72; PLUS NO. 4 ______ }

CURVE NO. 1 OF 1

STD. (ASTM D-698) ☒; METHOD A

MOD (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)



REMARKS

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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]

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

$$= 19.96\%$$

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

$$= 85\%$$

[2] At wettest point

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

$$= 23.53\%$$

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

$$= 93.5\%$$

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:

<u>Example 1</u>

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 optim 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?

<u>Solution</u>

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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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 "

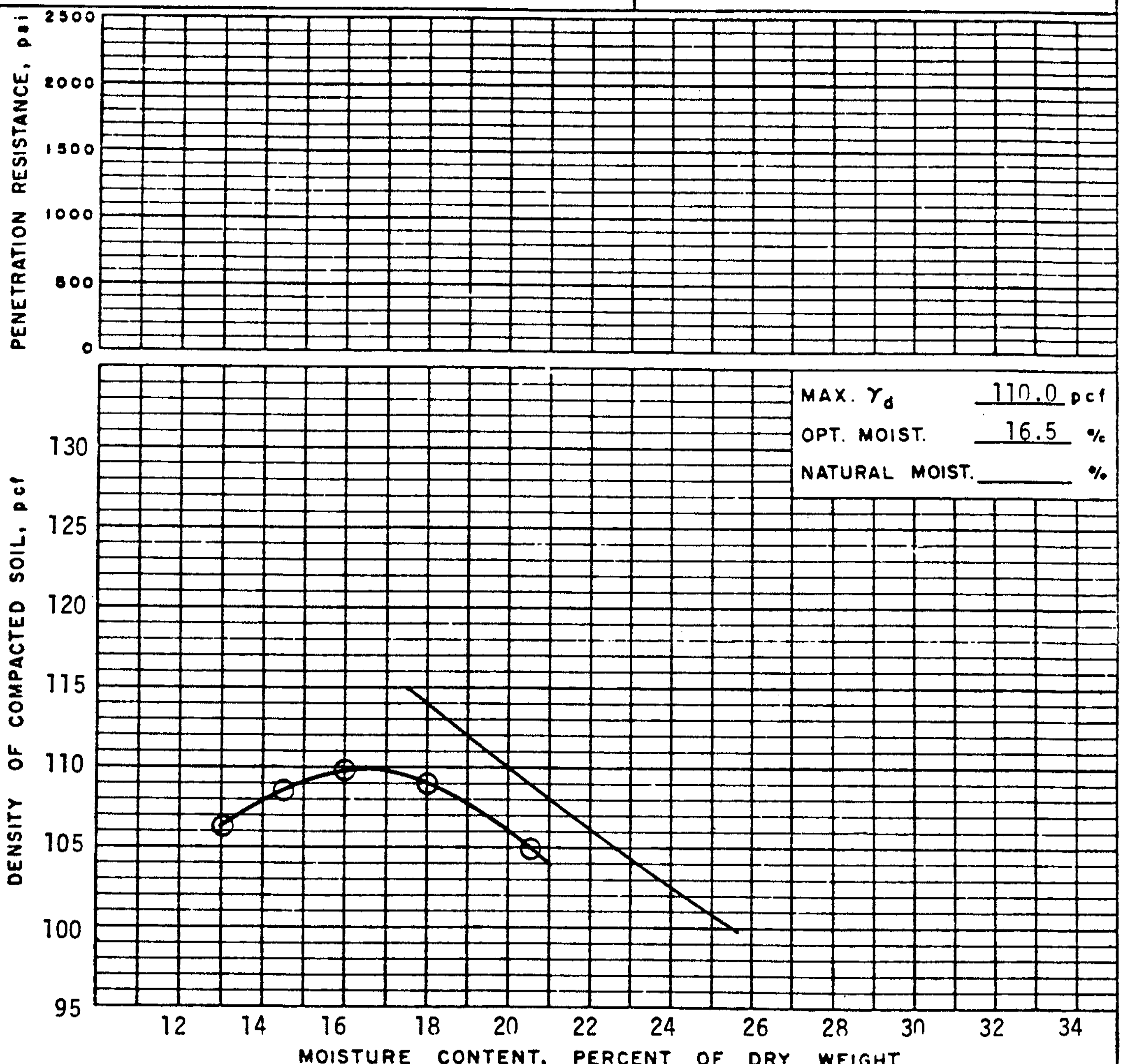
SPECIFIC GRAVITY (G_s) MINUS NO. 4 2.70; PLUS NO. 4 ______

CURVE NO. 1 OF 1

STD. (ASTM D-698) ☐; METHOD ______

MOD. (ASTM D-1557) ☒; METHOD A

OTHER TEST ☐ (SEE REMARKS)



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

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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 "

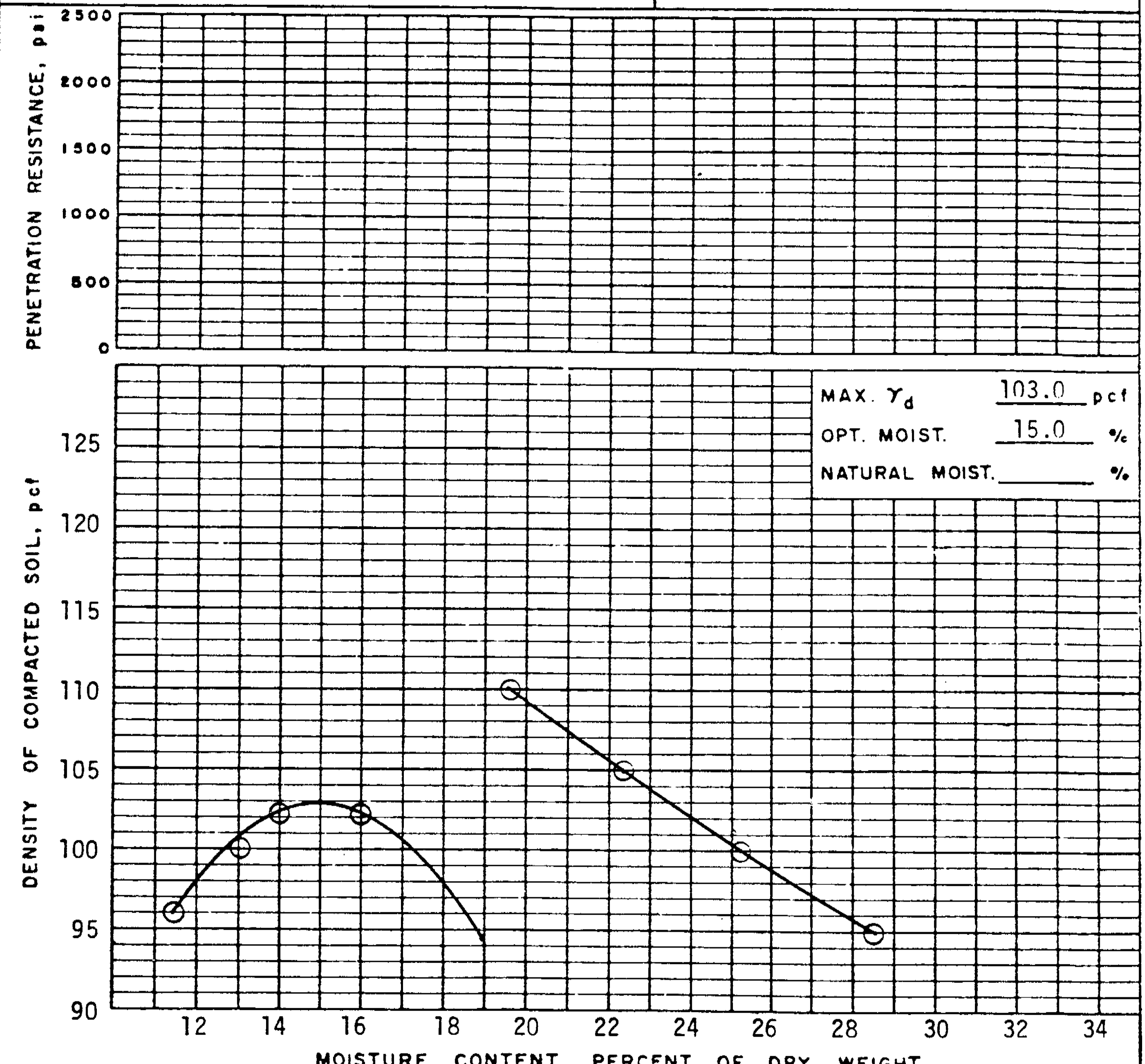
SPECIFIC GRAVITY (G_s) MINUS NO. 4 2.69; PLUS NO. 4 ______

CURVE NO. 1 OF 1

STD. (ASTM D-698) ☒; METHOD A

MOD. (ASTM D-1557) ☐; METHOD ______

OTHER TEST ☐ (SEE REMARKS)



REMARKS

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ACTIVITY 11, Problem 10 - Worksheet

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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

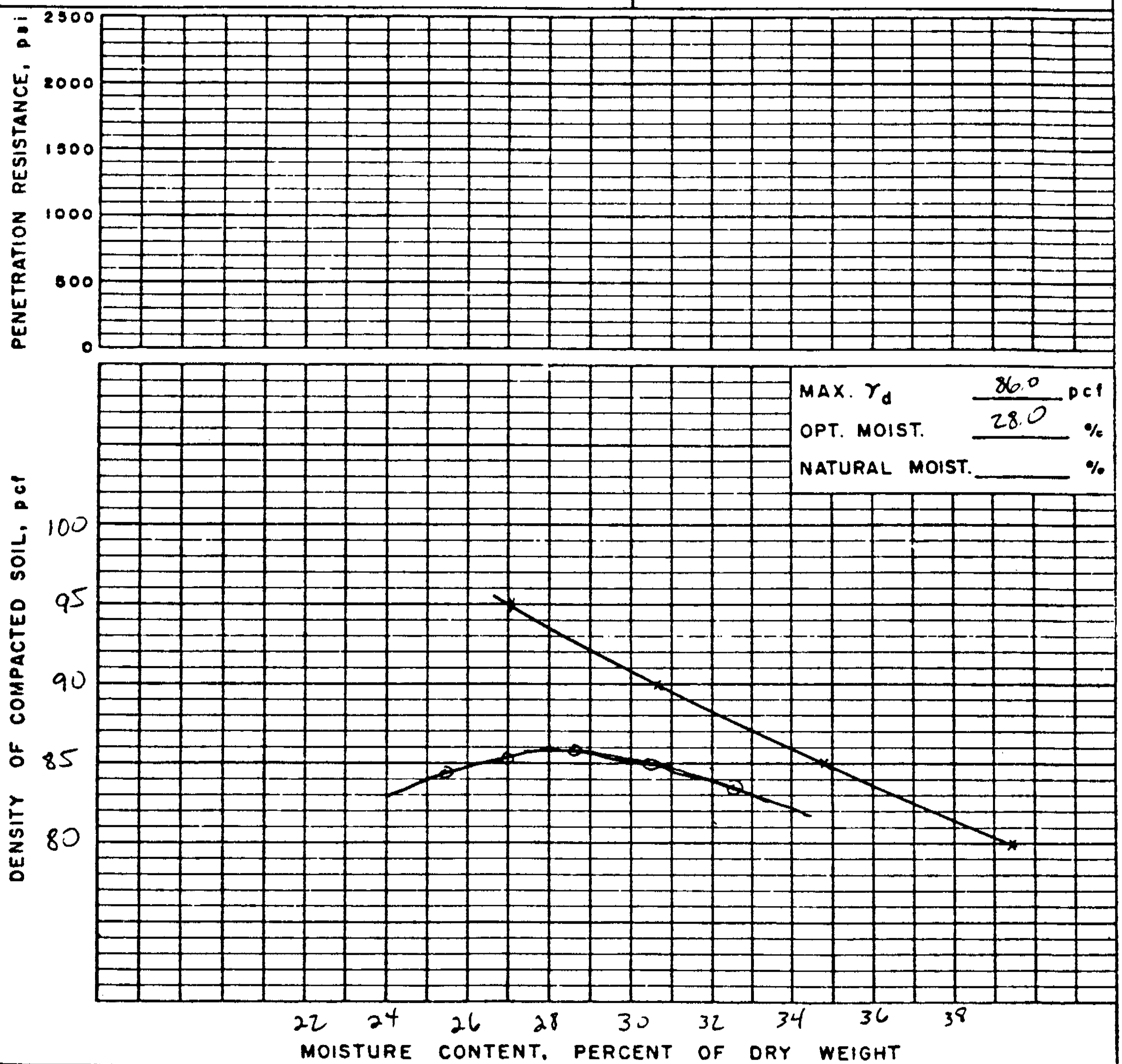
SPECIFIC GRAVITY (G_s) MINUS NO. 4 2.59; PLUS NO. 4 ______

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.

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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.

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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.

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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.

-

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

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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.
10 5. Weighing devices accuracy.

-

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
12 be inaccurate.

-

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

-

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
14 constant weight.

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

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ACTIVITY 3

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

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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.

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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.

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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.

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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.

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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.

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ACTIVITY 7
29

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

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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.

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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.

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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

36 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 the Activity.

ACTIVITY 9

37 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 complete that Activity.

38 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 of this Module, and based on previous test results.

39 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 economical.

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

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

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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.

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

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

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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.

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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 ____________________________ Signed ____________________________
Supervisor/Trainer 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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