19

HIGHWAY RESEARCH BOARD

Bulletin 319

Factors Influencing Compaction Test Results

National Academy of Sciences—
National Research Council

publication 967

HIGHWAY RESEARCH BOARD

Officers and Members of the Executive Committee

1962

OFFICERS

R. R. Bartelsmeyer, *Chairman* C. D. Curtiss, *First Vice Chairman*
Wilbur S. Smith, *Second Vice Chairman*
Fred Burggraf, *Director* William N. Carey, Jr., *Assistant Director*

Executive Committee

Rex M. Whitton, *Federal Highway Administrator, Bureau of Public Roads* (ex officio)

A. E. Johnson, *Executive Secretary, American Association of State Highway Officials* (ex officio)

Louis Jordan, *Executive Secretary, Division of Engineering and Industrial Research, National Research Council* (ex officio)

Pyke Johnson, *Retired* (ex officio, Past Chairman 1960)

W. A. Bugge, *Director of Highways, Washington Department of Highways* (ex officio, Past Chairman 1961)

R. R. Bartelsmeyer, *Chief Highway Engineer, Illinois Division of Highways*

E. W. Bauman, *Director, National Slag Association, Washington, D. C.*

Donald S. Berry, *Professor of Civil Engineering, Northwestern University*

Mason A. Butcher, *County Manager, Montgomery County, Md.*

J. Douglas Carroll, Jr., *Director, Chicago Area Transportation Study*

C. D. Curtiss, *Special Assistant to the Executive Vice President, American Road Builders' Association*

Harmer E. Davis, *Director, Institute of Transportation and Traffic Engineering, University of California*

Duke W. Dunbar, *Attorney General of Colorado*

Michael Ference, Jr., *Executive Director, Scientific Laboratory, Ford Motor Company*

D. C. Greer, *State Highway Engineer, Texas State Highway Department*

John T. Howard, *Head, Department of City and Regional Planning, Massachusetts Institute of Technology*

Burton W. Marsh, *Director, Traffic Engineering and Safety Department, American Automobile Association*

Oscar T. Marzke, *Vice President, Fundamental Research, U. S. Steel Corporation*

J. B. McMorran, *Superintendent of Public Works, New York State Department of Public Works*

Clifford F. Rassweiler, *Vice President for Research and Development, Johns-Manville Corporation*

Glenn C. Richards, *Commissioner, Detroit Department of Public Works*

C. H. Scholer, *Applied Mechanics Department, Kansas State University*

Wilbur S. Smith, *Wilbur Smith and Associates, New Haven, Conn.*

K. B. Woods, *Head, School of Civil Engineering, and Director, Joint Highway Research Project, Purdue University*

Editorial Staff

Fred Burggraf Herbert P. Orland
2101 Constitution Avenue Washington 25, D. C.

The opinions and conclusions expressed in this publication are those of the authors and not necessarily those of the Highway Research Board

N.R.C. **HIGHWAY RESEARCH BOARD**

Bulletin 319

Factors Influencing Compaction Test Results

A.W. JOHNSON, Engineer of Soils and Foundations
Highway Research Board

and

J.R. SALLBERG, Highway Research Engineer
Division of Physical Research
Bureau of Public Roads

National Academy of Sciences—
National Research Council
Washington, D.C.
1962

$1 3.00

Department of Soils, Geology and Foundations

Miles S. Kersten, Chairman
Professor of Highway Engineering
University of Minnesota
Minneapolis

COMMITTEE ON COMPACTION OF EMBANKMENTS, SUBGRADES AND BASES

L. D. Hicks, Chairman
Chief Soils Engineer
North Carolina State Highway Commission
Raleigh

W. F. Abercrombie, State Highway Materials Engineer, State Highway Department of Georgia, Atlanta
W. H. Campen, Manager, Omaha Testing Laboratories, Nebraska
Miles D. Catton, Technical Counselor, Research and Development Division, Research and Development Laboratories, Portland Cement Association, Skokie, Illinois
Lawrence A. DuBose, Testing Service Corporation, Lombard, Illinois
J. D. Geesaman, Highway Engineer, Portland Cement Association, Chicago, Illinois
C. A. Hogentogler, Jr., Hogentogler and Company, Chevy Chase, Maryland
James M. Hoover, Assistant Professor, Civil Engineering Department, Iowa State University, Ames
Delbert L. Lacy, Assistant Engineer of Materials, Kansas State Highway Commission, Topeka
William H. Mills, Consulting Engineer, Atlanta, Georgia
O. J. Porter, Managing Partner, Porter and O'Brien, Newark, New Jersey
C. K. Preus, Materials and Research Engineer, Minnesota Department of Highways, St. Paul
Thomas B. Pringle, Chief, Civil Engineering Branch, Engineering Division, Military Construction, Office, Chief of Engineers, Department of the Army, Washington, D. C.
Leo J. Ritter, Jr., Senior Editor, Engineering News-Record, New York, N. Y.
John R. Sallberg, Highway Research Engineer, Soils, Foundations and Flexible Pavement Branch, Bureau of Public Roads, Washington, D. C.
W. T. Spencer, Soils Engineer, Materials and Tests, State Highway Commission of Indiana, Indianapolis

Foreword

This bulletin is a companion to Bulletin 272, "Factors That Influence Field Compaction of Soils," which was published in 1960. As stated in the Foreword of Bulletin 272, this Committee has always recognized the importance of compaction, and, in addition to sponsoring numerous papers on the subject, has in the past prepared two publications summarizing the knowledge, then available, gained through research and experience. The first of these, Wartime Road Problems No. 11, "Compaction of Subgrades and Embankments," was published in 1945. The second, Bulletin 58, "Compaction of Embankments, Subgrades, and Bases," was published in 1952, and after two printings was adjudged out of date and in need of revision.

In bringing Bulletin 58 up to date, it became evident that two or more reports would be required to summarize all the new research information on compaction. The first report, Bulletin 272, "Factors That Influence Field Compaction of Soils," published in 1960, deals primarily with the compaction characteristics of field equipment. This second report, "Factors Influencing Compaction Test Results," summarizes research discoveries concerning factors that influence laboratory test results. A third report, dealing with the effect of compaction on soil properties and design, will be prepared as soon as possible, and will complete the revision of Bulletin 58.

The preparation of this bulletin has required much literature research in order to obtain the information, and many man-hours have been spent arranging the information in the proper form. This work was done by A. W. Johnson, Engineer of Soils and Foundations, Highway Research Board, and John R. Sallberg, Highway Research Engineer, Division of Physical Research, Bureau of Public Roads.

The Chairman wishes to thank the committee and the review subcommittee, which consisted of John R. Sallberg, Chairman, and James M. Hoover, Leo J. Ritter, Jr., and W.H. Campen, members, for their work in reviewing this bulletin.

L.D. Hicks, Chairman
Committee on Compaction of
Embankments, Subgrades, and Bases

Preface

The purpose of this bulletin is to examine the various factors that influence compaction test results for earth materials.

The bulletin begins with a brief history of the compaction test, its development and purpose, and descriptions of the principal compaction test methods currently being used. The main body of the text contains, in summary form, results of the many researches pertinent to the effect of variations in test apparatus, test procedures, soil type and state, the personal element, and other factors that influence the test results. This is followed by sections on factors influencing absolute maximum and minimum unit weights, methods for correcting for coarse aggregate content, comparisons of results from the different compaction test methods, reproducibility of compaction test results, methods for estimating optimum moisture content and maximum unit weight, methods for reporting test results, and references. Methods for calculating volume and weight relationships for soil, water, and air are given in Appendix A; definitions of terms are given in Appendix B.

The material contained herein has been obtained primarily from a search of the literature. Unfortunately, the results of many researches are never published. Information on several factors was not available, although it is likely that related studies have been made. Examples include the effect on compaction results of the shape of the tamping foot (the wedge-shaped foot is common on automatic compactors) and the effect of tapering the inside of the mold to simplify sample removal.

This bulletin is written for engineers and engineering technicians to acquaint them more fully with the nature of the compaction tests and factors that influence the results that are now so widely used as limiting values for construction specifications.

Acknowledgment to the many sources of information is given in the references. Appreciation is expressed to the entire committee for their encouragement and helpful suggestions and especially to W.H. Campen, J.M. Hoover, and L.J. Ritter, Jr., for critically reviewing the entire report.

A. W. J.
J. R. S.

Contents

List of Figures

Figure No. Legend Page No.

List of Tables

Factors Influencing Compaction Test Results

History of the Compaction Test

•EARLY CONSTRUCTION of roads in the United States usually involved only small amounts of earthwork, which was done by horsedrawn graders and scrapers with little thought given to compaction. Usually only the metalled or paved surfaces were rolled. The development of powered excavating and hauling equipment that followed the coming of the automobile resulted in marked increases in the depths of cuts, heights of fills, and total earthwork quantities in road construction. Early fills were constructed by end-dumping the loose soil without benefit of compaction as filling progressed. Fill "settlement" was usually considered largely a function of time. Paving was delayed until the fill had sufficient "time" to settle without knowledge of when settlement would be complete.

The rapid increase in the number of automobiles during the early 1920's brought increasing demand for a shortened time interval between the conclusion of earthwork construction and the commencement of paving. This resulted in soils being placed in layers, in some instances moistened, and either compacted by distribution of hauling equipment or "thoroughly compacted" by rolling in order to prevent settling. Controversy often arose over what constituted adequate compaction under the requirement "thoroughly compacted," "thoroughly rolled," or rolled "to the satisfaction of the engineer." This resulted in demands for controls for use in checking the results of the contractors' operations in highway construction.

According to an early report (8), "The first work along this line was done by the California Division of Highways in 1929 when an extensive series of tests was conducted from which was developed field equipment and methods of consolidating soil samples to determine optimum moisture requirements before construction and subsequently the relative compaction of the completed embankments. This procedure and equipment was adopted as standard in August 1929, and has been in use without substantial change to the present date (1938)." The work of the Bureau of Waterworks and Supply of the City of Los Angeles in the development of a compaction test method for use in earth dam construction was reported by Proctor (2) in August 1933 and is well known. The use of a compaction test by Kelso (3) during the construction of the Silvan earth dam for the City of Melbourne, Australia, water supply in the early 1930's is perhaps less well known; it has been described in a previous committee report (130).

The test apparatus developed by the California Division of Highways consisted of a 3-in. diameter cylinder, a 10-lb rammer having a 2-in. diameter striking face. An 18-in. free drop of the rammer was used. The original apparatus developed by Proctor consisted of a cylindrical container about 4-in. in diameter and 5-in. deep (Vol. = 0.0364 or $\frac{1}{27.5}$ cu ft). Each layer was subjected to 25 firm 12-in. strokes of a $5\frac{1}{2}$-lb rammer with a striking face 2 in. in diameter on each of three layers of soil. Kelso used a standard cement testing hammer-machine and subjected the soil to 150 blows in a 3-in. cubical mold.

Following the original publication of Proctor's series of articles, several state highway departments and other agencies, including the Portland Cement Association, began to study the compaction test. Some agencies made changes in the number of layers, the size of the container, or the compaction effort. Steps were taken to standardize the apparatus and test procedure. Standardization was accomplished by the American Association of State Highway Officials (AASHO) in 1938 (AASHO Designation: T99-38) and by the American Society for Testing Materials (ASTM) in 1942 (ASTM Designation: D698-42T). In standardizing the test, the original 25 firm 12-in. strokes became 25 blows from the rammer dropping free from a height of 12 in. above the elevation of the soil on each of three layers. Since the initial use of the 4-in. diameter by 5-in. deep container, Proctor (34, 38) has adopted a 1/20-cu ft mold and a 5.75-lb rammer.

Before World War II during the construction of air bases in the United States and overseas, the U.S. Army Corps of Engineers developed what became known as the Modified AASHO method of compaction for use in preparing specimens for the California bearing ratio test. This test employed a 6-in. diameter mold and a compacted specimen 5 in. high, and subjected the soil to 55 blows of a 10-lb rammer dropping free from a height of 18 in. on each of five layers of soil. The standard method (AASHO Designation: T99 and ASTM D698) required a compaction effort of 12,375 ft-lb per cu ft of compacted soil compared with 56,250 ft-lb per cu ft for the Modified test. During 1957 AASHO standardized the Modified test under AASHO Designation: T180*. In addition to these changes, other agencies in the United States and elsewhere have made changes in and have thus adapted these laboratory compaction test methods to suit their needs. Details of the various test apparatus and procedures are given later in this report.

Since the introduction of the compaction test, some misunderstanding and controversy have existed regarding its purpose and use. The test was originally developed with the concept that it could serve as a flexible tool (by varying the compaction effort) to produce a maximum unit weight that would reduce settlement, increase strength, and otherwise control soil properties within a given range that was practicable for construction equipment. However, some engineers accepted "maximum density" and "optimum moisture content" (as determined by the standard procedure) as fixed values and endowed them with a certain magic value regardless of type of soil or its use in the different elements of the road structure. Some expected that it yielded values for all soil types that could be duplicated in construction with various types and sizes of construction compaction equipment, not realizing that differences in either soil type or in compaction equipment resulted in different degrees of difficulty in attaining a unit weight equivalent to "maximum." Some engineers recognized early some of the potential values of the test in controlling soil properties by controlling the compacted unit weight and the moisture content by using the test as a guide. Thus, although the test was developed through need for a basis for control of compaction, perhaps one of its most significant uses has been in the study of the properties of soils compacted under a uniform compaction effort. It is evident now that much research is needed to determine the type of compaction effort, the degree of compaction, and the moisture content used that will produce the soil properties desired in the various elements of the road structure.

---

*AASHO Designation: T180-57 (Method C) is basically the same as the Modified AASHO compaction test; however, the compacted specimen is 4.59 in. high for T180 compared to 5 in. high in the Modified test.

Types of Compaction Effort

Three principal types of compaction effort are currently used in compaction tests. They are the impact type, the kneading type, and the vibratory type. Static compression, although seldom used in determining maximum unit weight and optimum moisture content is used on a limited scale in the preparation of test specimens. When used for that purpose, its effect on soil properties is sometimes significant.

In addition to the differences in the types of compaction effort, there are other variations that influence moisture content-unit weight relations. These include size of mold amount of compaction effort, maximum size of aggregate permitted, method of supporting the mold, method of preparing the soil for test and method for correcting unit weight and optimum moisture content for coarse aggregate content. It is of interest to examine these differences in apparatus and procedures and determine the degree that each of these differences, inherent to the methods, influence the values of maximum unit weight and optimum moisture content that are the objectives of the test.

Principal Methods for Determining Maximum Unit Weight And Optimum Moisture Content

MANUAL IMPACT-TYPE COMPACTION

The first impact-type compaction tests (8, 2, 3) were designed for manual operation. Although a large proportion of central laboratories and many district laboratories have either constructed compactors to their own design or have purchased commercially produced, mechanically operated, impact-type compactors, a large proportion of testing in the laboratory and practically all testing in the field continues to be performed with manually operated equipment. Also nearly all test procedures are based on manual methods.

In order to appraise the effect of differences in the several items previously given it is necessary to know the differences in test apparatus and procedures. The essential details of the test methods used in road and dam construction in the United States are given in Table 1. AASHO has now standardized the use of two sizes of molds, two rammers, and four compaction efforts. The table also lists the California impact method (which is similar in most of the essential details to the apparatus which it adopted as standard in 1929); the Corps of Engineers method which formed the basis for AASHO Designation: T180-57, and the Bureau of Reclamation method using a $1/20$-cu ft mold but using the same unit compaction effort as AASHO Designation: T 99, Methods A and C. A footnote to the table describes the details of a recent Proctor method (34, 38).

Although the AASHO methods are widely used, modifications have been made in the United States and other countries. Table 2 lists some essentials of some test apparatus and procedures used in other countries. The British standard compaction test is currently similar to AASHO Designation T99-57, Method C. British engineers (60) recognized early the need for using material up to $3/4$-in. maximum size in the test and the need for correcting for the quantity of oversize material. The standard test of the Secretaria de Recursos Hidraulicos of Mexico (a federal department having some duties similar to those of the U.S. Bureau of Reclamation) differs from AASHO Designation: T99 in that the volume of the mold is 1,000 cu cm, (approximately $1/28$ cu ft), the rammer is slightly heavier, and the compaction effort is greater. They also use a miniature compaction apparatus ($1/309$-cu ft mold) for fine grain soils. The compaction effort per unit volume is approximately the same for the standard and miniature tests.

Some British consulting engineers have used a modification of the Dietert test for compacting soils for earthwork and stabilization purposes. The Dietert test was devised for controlling compaction of foundry sands (American Foundrymen's Association, "Foundry Sand Testing Handbook," 1944). It has also been used to determine the workability of refractory clays (Workability Index of Fire-Clay Refractories, ASTM Designation C181-47, ASTM Standards, Part 3, pp. 677-679, 1955). Several adaptations of the Dietert test are described in the literature (25, 31, 49, 60, 83,). Details of the Dietert test used by Bruce (83) are given in Table 2.

A test (101) described as the U.S.S.R. Standard test employs 25 blows of a rammer weighing 4.5 kg (9.9 lb) and falling from a height of 30.5 cm (12 in.). The contact area of the rammer is approximately the same as the area of the cylindrical container used for compaction.

An apparatus described as the Abbott cylinder (65) was developed and introduced by an Indian army officer named Abbott. Two hundred grams of oven-dried soil passing the No. 10 U.S. Standard sieve are used. Soil is mixed with water and compacted with a 5.5-lb rammer in a cylinder 2.5 in. in diameter. The process is repeated with increasing percentages of water. Four separate compaction tests are performed

TABLE 1

ESSENTIALS OF IMPACT-TYPE COMPACTION TEST METHODS USED IN THE UNITED STATES

Test Identification	AASHO Designation T 99-57 ASTM Designation D 698-58T				AASHO Designation T 180-57 ASTM Designation D 1557-58T				California Impact Method	Corps of Engineers Method[a]	Bureau of Reclamation Method	Current Proctor Method[b]
	Method A	Method B	Method C	Method D	Method A	Method B	Method C	Method D				
Mold												
Diameter (in)	4	6	4	6	4	6	4	6	3	6	4 25	-
Height (in)	4 59	4 59	4 59	4 59	4 59	4 59	4 59	4 59	10-12	4 50	6	-
Volume (cu ft)	1/30	1/13 33	1/30	1/13 33	1/30	1/13 33	1/30	1/13 33	Var	1/13 58	1/20	1/20
Rammer												
Weight (lb)	5 5	5 5	5 5	5 5	10	10	10	10	10	10	5 5	5 75
Free drop (in)	12 0	12 0	12 0	12 0	18 0	18	18	18	18	18	18	12-in blows
Face diameter (in)	2 0	2 0	2 0	2 0	2 0	2	2	2	2	2	2	2
Layer												
Total number	3	3	3	3	5	5	5	5	5[c]	5	3	3
Surface area (sq in)	12 57	28 27	12 57	28 27	12 57	28 27	12 57	28 27	7 1	28 27	14 18	12 57
Compacted thickness (in)[d]	1 7	1 7	1 7	1 7	1 0	1 0	1 0	1 0	2 25	1 0	2 0	1 7
Compaction Effort												
Blows per layer	25	56	25	56	25	56	25	56	20	55	25	25
Energy (ft-lb/ cu ft)	12,375	12,317	12,375	12,317	56,250	55,986	56,250	55,986	33,000	56,022[e]	12,375	25,000[f]
Material												
Maximum size, % passing	No 4	No 4	¾-in	¾-in	No 4	No 4	¾-in	¾-in	¾-in	¾-in	No 4	No. 4
Correction for oversize	No	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	No
Source of Information (ref no)	122, 121	121, 122	121, 122	121, 122	122	122	122	122	95, 121	123	92	34, 38

[a] Similar to AASHO Designation T 180-57, Method D—initially mold was 7 in high and a 2-in spacer disk used; later, a 2½-in spacer disk used.

[b] Original Proctor Method called for 12-in firm blows of 5½-lb tamper (34) Mold was about 4 in in diameter and 5 in high Since then, Proctor has adopted a 5 75-lb tamper and found that a 1/20-cu ft mold is the minimum size that will provide reliable information on unit weight and on indicated saturated penetration resistance (38) Number of blows is adjusted to obtain desired indicated saturated penetration resistance or other properties

[c] Ten layers used for determining specification values for upper 2 ft below finished grade

[d] Approximate

[e] A sliding weight hammer, with a 10-lb weight sliding on a 5/8-in steel rod used Maximum allowable weight of assembled compaction hammer is 7 5 lb Inertia absorbed by dead weight of handle, rod and tamper foot will reduce the compaction effort somewhat

[f] Interpolated from tests on eight different types of soils (95)

with 10, 20, 30, and 40 blows so that the resultant compaction can be adjusted to that obtainable with different types and sizes of field compaction equipment.

A special type of impact test for obtaining the maximum unit weight of granular materials is the Michigan "Cone Test" (121). In this test the cone is truncated with a base diameter of $5\frac{9}{16}$ in., is $5\frac{13}{16}$ in. high from base to a truncated diameter of 2 in., and is equipped with a neck 2 in. in diameter by 2 in. high. Oven-dry or wet soil is placed in the cone to a height of $\frac{1}{3}$ the distance from base to neck, the throat covered, and the cone "tamped" by hand by striking the base against a wood block for about 2 min. Soil is added to the $\frac{2}{3}$ height and the operation repeated. The cone is then filled and the operation repeated until no more soil can be added to the cone.

MECHANICAL IMPACT-TYPE COMPACTION

A large proportion of the central laboratories of the state highway departments; the Bureau of Public Roads, Corps of Engineers, and other federal agencies; and commercial testing laboratories have either constructed mechanical compactors of the impact type to satisfy their own designs and special needs or have purchased commercially produced compactors. The Alabama (68) and the Corps of Engineers (51) "homemade" compactors are examples of this type. So also is the 20-in. diameter mold and special impact-type compactor with a metal rammer weighing 186-lb used by the Bureau of Reclamation (121) for obtaining moisture-density relations for gravelly soils containing 25 percent or more particles larger than the No. 4 sieve size up to a maximum size of 3 in. This compactor employs the same unit compaction effort (12,375 ft-lb per cu ft) as employed with the $\frac{1}{20}$-cu ft mold apparatus used by the Bureau of Reclamation (see Table 1). In most instances, the mechanical compactors have been calibrated and

TABLE 2
ESSENTIALS OF SOME ADDITIONAL COMPACTION TEST METHODS

Test Identification	British Standard Compaction Test B S 1377 1948 Test No 9	Secretaria de Recursos Hidraulicos (Mexico) Standard	Secretaria de Recursos Hidraulicos (Mexico) Miniature	Dietert Test ASTM C 181-47	Bruce Modification of the Dietert Test
Mold					
Diameter (in)	4	4 02	1 417	2	2
Height (in)	4 59	4.84	3 54	4 75	4 75
Volume (cu ft)	1/30	1/28 19	1/309	1/116	1/116
Rammer					
Weight (lb)	5 5	6 06	1 014	14	10 388
Free drop (in)	12 0	18	5 47	2	6
Face diameter (in)	2 0	1 97	0 71	2	2
Layer					
Total number	3	3	5	1	1
Surface area (sq in)	12 57	12 67	1 57	3 14	3 14
Compacted thickness[a] (in)	1 7	1 75	0 8	Var	Var
Compaction Effort					
Blows per layer	25	20	20	20	20
Energy (ft-lb cu ft)	12,375	15,382[b, c]	14,295[b, c]	-	Var 51,900[d]
Material					
Maximum size, % passing	¾-in	-	-	-	No 4
Correction for oversize	Yes	-	-	-	-
Source of Information (ref no)	60, 78	105	105	1955 ASTM Standards, Pt 3	83

[a] Approximate

[b] Values based on Tamez (105)

[c] Computed from units in this column

[d] Computed on basis of volume for unit weight of 110 pcf and a sample of 100 g (see text for data on other compaction test methods)

adjusted to produce compaction curves that approximately fit those obtained by manual compaction. This has been done because in many instances the mechanical compactors are used in producing routine test data for construction purposes that, in effect, become specification limits. Possible differences between moisture content-unit weight relationships produced by mechanical equipment compared with manual methods are discussed later.

COMPACTION BY MECHANICAL KNEADING-TYPE COMPACTORS

It was observed early that soil compacted by laboratory impact methods exhibited compaction curves that did not have the same characteristic shape as those produced by static compression. Later it was observed that the stress-strain characteristics of soils compacted by the two methods were quite different (18). Similar observations were also made of stress-strain characteristics of bituminous paving mixtures.

The early observations led to a consideration of the nature of the compaction effort produced by sheepsfoot and rubber-tired rollers, in which the load comes into contact with the soil with little or no impact. Rather, the pressure increases with time to a maximum, and the rotation of the roller drum or tire causes a small "kneading" or shoving action as the roller adjusts to the soil surface. This consideration of the nature of field compaction showed the desirability of developing a laboratory compaction test method that would more closely simulate field compaction.

The first-known mechanical kneading-type laboratory compactor was that developed by the California Division of Highways in 1937 (91). Knowledge gained from this and similar installations in the bituminous laboratories of oil companies in the San Francisco Bay area led to the design of a new compactor by F.N. Hveem of the California Division of Highways and its construction by the Institute of Transportation and Traffic Engineering at the University of California. The kneading compactor employs a combination of a hydraulic-pneumatic control system that permits control of the pressure and the time period during which the pressure is applied (52). Inasmuch as its application has been associated with the work of the Triaxial Institute, a West Coast organization devoted to the study of the triaxial compression test for soils and bituminous mixtures, it became known as the Triaxial Institute Compactor until adopted as AASHO Method T 173.

The compactor is shown in Figure 1. Through a tamping foot shaped like a sector of a circle (Fig. 2) it applies tamps to the soil specimen as it is built up in the mold

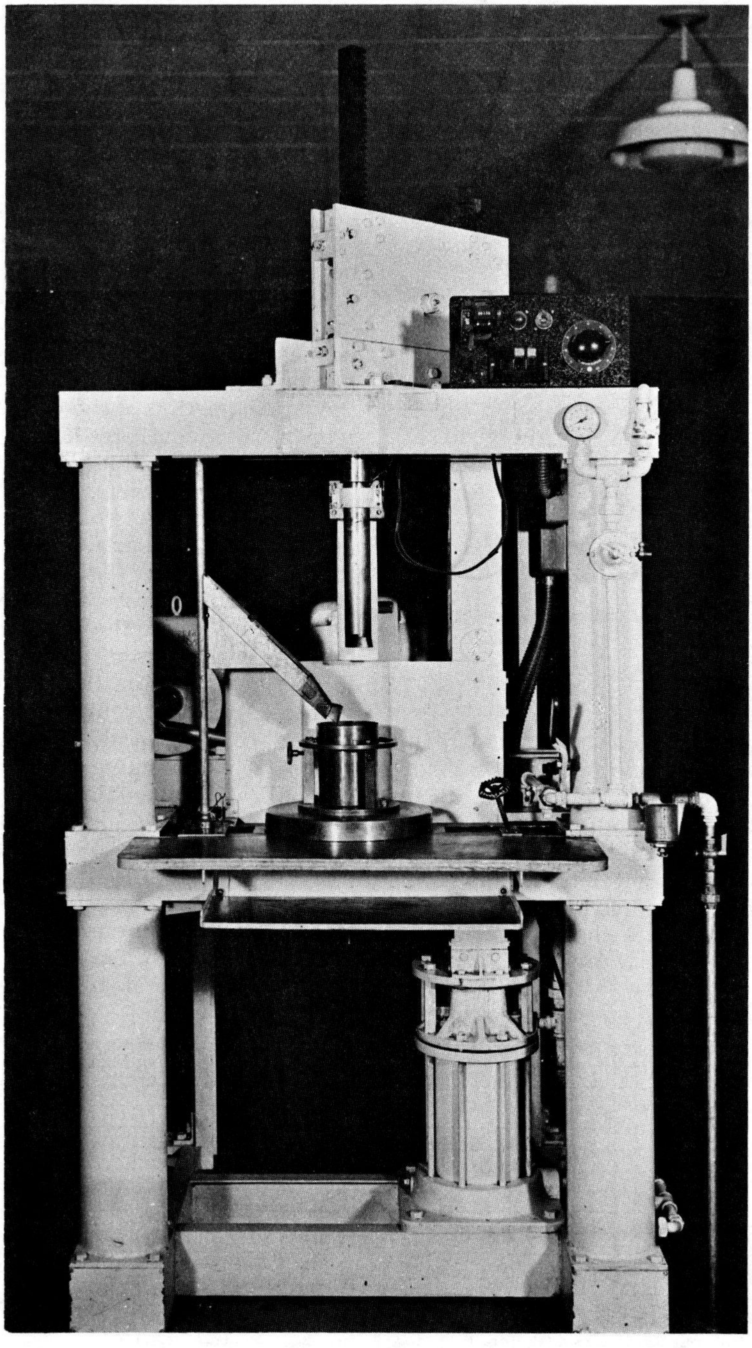


Figure 1. AASHO Method T173 kneading-type mechanical compactor (122).

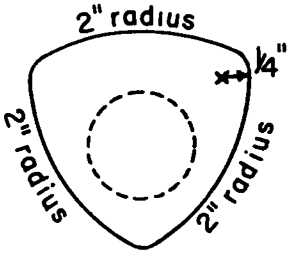


Figure 2. Outline of tamper shoe for AASHO Method T173 kneading-type mechanical compactor (122).

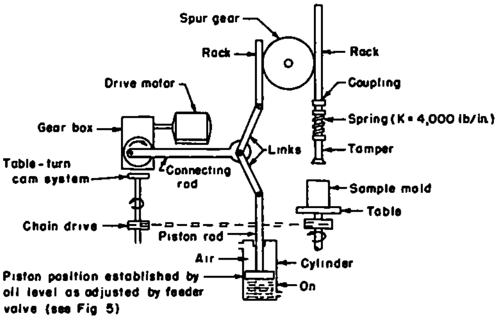


Figure 3. Mechanical tamping system for AASHO Method T173 kneading-type mechanical tamper (73).

and for a certain designated period after the specimen is formed. The mechanical system employs a toggle-press principle. Power for the operation of this system is provided by an electric motor through a speed reduction gear, flywheel, and connecting rod as is indicated in Figure 3. The action is such that in any one tamp the pressure is gradually built up, then allowed to dwell on the sample for a fraction of a second before being gradually released. The compaction rate is 30 tamps per min. A typical time-pressure trace showing load vs time relationship for the Triaxial Institute Compactor is shown in Figure 4 (73).

In order to control the pressure exerted on the test specimen, a combination hydraulic-pneumatic control system is used (Fig. 5). Air from a high pressure line passes through a pressure regulator, which can be set at a predetermined value, into the upper portion of the oil reservoir. A feeder valve controls the flow of oil into the cylinder containing the piston, which is attached to the lower link of the press. This feeder valve is used to adjust the height of the tamper foot in the mold before the start of the compacting procedure. When the compactor is started, and as the sample builds up, the load on the tamper foot remains constant because as soon as the piston exerts more pressure on the oil than exists in the compressed air above the oil, a pop valve, also set at a predetermined pressure, allows air to escape, and oil is squeezed out from under the piston through a one-way check valve and back into the oil reservoir. To make sure that the full pressure will always develop on the sample, it is important to keep the feeder valve open a certain amount during the entire process. The compactor operates practically as an automatic machine. An endless belt may be used to feed the sample into the mold.

The mechanical compactor may be set to compact the soil under a wide range of pressures. AASHO Method: T 173-56 (122) which describes the procedures for compacting test specimens for the Expansion Pressure and Hveem Stabilometer Tests re-

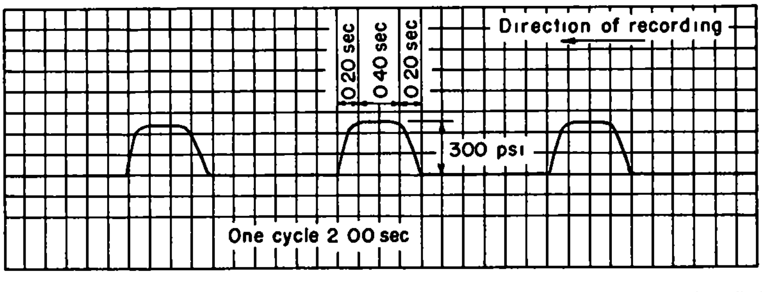


Figure 4. Typical oscillogram showing load vs time relationship for the Triaxial Institute Kneading Compactor (73).

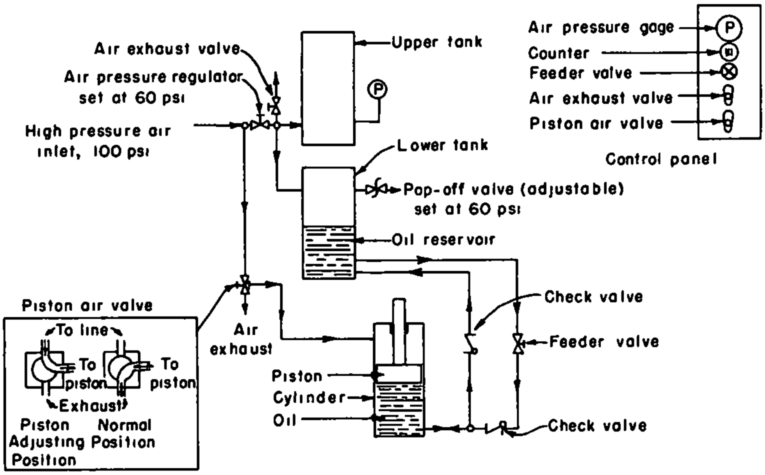


Figure 5. Hydropneumatic control system for the AASHO Method T173 kneading-type mechanical compactor (73).

quires a ram pressure of 350 psi applied without impact over an area of approximately 3.1 sq in. with the pressure being maintained for approximately $\frac{1}{2}$ sec. The soil is fed into the mold in 20 increments with one application of the ram for each increment. After all of the soil is introduced into the mold (sufficient to form a specimen 4 in. in diameter by 2.5 in. high) an additional 100 applications of the ram are given.

McRae and Rutledge (62) set up the following desirable characteristics for a laboratory soil compaction device: (a) the compacting foot should not apply impact to the soil; (b) the compacting foot should apply a controlled pressure to the soil for a controlled period of time, and variation of both the contact pressure and the contact time over reasonable ranges corresponding to those anticipated in the field should be possible: (c) the compacting foot should cover a moderately small portion of the surface area of the soil sample being compacted so that shear deformations involving lateral flow of the soil can take place; and (d) the operation of the device should be as nearly automatic as possible. They designed a kneading-type compactor that could be operated to satisfy these desirable characteristics and also be operated as an impact-type machine. It is a compressed air operated machine.

The Idaho Department of Highways also designed and constructed a compressed air operated kneading-type compactor that satisfies the desirable characteristics.

The California compactor is described at length because it has been adopted as a Standard AASHO method for compaction of soils and soil mixtures for the expansion pressure and Hveem Stabilometer Tests, (AASHO Designation: T 173-56).

Comparisons showing the differences between moisture content-unit weight relationships (compaction curves) obtained under kneading and other types of compaction are given later.

COMPACTION BY MANUAL KNEADING-TYPE COMPACTORS

After it was recognized that laboratory impact-type compaction tests do not duplicate field compaction with sheepsfoot rollers insofar as some soil properties are concerned, it was suggested that a small, manually operated compaction device could be developed that would duplicate the kneading action of sheepsfoot rollers more closely than the impact type of test (53).

The result was the development of the Harvard miniature kneading compactor. The apparatus consists of (a) a mold $1\frac{15}{16}$ in. in diameter by 2.816 in. high having a volume of $\frac{1}{454}$ cu ft and equipped with a detachable collar; (b) a metal tamper 0.5 in. in diameter with a grooved handle enclosing a compressed spring (the amount of compression is adjustable); (c) a collar remover; and (d) an ejector for removing compacted specimens.

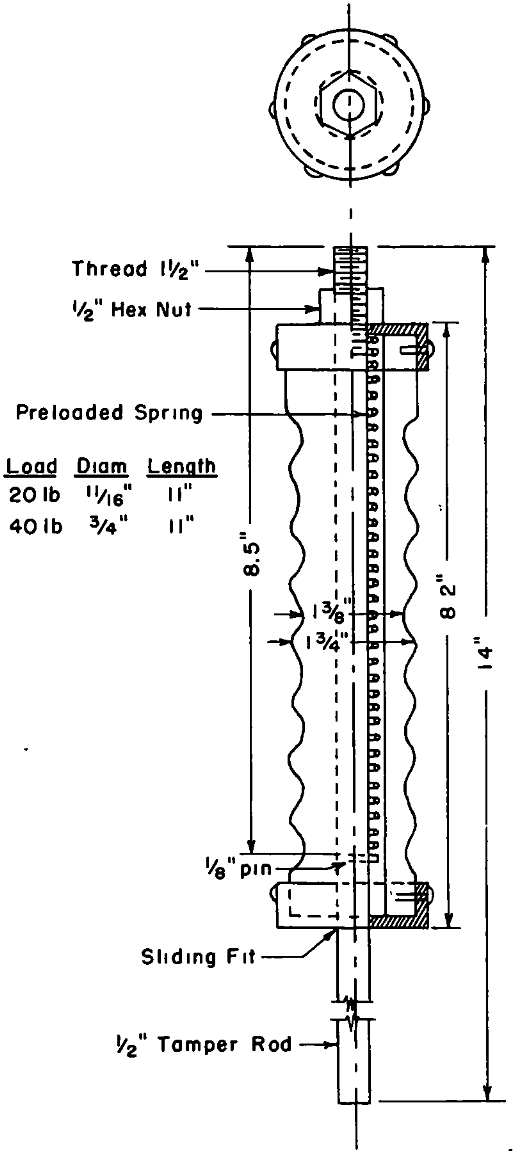


Figure 6. Sketch showing essentials of kneading-type tamper used in the Harvard miniature compaction device (53, 121).

The most significant part of the apparatus is the tamper equipped with the preloaded spring. The essential working parts of the tamper are shown in Figure 6. In using the tamper it is pushed into the soil with just enough pressure to overcome the spring pressure causing it to compress slightly. The pressure is released and the tamper shifted to a new position. Results obtained with the Harvard miniature compactor compared to results obtained with impact-type apparatus and results from field rolling are discussed later. The apparatus is used principally on fine grain soils all of which passes a No. 4 sieve. The apparatus and testing procedure are described in detail as an ASTM suggested method of test (121).

The University of California has developed a hand-operated kneading-type compactor designed mainly for laboratory use (91). In developing this equipment they found that for specimens of 3-in. diameter, the area of the tamping foot should desirably be about 0.75 sq in., and for a tamping foot pressure of 350 psi the total force would be about 270 lb. However, as development progressed, it was found that the apparatus could readily be adapted to the preparation of specimens up to 4 in. in diameter with tamping pressures up to 500 psi. The resulting equipment is shown in Figure 7.

The lever system for the compactor was obtained by adapting an Arbor press (Dake, Model O) by sawing off part of the base and mounting it on a steel beam as indicated in Figure 7. This type of press occupies little space and provides a lever ratio of 36:1. The ram has a

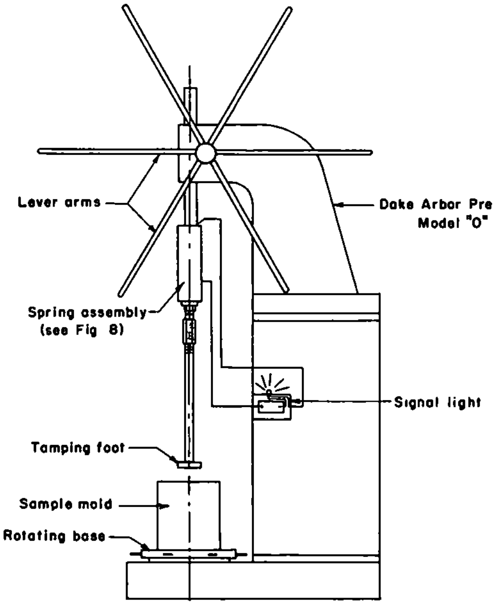


Figure 7. Hand-operated kneading compactor, developed at University of California (91).

stroke of about 8 in. The single lever arm of the original press was replaced by six radial arms for convenience in load application.

As in the Harvard apparatus, a significant part of the device is the precompressed spring assembly that permits loading by kneading action to a unit pressure predetermined by the spring setting. The position of the spring assembly is shown in Figure 7. Details of the spring assembly and its arrangement in the system are shown in Figure 8. The spring is precompressed to the desired load by the load control nut, thus holding the tamping rod away from the head piece. When pressure is applied through the ram to the tamping foot there is no relative movement between the tamping rod and the head piece until the precompression force in the spring is exceeded. However, as soon as this stage is reached, the spring is compressed slightly and the control screw mounted at the top of the tamping rod comes in contact with the microswitch, causing the signal light to illuminate. In this way the applied load can be controlled and duplicated within narrow limits and be maintained for any desired length of time. A rotating base (Fig. 7) is turned ⅙ revolution between tamps.

It is necessary to calibrate the instrument initially by measuring the load on the tamping foot for various settings of the spring and load control nut. By means of two springs the load can be varied up to 1,600 lb corresponding to a maximum unit tamping pressure of about 550 psi. Comparative tests have been made with the mechanically operated kneading-type compactor, discussed later.

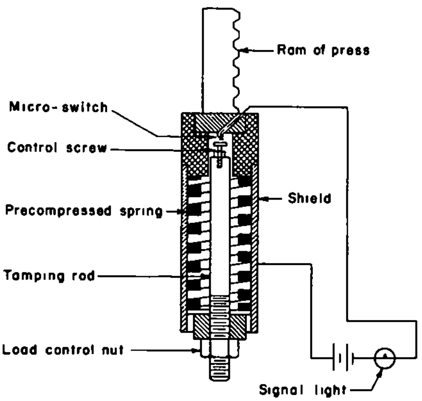


Figure 8. Spring assembly for University of California hand-operated kneading compactor (91).

A manually operated kneading-type compactor of somewhat different design has been built by the Oregon State Highway Department. Details of this unit have not been published.

VIBRATORY COMPACTION TEST EQUIPMENT AND PROCEDURES

There is currently no standard AASHO or ASTM laboratory compaction test method involving vibration that is used for determing the maximum unit weight of cohesionless sands and gravels. There are, however, a number of methods involving vibration that have been or are currently being used by different engineering organizations for establishing maximum unit weight. Also some experimental studies have been made using laboratory vibratory compactors. Not all of the methods being used have been made available through the published literature. Some details concerning the apparatus and procedures used in fifteen methods have been assembled and are summarized in Table 3.

The methods may be classified into two broad types: one in which sustained vibration is the compacting force; and the other in which a series of "momentary" vibrations resulting from the striking of sharp blows against the mold constitute the principal source of vibrations that make up the compacting force.

Ten of the methods listed in Table 3 have been under study by Subcommittee R-3, Committee D-18 of ASTM (120). The relative effectiveness of these, and others for which data are available, in establishing maximum unit weight as compared to results from standard impact tests are discussed later.

COMPACTION OF SOILS BY STATIC COMPRESSION

Although static compression was used to a limited extent in early soil testing for determining maximum unit weight and optimum moisture content, there is currently no standard AASHO or ASTM method involving its use for this purpose. However, examination of ASTM Suggested Methods of Test (121) reveals that static compression alone, in combination with another method of compaction, or as an alternate method is given as a means of preparing test specimens for permeability, volume change expansion pressure, consolidation, and triaxial compression tests. It is also used in preparation of test specimens for four test methods for bituminous mixtures.

Perhaps one of the best known procedures for static compaction is one used by the California Division of Highways as a central laboratory compaction test method (1, 8, 16), but whose principal use was in the preparation of specimens in the California Bearing Ratio Test (16). In this test the following procedure was used:

> A test sample of approximately 4,000 g is used. Three to six such samples are prepared in the event that maximum dry weight per cu ft and optimum moisture content has not previously

TABLE 3
LABORATORY EQUIPMENT AND PROCEDURES INVOLVING MOMENTARY OR SUSTAINED VIBRATION USED IN OBTAINING MAXIMUM UNIT WEIGHT OF GRANULAR MATERIALS

Method	Type of Test	Felt (121) Method	Apparatus	Procedure	Source Reference
1[a]	Vibratory table	7	Volume of molds 0 5 or 0 1 cu ft, vibratory device attached to bottom side of table, frequency 3,6000 cpm, average amplitude 0 012 in	Tests on oven dry and saturated soils Surcharge weight of 1 psi gave maximum density Vibration time 8 min or more	120, 137
2[a, b]	Vibratory table	9	Mold 4 in in diameter by 9 in high attached to 13- by 24-in table to which is attached specially built vibrator, frequency 3,600 cpm	Surcharge weight of 22 lb (1 75 psi) on sufficient material for 2-in specimen Vibration for 20 min at each of several moisture contents	120, 121
3[a]	Vibratory table	8	Mold 6 in in diameter by 6 in high attached to plank platform to which is attached vibrator, frequency 3,500 cpm	A 5-lb sample at desired moisture content is loaded with 3-psi surcharge and vibrated for 30 min	120
4[a]	Vibratory table	10	Mold 4 in in diameter attached to table vibrated by electromagnetic vibrator, frequency 7,200 cpm, amplitude 1/32 in	Material for 2- to 3-in high specimen is loaded with 1 75 psi surcharge Vibration until change in height is less than 0 001 in in 2 min	120
5	Vibratory table		Measure 10 in in diameter by 11 in high (½ cu ft), external concrete form vibrator attached to table top	Full measure of soil with approximately 6 percent water is vibrated 1 min Measure filled and vibration repeated until no further compaction	97
6[b]	Vibrating mold or table		Size of mold depends on maximum size and aggregate, pneumatic or electric form type or foundry type vibrator with mounting pin for attachment to mold or to a surface on which measure can be placed.	Measure is filled, saturated, and vibrated for about 1 min, measure again filled and vibrated until no further compaction	121
7	Vibrating table or hammer blow		Mold 7 in in diameter, loading screw applies 1,000 lb load (26 psi) through calibrated spring; vibratory force from vibrating table or from 50 to 75 sharp forceful blows of 2½-lb hammer on sides of mold	Vibration or hammer blows continue until change in depth of sample is less than 0 001 ft	30
8[a]	Vibrating mold	2	Mold ½ cu ft or CBR (6 in in diameter) size, specially built spring load vibratory compactor gives approximately 1,000 blows per min on mold.	Soil plus sufficient water to saturate is rodded in mold (3 layers, 25 blows per layer) Load is applied in 3 increments up to 2,000-lb total pressure and vibrated several times	102, 120
9[a, b]	Vibrating tamper	6	Mold 6 in in diameter by 6 in high, vibrator fastened to a 0 5-in rod attached to a thick metal foot 2 in in diameter used to compact soil, frequency 14,000 cpm	Soil placed in layers 0 5 to 1 in thick, and compacted	120, 121
10[a]	Vibrating tamper	4, 5	Mold 2 in in diameter, vibrating tamper fitted with a 2-in diameter tamping foot, vibrator of high frequency	Soil placed in nine 100-g increments	120
11	Vibrating Surface load		Various size molds, Barber-Greene experimental vibrator with loading platform for holding surcharge weights, weight of entire vibrator assembly and surcharge weights rests directly on soil in mold.	Various surcharge weights, frequencies, and amplitudes used in experimental testing	51
12[a]	Free-fall	11	Mold 3 5 in in diameter by 6 in high, welded to a 0 5-in thick steel base, loading screw applies desired surcharge load through a spring	Assembled unit is dropped a number of times from a specified height	120
13[a]	Vibrating free-drop	12	Apparatus similar to that for Method 12	Compaction is obtained by dropping the soil container 0 25 in at a frequency of 400 rpm	120
14	Drop table		Machine is similar to a concrete flow table, sand-filled mold raised 2 5 in by cam arrangement and dropped suddenly on a solid plate	Surcharge weight placed on sample resulted in high densities Tests made on soil in a saturated state	51
15[a, b]	Truncated cone "tamp" test	3	Mold is a truncated cone with base diameter of about 5-7 in , a truncate diameter of 2 in. and a height of about 5 8 in plus a 2-in neck.	Soil is placed in 3 layers, each layer being "tamped" by striking bottom of mold repeatedly against wood block for 2 min After compaction of third layer more soil is added and tamping continued until cone can not accomodate more material	120, 121

[a] Studied by a committee of ASTM (120) A summary of findings is given later comparing results of test methods

[b] Listed as ASTM Suggested Methods of Test (121)

> been determined. Rock particles retained on the 3/4-in. sieve are replaced in the same proportion by substituting material between the 3/4-in. and No. 4 sieves.
>
> The sample is lightly tamped into the tared mold and then compacted to its maximum dry weight per cu ft under a load of 2,000 psi. In applying the load between 1,000 and 2,000 psi, the head of the testing machine or hydraulic press is operated at a rate of 0.05 in. per min. The static load of 2,000 psi is maintained on the sample for 1 min and then gradually released during a period of about 20 sec.

Static compaction has been used to prepare moisture content-unit weight relationship curves by a number of organizations for purposes of preparing specimens for determination of swell, CBR, shear strength, and other physical properties (4, 40, 41, 72). Details of the test procedures used were not given in the reports.

Inasmuch as there exists no standard method for determining moisture content and unit weight by static compression, no effort is made here to summarize those factors of mold diameter, specimen thickness, compression from one or both ends of specimens, rate of loading, and time of load application that are expected to influence maximum unit weight and optimum moisture content. However, because the method of applying the compaction effort has some influence on the properties of compacted soils, mention is made of the above variables because of their potential influence on properties of compacted soils.

MEASUREMENT OF ABSOLUTE MAXIMUM AND MINIMUM DRY UNIT WEIGHTS FOR DETERMINATION OF DENSITY RATIO, RELATIVE DENSITY, AND COMPACTION RATIO

The use of "percent density", (also termed "percent unit weight," "percent compaction," and "relative compaction") as a specification item requires only the determination of maximum unit weight for the existing soils. However, the use of Density Ratio (30), Relative Density (39) or Compaction Ratio (71), as specification items require the measurement of a minimum or "loose" unit weight as well as an "absolute" maximum unit weight. Although Standard Impact Compaction methods for establishing maximum unit weight for soils are available for moderate compaction effort (AASHO Designation: T 99-57, and ASTM Designation: D 698-57T) and high compaction effort (AASHO Designation: T 180-57) it is believed by many engineers that these methods do not provide the uniformly high unit weights for cohesionless sands and gravels that are needed as limits for determining Density Ratio, Relative Density, or Compaction Ratio. The vibratory compaction methods in Table 3 have been devised with the expectation that each will provide a value of laboratory maximum dry unit weight sufficiently great that it will not be exceeded in construction. These methods have been studied by a committee of ASTM for consideration in the development of a standard method for determining the "absolute" maximum unit weight for cohesionless granular materials. Comparative results obtained by the various methods are discussed later.

Table 4 describes in summary form a number of "placement methods" for establishing a minimum or "loose" dry unit weight that may be used in determining Density Ratio, Relative Density, or Compaction Ratio. None of these methods is an AASHO or ASTM Standard. Methods 3 through 8 in Table 4 have been studied by a committee of ASTM for consideration in the future development of a standard method for determining minimum or "loose" dry unit weight. Comparative results obtained by the six methods are given later.

One typical procedure for determining relative density is presented in detail. This procedure (137) has been devised by the U.S. Bureau of Reclamation for cohesionless free-draining soils and requires a vibratory table. Another USBR method, using a foundry-type vibrator, is described elsewhere (129).

1. Scope.—This procedure describes the method for obtaining the relative density of cohesionless free-drainage soils using a vibratory table for determination of maximum density.

2. Definition. —Relative density (See Appendix B, "Definition of terms").

3. Apparatus. —The apparatus shall consist of the following: (a) Vibratory table: A steel table with a cushioned steel vibrating deck about 30 by 30 in. and actuated by an electromagnetic vibrator. The vibrator should be a seminoiseless type with a net weight over 100 lb and a frequency of 3,600 vibrations per min, a vibrator amplitude variable between 0.002 and 0.025 in. under a 250-lb load, and be suitable for use with a 115-volt AC electric circuit. (b) Guide sleeve, with clamp assemblies, one for each size measure (Fig. 9); (c) Surcharge base plate, one for each size measure (Fig. 9); (d) Weights, surcharge, one for each size measure (Fig. 9); (e) Holder, dial indicator gage (Fig. 9); (f) Surcharge base plate handle, one each (Fig. 9); (g) Measures, unit weight, cylindrical, metal, 0.1 and 0.5 cu ft; (h) Pouring device; (i) Mixing pan; (j) Scoop; (k) Scale; (l) Dusting brush; (m) Stopwatch; (n) Metal straightedge; (o) Gage, dial indicator, (Fig. 9); (p) Hoist; rope, chain, or cable; electric, air, or manually operated; 300-lb minimum capacity.

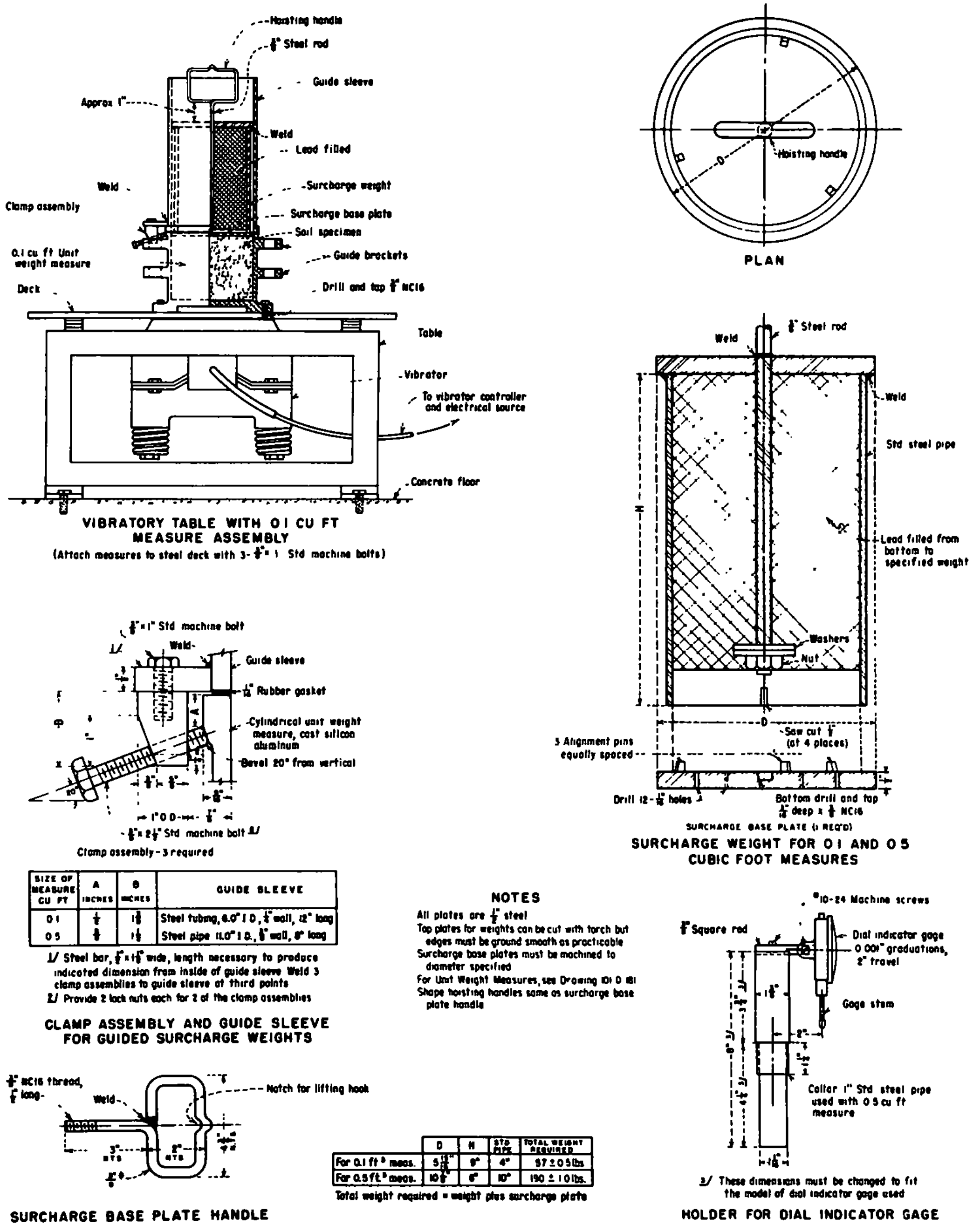
4. Calibration. —Determine the volumes of the unit weight measures by measurement. Linear measurements for this and other purposes in this test should be made to 0.001 in. Calculated volumes for the 0.1-cu ft measure should be recorded to the nearest 0.0001 cu ft and for the 0.5-cu ft measure to the nearest 0.001 cu ft.

TABLE 4

LABORATORY METHODS FOR DETERMINING MINIMUM UNIT WEIGHTS OF COHESIONLESS GRANULAR MATERIALS

Method	Apparatus and Procedures	Source Reference
1	Determined by placing soil in a cylinder using a spoon to prevent appreciable fall A 4-in diameter "Proctor" cylinder is used for sands A 6-in or 7-in diameter cylinder is used for gravels	30
2	For clean sands and gravelly materials use AASHO Designation T 19-56 (ASTM C 29-55 T) which gives dry rodded weight (25 strokes of ⅝-in rounded tamping rod on each of 3 layers.) For other materials determine the dry unit weight in pcf of soil shrinkage pat as it is molded at the liquid limit and corrected for the plus No 4 sieve material	71
3	Dry material is placed in a 0 10-cu ft measure by pouring from a funnel having a 2-in diameter spout Funnel is moved in a slow spiral motion lifting it as the mold fills	120 (Method 15)
4	Method generally similar to that of Burmister (120) Appropriate size funnels to place aggregate in known volume containers With No 4 minus aggregate, container is overfilled and struck off level With large coarse aggregate the material is placed with a scoop Loose density is observed at a low moisture content and is defined as the minimum loose density obtained without bulking	120 (Method 18), 102
5	Dry material is placed in a measure by pouring from funnel with a spiral motion from outside toward center Three sizes of measures are used for different maximum size particles For materials having maximum size particles of ¾, ⅜, and ¼ in , the funnel spout has diameters of 1½, 1, and ½ in respectively A handscoop is used for placing materials having particles larger than ¾ in	120 (Method 17), 121
6	1,200 to 1,500 g of oven dry soil is placed through a funnel into a 1,000-ml glass graduate, filling it to a point between the 700- and 1,000-ml marks Then the graduate is inverted 3 times, placed upright, and the volume of material read from the graduate scale	120 (Method 14), 121
7	Oven-dry sandy soils poured into 1,000-ml graduate Oven-dry coarser materials poured into 6-in. mold	120 (Method 13)
8	Mold is a 6-in cubic container of about 0 12-cu ft volume for soils coarser than ¾ in and a 4-in cubic container of about 0 04-cu ft volume for finer soils Oven-dry soils are placed in large container through a grating 3 in high with 1.5-in square openings, and into the smaller container through a grating 2 in high with 1-in square openings Grating is placed in the container, each opening is filled with soil, then it is lifted and allowed to rest on soil and process repeated until container is full Excess material is struck off	120 (Method 16)
9	Select a cylinder having a diameter not less than 8 times the maximum size particle Soil is placed in the appropriate size funnel Use funnel having 1-in cylindrical spout for ⅜-in maximum size and coarser material and a ½-in spout for No 4 sieve maximum size material and smaller Spout should be at least 6 in long Soil is placed in layers from outside to center to minimize segregation Layers are repeated until cylinder is filled, then struck off	121

Check the volume of each unit weight measure by dividing the weight of water required to fill the measure by the unit weight of water at test temperature. A glass plate should be used to remove excess water above the top of the measure caused by the meniscus. All weights in this test should be made to 0.01 lb.



VIBRATORY TABLE WITH 0.1 CU FT MEASURE ASSEMBLY
(Attach measures to steel deck with 3 - 3/8" x 1 Std machine bolts)

PLAN

SIZE OF MEASURE CU FT	A INCHES	B INCHES	GUIDE SLEEVE
0.1	1/4	1 3/8	Steel tubing, 6.0" I D, 1/4" wall, 12" long
0.5	3/8	1 1/2	Steel pipe 11.0" I D., 3/8" wall, 8" long

1/ Steel bar, 3/8" x 1 1/2" wide, length necessary to produce indicated dimension from inside of guide sleeve. Weld 3 clamp assemblies to guide sleeve at third points

2/ Provide 2 lock nuts each for 2 of the clamp assemblies

CLAMP ASSEMBLY AND GUIDE SLEEVE FOR GUIDED SURCHARGE WEIGHTS

SURCHARGE WEIGHT FOR 0.1 AND 0.5 CUBIC FOOT MEASURES

NOTES

All plates are 1/2" steel

Top plates for weights can be cut with torch but edges must be ground smooth as practicable

Surcharge base plates must be machined to diameter specified

For Unit Weight Measures, see Drawing 101 D 181

Shape hoisting handles same as surcharge base plate handle

	D	H	STD PIPE	TOTAL WEIGHT REQUIRED
For 0.1 ft³ meas.	5 15/16"	9"	4"	97 ± 0.5 lbs
For 0.5 ft³ meas.	10 3/4"	6"	10"	190 ± 1.0 lbs.

Total weight required = weight plus surcharge plate

SURCHARGE BASE PLATE HANDLE
(1 Req'd per set of equip.)

3/ These dimensions must be changed to fit the model of dial indicator gage used

HOLDER FOR DIAL INDICATOR GAGE

Figure 9. Maximum density test equipment for 0.1- and 0.5-cu ft unit weight measures, vibratory table method.

EARTH TESTING
RELATIVE DENSITY TESTS
VIBRATORY TABLE METHOD

Project ______________ Feature ______________ Sample No ______

Tested by __________ Computed by __________ Checked by __________ Date __________

Minimum Density Determination (0% Relative Density)

Test No			
Wt soil + meas lb			
Wt meas lb			
Wt soil (W_s) lb			
Volume of meas (V_c) cu ft			
Minimum Density $= \frac{W_s}{V_c}$ = pcf			

Maximum Density Determination (100% Relative Density)

Test No.			
Left gage read. inches			
Right gage read inches			
Avg gage read R_f			
Initial gage read R_1			
Area of sample surface-sq ft A			
Calib vol of meas cu ft V_c			
Soil vol $= V_c - \frac{R_1 - R_f}{12} \times A$ V_s			
Wt soil + measure lb			
Wt meas lb			
Wt soil lb W_s			
Maximum density $= \frac{W_s}{V_s}$ pcf			

Relative Density Computation

Test No			
① In-place Density-pcf			
② Max. lab Density-pcf			
③ Min lab Density-pcf			
④ ①-③			
⑤ ④×②			
⑥ ②-③			
⑦ ①×⑥			
Relative Dens. % $= \frac{⑤}{⑦} \times 100$			

Measure No ______ Surcharge base plate No ______

Surcharge base pl thick ________ in

Straight edge thickness ________ in

Left dial read ______ ______ ______

Right dial read. ______ ______ ______

R_1 = Avg dial gage reading + surchg base pl thick - straight edge thk.

R_1 ________ in

Figure 10. Data card for relative density determinations.

The method of obtaining the average value of R_i (initial dial indicator gage readings plus thickness of surcharge base plate) on Figure 10 and Section 7B of this procedure should be consistent. The dial indicator gage holder should be placed in the same position in the guide brackets on the measure each time by means of matchmarks scratched on the guide brackets and the holder. A steel straightedge approximately $^3/_{16}$ in. thick is laid across the diameter of the measure along the axis of the guidebrackets, and the dial indicator gage is read with the stem on top of the straightedge, and recorded on Figure 10. The thickness of the straightedge used should be obtained by means of micrometer, and this thickness should be subtracted from the dial indicator gage reading. To this difference add the thickness of the surcharge base plate to obtain the value of initial dial indicator gage reading (R_i). This value is constant for a particular measure and surcharge base plate combination and can be used repeatedly.

5. Sample.—Select a representative sample of oven-dried soil. The weight of soil sample is determined by the maximum particle size as given in Table 5.

TABLE 5

SAMPLING AND TESTING GUIDES FOR MINIMUM DENSITY DETERMINATION

Maximum Size Soil Particles (in.)	Sample Required (lb)	Pouring Device Used in Minimum Density Tests	Unit Weight Measure (cu ft)
3	100	Shovel or extra-large scoop	0.5
$1^1/_2$	25	Scoop	0.1
$^3/_4$	25	Scoop	0.1
$^3/_8$	25	1-in. spout	0.1
No. 4	25	1-in. spout	0.1

6. Procedure:

A. Minimum density (maximum void ratio, zero relative density):

(1) Select the pouring device and measure according to the maximum particle size as given in Table 5.

(2) Oven-dried material shall be used. Soils containing $^3/_8$-in. maximum size or smaller should be placed as loosely as possible in the measure by pouring the soil from the appropriate size spout in a steady stream, at the same time maintaining the spout so that the free fall of the soil is 1 in. as it issues from the mouth of the spout. Also, at the same time rotate the pouring device in a spiral-like motion from the outside toward the center to form a soil layer of uniform thickness without segregation.

(3) Soils containing material larger than $^3/_8$ in. should be placed by means of a large scoop (or shovel) held as close as possible to and just above the soil surface to cause the material to slide rather than fall onto the previously placed soil. If necessary, large particles may be held back by hand to prevent them from rolling off the scoop.

(4) Fill the measure approximately 1 in. above the top and screed off the excess soil level with the top by making one continuous pass with a steel straightedge. During the pouring and trimming, great care should be exercised to avoid jarring the measure.

(5) Weigh the measure and soil and record the results on Figure 10 data card for relative density determination.

B. Maximum density (minimum void ratio, 100 percent relative density):

(1) Dry method:

(a) The soil sample shall be oven dried and mixed to provide an even distribution of particle sizes with as little segregation as possible.

(b) Assemble the guide sleeve on the top of the unit weight measure so the inner wall of the sleeve is in line with the inner wall of the measure. Two of the three set screws on the clamp assemblies should be provided with lock nuts so these screws can be left tightened. The guide sleeve can then be held in the correct alinement during succeeding tests when the third screw is tightened.

(c) Remove the guide sleeve and fill the measure with soil by the same procedure used for the minimum density test. Normally, the measure filled with soil for the minimum density determination may be used for the maximum density test without refilling the measure.

(d) Attach the guide sleeve to the measure and place the surcharge base plate on the soil surface. Lower the surcharge weight onto the surcharge base plate; a hoist will be required for the weight used in the 0.5-cu ft mold.

(e) Vibrate the loaded specimen for 8 min. Set the vibrator control at maximum amplitude except as otherwise specified. After the vibration period, remove the surcharge weight and guide sleeve from the measure and obtain dial indicator gage readings on the two opposite sides of the surcharge base plate and record R_f on Figure 10. Weigh the specimen in the measure (if it has not already been weighed in the minimum density test or if an appreciable amount of fines has been lost during the vibration period) and record the weight on Figure 10.

(2) Wet Method:

(a) While the dry method is preferred from the standpoint of securing results in a shorter period of time, for some soils, the highest maximum density is obtained using saturated soil. At the beginning of a new job, or when a radical change of materials occurs, the maximum density test should be performed on both wet and dry soil to determine which method results in the highest maximum density. If the wet method produces higher maximum densities, in excess of 1 percent, that method shall be followed in succeeding tests.

(b) The wet method can be conducted on oven-dried soil to which sufficient water is added, or, if preferred, on wet soil from the field. If water is added to dry soil, a minimum soaking period of ½ hr should be allowed.

(c) Fill the measure with wet soil by means of a scoop or shovel. The amount of water added to the soil should be just sufficient to allow a small amount of free water to accumulate on the soil surface during filling. The correct amount of water can be estimated by a computation of void ratio at expected maximum density or by experimentation with the soil. During and just after filling the mold, vibrate the soil for 6 min. During this period, the amplitude of the vibrator should be reduced as much as necessary to avoid excessive boiling and fluffing of the soil, which occur in some materials. During the final minutes of vibration, any water appearing above the soil surface should be removed.

(d) Assemble the guide sleeve, surcharge base plate and surcharge weight as in the dry method.

(e) Vibrate the specimen and surcharge for 8 min. After the vibration period, remove the surcharge and guide sleeve from the measure and record the dial indicator gage readings from the two opposite sides of the surcharge base plate on Figure 10. Weigh the specimen and record on Figure 10.

(f) Dry the complete soil sample to constant weight and record as W_s on Figure 10.

7. <u>Calculations:</u>

A. Minimum density. Calculate the minimum density as follows:

$$\gamma_{min} = \frac{W_s}{V_c}$$

B. Maximum density. Calculate the maximum density as follows:

$$\gamma_{max} = \frac{W_s}{V_s}$$

in which γ_{min} = minimum dry density in pcf
γ_{max} = maximum dry density in pcf
W_s = weight of dry soil in pounds
V_s = volume of soil in cubic feet
$V_s = V_c - \left(\frac{R_i - R_f}{12}\right) A$
V_c = calibrated volume of measure in cubic feet
R_f = final dial gage reading on the surcharge base plate after completion of the vibration period, in inches
R_i = initial dial gage reading in inches (See Section 4, calibration)
A = area of sample surface in square feet (cross sectional area of unit weight measure)

C. In-place density (γ_d). This determined by a field density test in a compacted fill or a natural deposit.

D. Relative density (D_d). Calculate relative density, expressed in percentage, as follows:

$$D_d = \frac{\gamma_{max} (\gamma_d - \gamma_{min})}{\gamma_d (\gamma_{max} - \gamma_{min})} \times 100$$

or in terms of void ratio

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

where void ratio $e = \frac{\text{vol of voids}}{\text{vol of solid particles}}$

e_{max} = void ratio in loosest soil state
e_{min} = void ratio in most compact soil state

ONE-POINT COMPACTION TEST

The one-point compaction test is basically a field compaction control measure made during construction. It consists of taking a soil sample at the field in-place moisture content, compacting it into the standard mold according to the standard compaction test procedure, and determining the wet unit weight and moisture content of the soil. These values are then used with a family of compaction curves, previously established for the local soils, to identify the soil being tested, and thereby the maximum dry unit weight and the optimum moisture content.

The Ohio (9, 120) and Wyoming (47A) methods are variations of the one-point compaction test. These methods require penetration resistance measurements instead of moisture content measurements. The wet unit weight and penetration resistance values are then used in conjunction with a family of compaction curves and corresponding penetration resistance curves to identify the soil being tested.

Three-point compaction tests have also been developed as field compaction control measures. The use of a three- or four-point compaction curve provides the inspector sufficient data to determine the relative compaction of the in-place soil without actually measuring the moisture content. California uses such a procedure (128A) as does the U.S. Bureau of Reclamation (the Hilf method) (129, 130). The latter method even provides for determining the difference between the in-place moisture content and optimum without requiring any moisture content measurements.

UNIT WEIGHT OF AGGREGATE TEST

The unit weight of aggregate test (AASHO Designation: T 19-56; ASTM Designation: C 29-60) is a type of compaction test. It consists basically of rodding or tamping the aggregate sample into a mold in three layers. Each layer is rodded with the tamping rod with 25 strokes. The rod is $\frac{5}{8}$ in. in diameter and approximately 24 in. in length.

The results of the test are used mainly in trial proportioning of portland cement concrete mixtures and have been used to specify quality of slag and lightweight aggregate. The test results are not intended for control of earthwork.

Factors influencing the results of this test are given by Hosking (131B).

ESTIMATION OF OPTIMUM MOISTURE CONTENT AND MAXIMUM DRY UNIT WEIGHT

Correlation of test data shows that relationships exist between the various index properties of a soil (see definitions in Appendix B). These relationships permit a close estimation of optimum moisture content and maximum dry unit weight of a soil if other index properties are known. This may now be done with reasonable accuracy. It also permits the computation of the effect of coarse aggregates, larger than the maximum size ($\frac{3}{4}$-in.) permitted by standard tests, on the dry unit weight of the total material. Methods of computation that have been developed for these purposes are discussed later under "Methods for Estimating Moisture Content-Unit Weight Relationships."

Principal Factors Influencing Maximum Dry Unit Weight And Optimum Moisture Content in the Compaction Tests

The aim of the preceding discussion has been to describe the different types of compaction effort used in the compaction tests, and, to present in summary form, generalized information on the apparatus and procedures used in the various compaction tests. Although this form of summarized information is no substitute for detailed test procedures, it is hoped that it will make possible a quick appraisal of some of the major differences in test apparatus and procedures. Such appraisal is necessary for the appreciation of the factors that influence the maximum unit weight and optimum moisture content obtained in the compaction test that are brought out in the discussion that follows.

It was shown in the discussion under "The Moisture-Unit Weight Compactive Effort Relationships" in HRB Bull. 272 that there are several general factors that influence maximum unit weight and optimum moisture content, whether they be obtained in laboratory testing or field compaction. There are also factors inherent to the laboratory test that have significant influence on the moisture content-unit weight relationships obtained. These include the size and shape of the mold, type and amount of compaction effort, methods used in processing the soil and compacting it, the method of determining the moisture content, and soil temperature and type. It is the purpose here to present the available information on those factors that influence the results obtained under variations in test apparatus and methods and, where possible, to compare the results and assess their significance.

THE SIZE AND SHAPE OF THE MOLD

There has been no systematized effort to determine the relative effects of diameter and depth of mold, individually and collectively on the resulting maximum unit weight and optimum moisture content. However, several individual studies have been made of different sizes (volumes) of mold to indicate the significance of size, particularly as it regards diameter. These studies have been made with the compaction effort per unit volume held constant.

Zeigler (28) compacted mixtures of soil and gravel in two different sizes of mold to determine the effect of mold size on maximum unit weight and optimum moisture content. The soil (97 percent passing No. 40 sieve, 58 percent passing No. 200 sieve, LL = 24, PI = 7, SL = 14, $G_s = 2.69$) was mixed with various percentages of gravel consisting of 50 percent ¾- to ⅜-in. size, and 50 percent ⅜-in. to No. 4 sieve sizes. The materials were compacted in the standard $1/30$-cu ft (AASHO Designation: T 99-38) mold and in a CBR mold that was 6 in. in diameter by 6 in. high and was reported as having a volume of 0.1025 cu ft. Compaction effort for the 6-in. mold was 74 blows per layer, 3 layers, 5.5-lb rammer, 12-in. drop. The results of the tests for 0 percent gravel and for 30 percent gravel for the two sizes of mold are shown in Figure 11. For the soil with no material retained on the No. 4 sieve and for the soil with 30 percent gravel admixture the smaller mold produced maximum dry unit weights 1.7 to 3.3 pcf higher than the larger mold. The difference may be due to the slightly smaller compaction effort in the large mold (11,912 vs 12,375 ft-lb per cu ft) and to the greater degree of confinement in the smaller mold.

The Corps of Engineers (51), in its studies of factors influencing the California Bearing Ratio (CBR), performed tests on five soils at each of three compaction efforts (Standard AASHO Designation: T 99, Modified AASHO,* and one compaction effort in-

---

*U.S. Corps of Engineers method at the time of the report of the study (June 1950) (see Table 1).

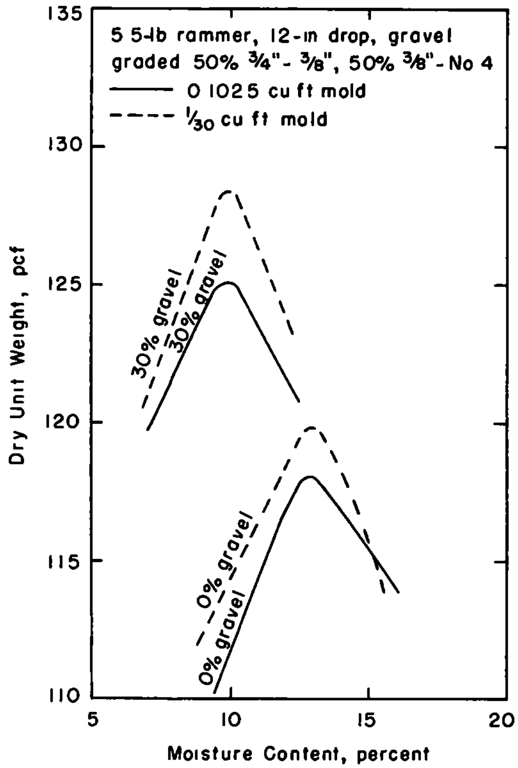


Figure 11. Effect of size of mold on moisture-unit weight relations of soil and soil-gravel mixtures. For 1/30-cu ft mold, AASHO Method T 99-38 compaction effort (12,375 ft-lb per cu ft) was used; for 0.1025-cu ft mold, compaction effort was 74 blows per layer, 3 layers, 5.5-lb rammer, 12-in. drop or 11,912 ft-lb per cu ft (28).

between the two) in each of three sizes of molds. The soils were (a) a clayey silt, (b) a fairly well-graded clay gravel, (c) a clayey sand of low plasticity, (d) a silty clay, and (e) a sand gravel. The grain size curves of three of the materials, representative of the range of textures used, are shown in Figure 12. Results of compaction tests by using three different sizes of molds (6.0, 7.4, and 12 in. in diameter) and holding the compaction effort per unit volume constant for the three soils are shown in Figure 13. These results are generally representative of the trend for all of the soils tested in that a very slight decrease in unit weight occurred with increase in mold diameter. If the results of the Standard AASHO and Modified AASHO compaction efforts are summarized for all soils, the unit weights increased slightly with increase in mold diameter in 5 tests and decreased slightly with increase in mold diameter in 9 of 14 tests. The greatest differences in maximum dry unit weight were for the gravels (up to 3.5 pcf decrease with increase in mold diameter). The differences in unit weight for the clayey silt and clay sand for each of the two compaction efforts for the three mold sizes ranged from a low of 0.2 pcf for the clayey silt to a high of 3.0 pcf for the clayey sand.

Mainfort and Lawton (64, 67) compacted various gradations of gravel, crushed limestone and slag into two sizes of molds, 4 in. in diameter by 4.6 in. high (0.0333 cu ft) and 6 in. in diameter by 4.6 in. high (0.075 cu ft). Samples were compacted in three layers by 42 blows per layer using a 10-lb rammer for the 4-in. mold and a 22.5-lb rammer for the 6-in. diameter mold. Compaction effort for each mold was about 56,700 ft-lb per cu ft.

The influence of the mold diameter on the maximum dry unit weight varied with the type and, to a lesser extent, the gradations of the material compacted. In most tests slightly higher unit weights were obtained in the 4-in. diameter mold. Results from 3 of 9 tests, however, that included minus No. 4 material showed a trend for higher unit weights in the larger mold as the mixtures became harsher. This is shown in Figure 14. The maximum differences in dry unit weight are of the order of 3 pcf with most values not exceeding the 1 to 1.5 pcf range.*

With the crushed slag, higher unit weights were obtained in the smaller mold in all tests. Differences averaged 3 to 4 pcf. Lesser differences were obtained for gravel and crushed limestone. In general, the tests indicated no undue particle interference in the 4-in. mold for tests of coarse mixtures. This is indicated by the fact that it produced slightly higher unit weights than did the 6-in. mold.

Walker and Holtz (70) reported Bureau of Reclamation tests in 1949 on 13 samples of soil from the Falcon Dam on the Rio Grande to determine the differences in maximum unit weight and optimum moisture content obtained in the standard 1/30-cu ft mold from those obtained in the Bureau of Reclamation 1/20-cu ft mold when identical compaction efforts per unit volume (12,375 ft-lb per cu ft) were used. The maximum unit

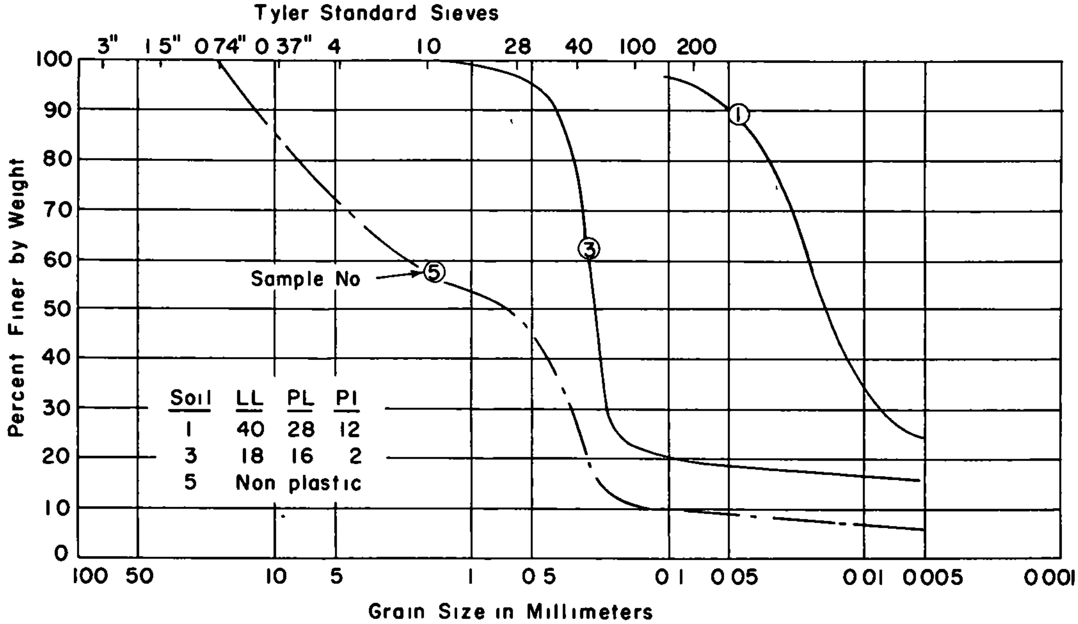


Figure 12. Classification data for soils studied in connection with effect of size of mold on CBR (51).

weights obtained in the standard 1/30-cu ft mold averaged 1.7 pcf higher than for the 1/20-cu ft mold. Maximum dry unit weights were attained at a moisture content 0.5 percent higher in the 1/20-cu ft mold.

Proctor (34) used both the 1/20- and 1/30-cu ft molds and controlled distance of rammer drop to determine their effect on saturated penetration resistance and on maximum dry unit weight and optimum moisture content. The variables in the Proctor studies were as follows:

1. A 5½-lb tamper dropped 18 in. for 25 blows on each of 3 equal soil layers in a 1/20-cu ft container (12,375 ft-lb per cu ft).
2. A 5½-lb tamper dropped 12 in. for 25 blows on each of 3 equal layers in a 1/30-cu ft container (12,375 ft-lb per cu ft).

The soil on which tests were made was clayey with 98 percent passing a No. 200 sieve, a liquid limit of 45, a plasticity index of 15 and $G_S = 2.72$. Method 1 gave a maximum dry unit weight of 92.5 pcf and an optimum moisture content of 25; values for Method 2 were 98.0 and 21, respectively. These marked differences due to mold size are the greatest that the authors have found in the published reports investigated.

Tamez (105) performed compaction tests on three soils in molds of 1/30 cu ft (AASHO Designation: T 99-57) and 1/20 cu ft (Bureau of Reclamation size) under nearly identical compaction efforts. He also performed compaction tests in molds of 1-cu dm (1,000 cu cm) volume and in a miniature mold of 91.6-cu cm capacity, using identical unit compaction efforts. The specifications for the AASHO and Bureau of Reclamation tests are given in Table 1 and for the two other tests in Table 2. Tests were made on three soils: (a) a highly plastic inorganic clay, (b) a well-graded moderately plastic clayey sand, and (c) a moderately plastic organic clayey silt. The tests resulted in practically identical values of maximum dry unit weight and optimum moisture content for the 1/20- and 1/30-cu ft molds. Likewise nearly identical values were obtained for the 1,000 and 91.6-cu cm molds.

Holtz and Lowitz (106) reported results of extensive tests in a study of the compaction characteristics of gravelly soils by the Bureau of Reclamation. Direct comparison

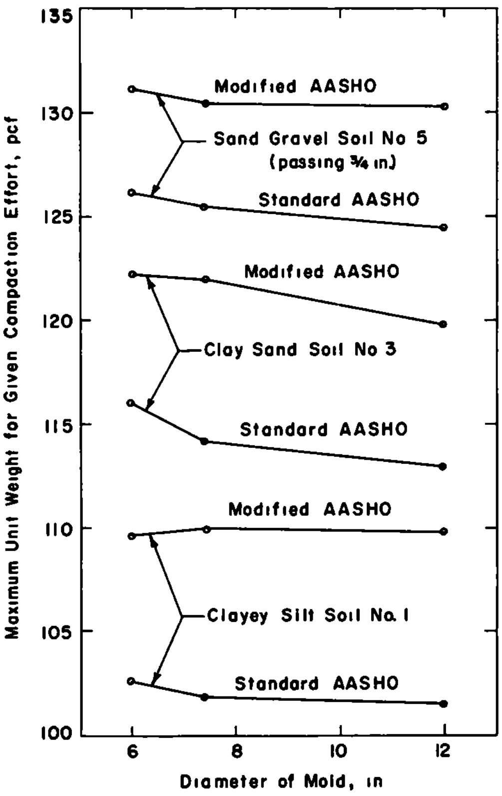


Figure 13. Effect of size of mold on maximum unit weight at two compaction efforts for three different types of soils (51).

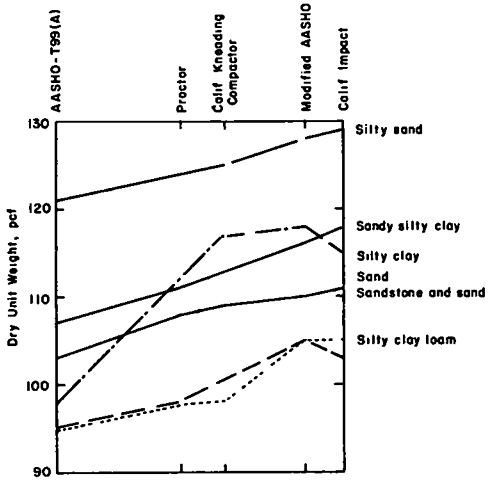


Figure 15. Comparison of different laboratory methods used to establish maximum unit weight for compaction control (95).

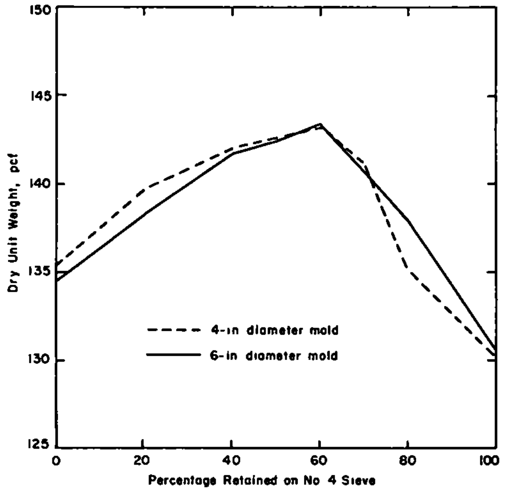


Figure 14. Relation between mold size and maximum dry unit weight for different gradations of sand-gravel. Percentage retained on No. 4 sieve was determined before compaction and consisted of equal portions of No. 4 to 3/4-in. and 3/4-in. to 1 1/2-in. material (64,67).

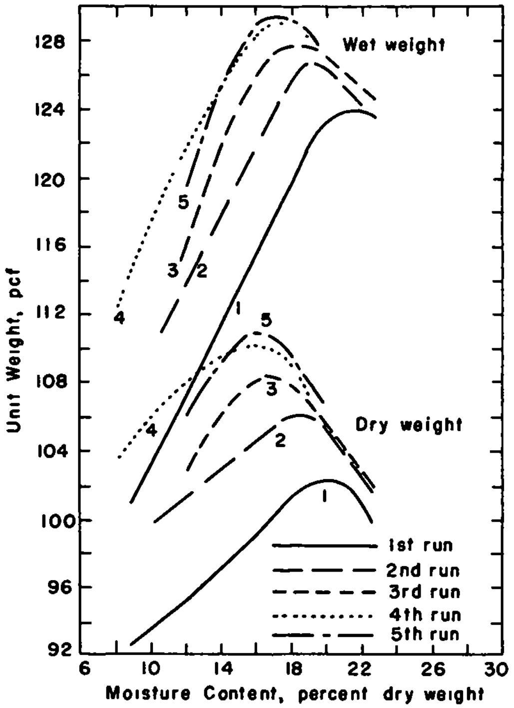


Figure 16. Results of rerunning air-dried sample that has been oven dried between runs (9).

of results of tests for the minus No. 4 sieve material can be made for a small and a very large mold because the tests were made at equivalent compaction efforts per unit volume. The two sets of apparatus used were as follows:

1. 5.5-lb, 2-in. diameter (3.14-sq in.) rammer, 18-in. drop; cylinder 14.42 sq in. (about 4.3 in. in diameter) and 6 in. deep; 3 layers, 25 blows per layer (unit energy input 12,375 ft-lb per cu ft).
2. Special large apparatus including a mechanical tamper; 187.5-lb rammer, 70.9 sq in.; 18-in. drop; cylinder 291-sq in. area (about 19.2 in. in diameter) and 9 in. deep; 3 layers, 22 blows per layer (unit energy input 12,135 ft-lb per cu ft).

The results of compaction tests on the minus No. 4 material for each of three soils: (a) a non-plastic sandy soil with 86 percent sand, (b) a silty soil with 35 percent sand and plasticity index of 4, and (c) a clayey soil with 52 percent sand and a plasticity index of 28, are shown in Table 6.

TABLE 6

RESULTS OF COMPACTION TESTS ON THREE SOILS USING SMALL AND VERY LARGE COMPACTION MOLDS (106)

Soil (-No. 4 Sieve Size)	1/30-Cu Ft Mold		Large, 1.5-Cu Ft Mold	
	Max. Dry Unit Wt. (pcf)	Opt. Moist. Cont. (%)	Max. Dry Unit Wt. (pcf)	Opt. Moist. Cont. (%)
Sandy	116.1	10.1	117.5	9.4
Silty	120.0	11.7	120.0	11.7
Clayey	105.9	18.5	108.5	16.8

These tests show slightly higher maximum dry unit weights for the sandy and clayey soils in the large mold; a trend that is counter to that found by some other investigators using molds with smaller differences in size.

The ratio of cross-sectional areas of the molds (14.41:291 sq in.), used by Holtz and Lowitz is higher than used by other investigators as are the depths of the molds (6 in. for the small mold and 9 in. for the large mold). This could be an influencing factor in producing results that differ slightly from those obtained by other investigators; evidence of the influence of depth of mold alone as a factor is not available.

The results previously presented have shown that when the compaction effort per unit volume is constant, the size of the mold, within the range of sizes (diameters and depths) tested, has very small influence on the maximum dry unit weight and optimum moisture content. In more than half of the instances, increasing the size of the mold resulted in slight decreases in maximum unit weight. These ranged from less than 1 pcf to a maximum of 3.5 pcf with most of the results showing less than 1.5 pcf difference. From these results it may be concluded that when the compaction effort per unit volume is constant, the ratio of hammer diameter to mold diameter is approximately 1/2 (as was the case in most of the tests); and as the ratio of diameter to depth of mold does not vary appreciably, the size of the mold is not a significant factor in influencing the maximum dry unit weight or the optimum moisture content for a given soil.

It has not been possible to compare the results of the California Impact Test directly with those of other methods on the basis of equivalent compaction effort per unit volume because comparable data are not available. The California Impact Method differs markedly in ratio of mold diameter to depth and in ratio of rammer area to mold area from those whose results have been compared previously. It employs a 2-in. diameter rammer in a 3-in. diameter mold (see Table 1). Inasmuch as the mold is not designed so the compacted specimen can be struck off to a predetermined volume, the volume of the compacted specimen is variable, depending on the quantity of soil used and the unit weight to which it is compacted, between about 1/20th and 1/24th cu ft. For these volumes, the compaction efforts per unit volume range from about 30,000 to 36,000 ft-lb per cu ft.

Although data are not available for making direct comparison of the California Test with others, some indirect comparisons are possible which indicate that the relationships that hold for other combinations of mold and rammer described previously may not hold for the California apparatus that employs a smaller ratio of area of mold to depth of compacted specimen and the higher ratio of rammer diameter to mold diameter already mentioned. Tests have been made using the California, Modified AASHO, original Proctor, and California Mechanical Compactor Methods for purposes of comparing the values they produce with values obtained under field compaction in construction (95). Among the information sought was a determination of the method whose results with all types of soil most nearly parallels the results obtained with construction equipment.

An analysis of this data shows that the California Impact method with a compaction effort in the range of about 30,000 to 36,000 ft-lb per cu ft produced greater dry unit weights on several soils than did the Modified AASHO method employing a compaction effort of 56,250 ft-lb per cu ft. The characteristics of the soils tested are shown in Table 7. The maximum dry unit weights obtained on three of these soils, (a) a silty sand, (b) a sandy silty clay, and (c) a sandstone and sand, were plotted in ascending order of unit weight for the five different compaction methods indicated in Figure 15. In each of the three instances the California Impact method produced unit weights slightly higher than did the Modified AASHO Method.

TABLE 7

CHARACTERISTICS OF SOILS USED IN COMPARING THE CALIFORNIA IMPACT METHOD WITH OTHER METHODS OF COMPACTION (95)

	Percent Passing Sieve Sizes					
Soil	No. 30	No. 100	No. 200	0.005 mm	LL	PI
Sand	93	3	1	-	NP	-
Silty sand	96	60	45	14	21	3
Sandy silty clay	97	84	71	33	46	24
Silty clay	100	97	92	55	62	40
Silty clay loam	100	99	94	22	43	12
Sandstone and sand (minus ¾ in.)	53	36	20	1	NP	-
Sandstone and sand (minus No. 4)	88	59	33	3	NP	-

The comparative values obtained by the five compaction tests on three other soils, (a) a silty clay, (b) a clean sand, and (c) a silty clay loam are also plotted in Figure 15. The results for the silty clay loam obtained by the California Impact method are equal to the results obtained by the Modified AASHO method; and those for the clean sand and the silty clay are less than those obtained by the Modified AASHO method.

These results show that the California Impact method does not produce maximum dry unit weights that are consistently higher or lower than those produced by other methods on all soils. From this it may be inferred that the size of the mold, expressed not simply in terms of volume in cubic feet but also in terms of ratio of diameter to height, may be significant when considered together with the area of the rammer.

SUPPORT FOR THE MOLD

Ray and Chapman (78) performed a series of tests to measure the influence of type of support on the resulting maximum dry unit weight and optimum moisture content. Eight soils were used in the tests. They included two non plastic gravelly sands, a slightly plastic sand, two non plastic sands, a moderately plastic sandy loam and sandy clay loam, and a highly plastic clay. All tests but one were made with 5.5-lb rammer, 12-in. drop, 3 layers, 25 blows per layer in a $1/30$-cu ft mold. The exception was the

Modified AASHO method using a 10-lb rammer, 18-in. drop, 5 layers, 25 blows per layer.

The tests were made with the mold (a) resting on a concrete floor, (b) resting on the middle of a stout wooden table (the table resting on a concrete floor), (c) resting on a steel plate weighing 63 lbs placed on the table, and (d) resting on a 213-lb weight placed on the table.

The results showed that maximum dry unit weights varied with type of support and with the soil type. Results with the 213-lb weight were equivalent to those with the mold resting on the concrete floor. The largest differences in maximum dry unit weight were for the mold resting on the table and on the concrete floor (or on the 213-lb weight). Greatest differences in maximum dry unit weight were approximately as follows for the standard test:

Clay and gravelly sand soils	1½ pcf
Sandy clay loam	1 pcf
Sandy loam and sand	½ to ¾ pcf

Differences in optimum moisture content ranged from 0 to 1 percentage unit. Differences in maximum dry unit weight for the Modified AASHO Test performed on a non plastic sand was about 2½ pcf.

AASHO compaction test Designations: T 99-57 and T 180-57 (ASTM Designations: D 698-58T and D 1557-58T, respectively) require that the mold rest on a uniform, rigid foundation, such as provided by a cube of concrete weighing not less than 200 lb. The authors could not determine the basis for the 200-lb value.

METHODS OF PREPARING THE SAMPLE AND COMPACTING THE SOIL

In every laboratory test on soil, the results obtained depend on the manner in which the sample is prepared for the test as well as how it is compacted in the test. Standard AASHO—ASTM methods call for air drying at a temperature not exceeding 140 F. When water is added, thorough mixing is required followed by allowing the covered mixture to stand for not less than 5 min to permit more complete absorption of the moisture. The soil is reused after each compaction; that is, water is added and the same soil is recompacted several times until the condition for maximum unit weight and optimum moisture content is exceeded.

In preparing the sample some operators have oven-dried the soil as a matter of expediency, others have air-dried the soil, and others have merely reduced the moisture content by air drying to a moisture content equal to the lowest desired for the compaction curve. In performing the compaction test some engineers prefer to use a new batch of soil, for each point on the moisture content-unit weight curve, in preference to the standard method of reusing (recompacting) the same soil for each of the several points on the compaction curve. It is of interest here to examine differences obtained by performing the compaction test in accordance with such markedly different test procedures.

Air-Drying Compared to Oven-Drying

Quite different moisture content-unit weight relationship curves may be obtained on samples of the same soil previously oven-dried compared to those in which the sample is allowed to retain a portion of the field moisture before performing the test (9). The compaction curves in Figure 16 show the effect of rerunning an oven-dried sample. One 8-lb sample was used for the entire set of five runs. The only deviation from the standard procedure consisted of oven-drying the entire sample between runs and then adding about 8 to 12 percent water before starting a run. The curves for the five runs are similar; the weight for any given moisture content increases in each succeeding run for the first four runs; and the optimum moisture content is decreased with each successive run.

Figure 17 offers an opportunity to compare the relative effects of air-drying and oven-drying. The results here indicate that for the soil tested there is little difference between rerunning air-dried and oven-dried samples; it also shows (as does Figure 16)

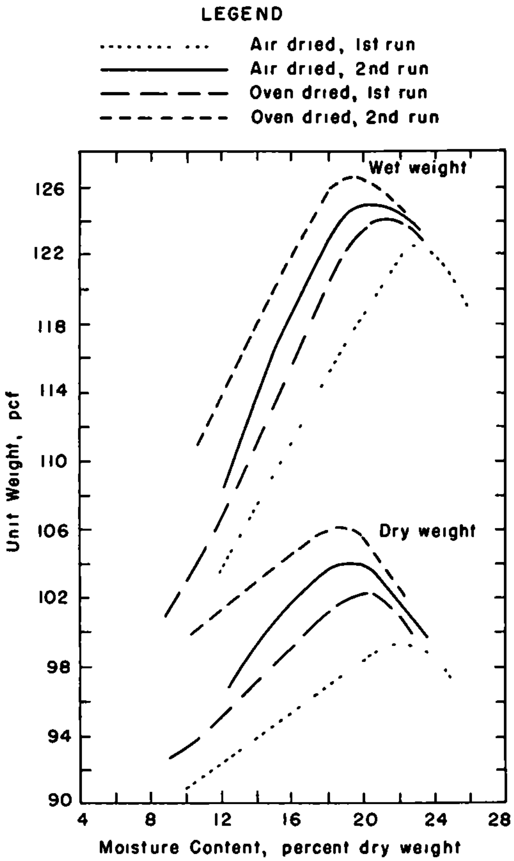


Figure 17. Comparison of the effects of oven drying and air drying between compaction tests (9).

that continued rerunning results in greater maximum unit weights and lower optimum moisture contents than were obtained from a single run.

Figure 18 shows the effect or rerunning (recompacting) a moist sample. A marked increase in maximum unit weight and reduction in optimum moisture content resulted between the first and second runs. Succeeding recompactions had practically no effect on either the maximum unit weight or optimum moisture content.

Recompaction vs Use of Separate Portions of the Sample for Each Point on the Compaction Curve

It has long been known that recompacting the soil yielded values of maximum dry unit weight and optimum moisture content that differed from values obtained by using a new batch of soil for each point on the compaction curve. The fact that the standard method requires reusing the soil is largely one of practicability relative to the size of the original soil sample.

The compaction curves in Figure 18 are indicative of the nature of the problem. Here the effect of recompaction is not detectable after the first run. But this does not satisfy the question completely. It is desired to compare results obtained by recompaction with those made by using a new sample for each point on the moisture-unit weight curve. Sowers and Nelson (46) undertook to determine this effect. Sixty-pound samples were prepared in accordance with standard methods by air-drying the soil and pulverizing it. Water was added in the desired increments and the soil was compacted in accordance with AASHO Method: T 99. For two of the soil types the Modified AASHO test procedure was also used. The investigators reported test results on nine different types of soils and on a sample of fly ash.

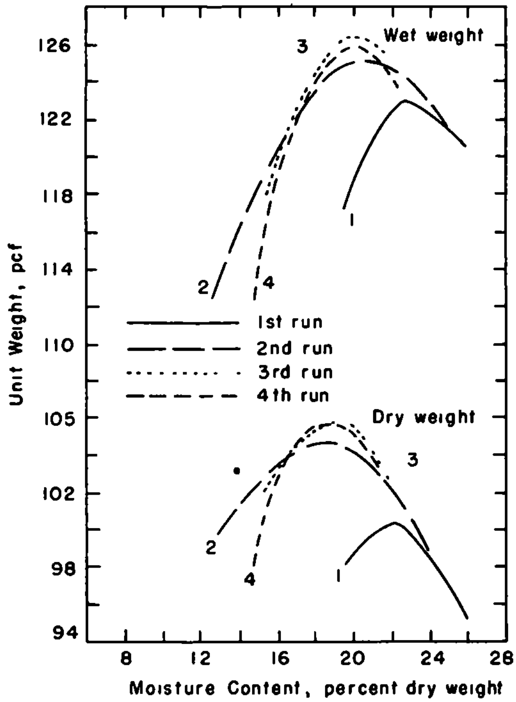


Figure 18. Results of rerunning a moist sample in the standard compaction test (9).

The nature of their results is in part in Figure 19 which shows (a) the compaction curve obtained by recompacting the soil, and (b) the curve obtained by using separate batches of the same soil for each point on the curve. The data are for a medium clay of the A-7-5 (19) soil group compacted in accordance with AASHO Designation: T 99. Figure 20 shows the results of the two procedures for a fine, non plastic sand of the A-3 (0) group compacted in accordance with both AASHO Method: T 99 and the Modified AASHO method. Complete reported results of the tests are summarized in Table 8 to permit comparison of results on the several types of soil. Examination of Table 8 shows that for two of the soils the difference is only 1 pcf and for three of the soils, the difference is 2 pcf. Other values range from 3 to 6 pcf for the soils and 8 pcf for the fly ash. The greater differences are for the higher compaction efforts.

In Table 8 the lesser differences are of the order of those within the range of reproducability of the test for a given method. Nevertheless, the differences are consistent in that the higher values are always in the group included in recompaction of the soil. It is reasonable to expect that the differences encountered may, in part at least, be due to soils that break down progressively under the impact of the rammer. However, again this cannot be the answer for the definite trend of unit weights shown. Some types of cohesive soils are slow to absorb moisture. Continually adding water to, mixing, and recompacting such soils may influence their workability and influence their maximum unit weights and optimum moisture contents by this alone does not explain the differences found.

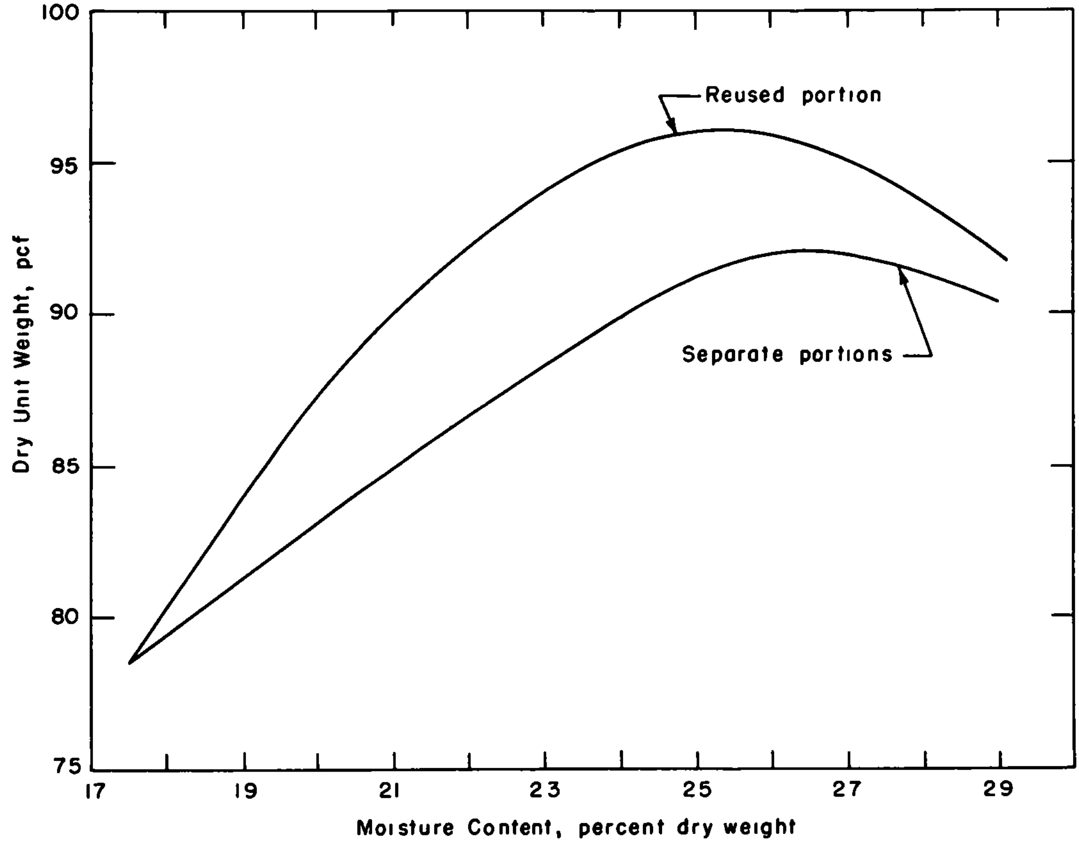


Figure 19. Moisture-dry unit weight relationships using separate samples for each point on the compaction curve compared with test reusing the soil for each point. Soil is an A-7-5 (19) clay, with 95 percent passing No. 40 sieve, 83 percent passing No. 200 sieve, LL = 67, PI = 27 (46).

TABLE 8

COMPARISON OF MAXIMUM DRY UNIT WEIGHTS AND OPTIMUM MOISTURE CONTENTS OBTAINED BY USING SEPARATE SAMPLES OF SOIL FOR EACH POINT (ON M-D CURVES) TO DRY UNIT WEIGHTS AND OPTIMUM MOISTURE CONTENTS OBTAINED BY USING SAME PORTION FOR ALL POINTS (46)

Soil Type (Revised PRA)	Percent Passing		Liquid Limit	Plastic Index	Maximum Dry Unit Weight (pcf)		Differences in Max. Unit Weight		Opt. Moisture (%)		Differences in Opt. Moist. (%)
	No. 40 Sieve	No. 200 Sieve			Re-used	Separate	Pcf	Percent Re-used Max.	Re-used	Separate	
(a) Compaction in 3 layers with 5.5-lb hammer (AASHO T 99-38)											
A-2-4 (1)	72	35	19	0	126	125	1	0.8	9.7	9.7	0
A-3 (0)	86	12	NP	NP	108	104	4	3.7	14.5	14.5	0
A-4 (1)	78	41	30	0	122	118	4	3.3	11.5	11.5	0
A-5 (1)	85	41	44	0	106	103	3	2.8	16	16	0
A-6 (16)	94	76	40	12	108	106	2	1.9	18	18.8	0.8
A-7-5 (13)	99	92	52	17	99	97	2	2.0	25	24	1.0
A-7-5 (18)	100	100	67	25	81	79	2	2.5	33	32	1.0
A-7-5 (19)	95	83	67	27	96	92	4	4.2	25.5	26.7	1.2
A-7-6 (18)	100	97	48	26	101	100	1	1.0	23	23	0
Fly Ash	61	14	NP	NP	71	63	8	11.3	30	26	4.0
(b) Compaction in 5 layers with 10-lb hammer (Modified AASHO)											
A-2-4 (1)	72	35	19	0	131	128	3	2.3	8.8	8.8	0
A-3 (0)	86	12	NP	NP	118	112	6	5.1	12.5	12.3	0.2

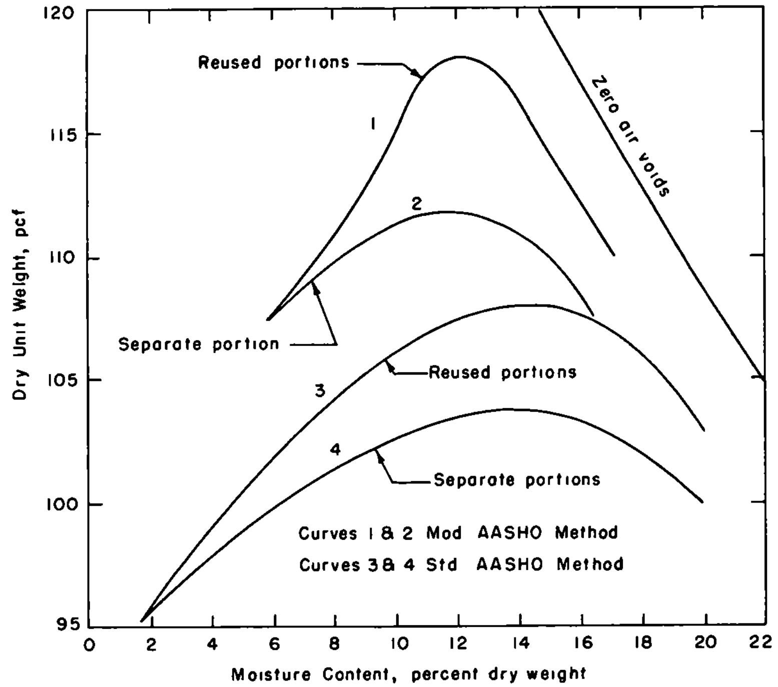
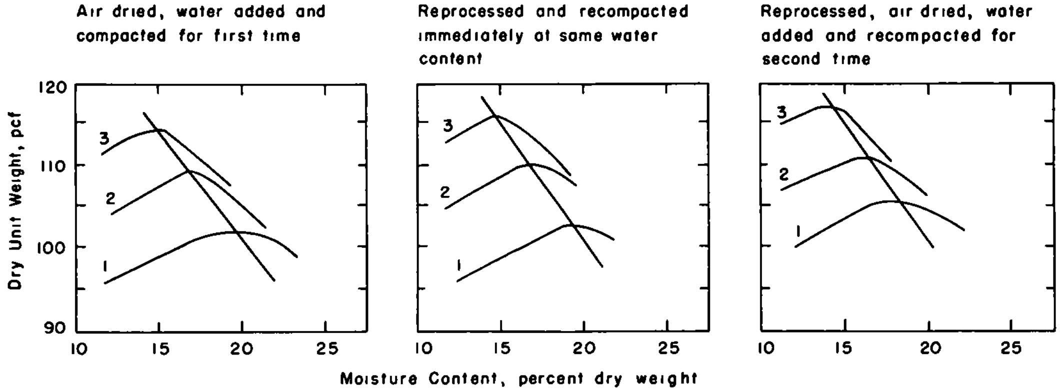


Figure 20. Moisture-unit weight relationships for tests using separate samples for each point on the curve compared with test reusing the soil for each point. Soil is an A-3 (0) nonplastic loamy fine sand with 86 percent passing No. 40 sieve, 12 percent passing No. 200 sieve (46).



LEGEND

Curve No	Layers	Blows per Layer	Weight of Rammer (lb)	Drop in Inches
1	5	12	10	18
2	5	26	10	18
3	5	55	10	18

Figure 21. Effect of air drying and recompaction on optimum moisture content and maximum dry unit weight of a silty clay with LL = 36, PI = 15, G_s = 2.72 (89).

The Corps of Engineers (89) performed a series of tests on a Vicksburg lean clay (LL = 36, PI = 15) to determine the effect of reprocessing and recompacting the soil on the maximum unit weight, optimum moisture content, and CBR. The results of these tests are shown in Figure 21. In order to obtain the data in the lefthand plot, the soil was air-dried, water added, and the soil compacted for the first time. Immediately after the test was completed, the soil was removed from the molds, reprocessed, and recompacted at the same moisture content to yield the moisture content-unit weight curves in the middle plot of the figure. After CBR tests (unsoaked), the soil from these recompacted specimens was screened through a No. 4 screen and air-dried; water was added and the soil was recompacted a second time. The results are shown in the righthand plots of the figure.

Comparison of the results shows that each time the soil was recompacted a slight increase in maximum unit weight occurred. A recapitulation of the values of maximum dry unit weight scaled from values shown in Figure 21 are given in Table 9, which shows that reprocessing and recompacting immediately yielded increases of 0.5 to 1.4 pcf depending on the compaction effort. However, the results of reprocessing, air-drying, adding water, and recompacting were somewhat erratic but yielded increases ranging from 1.5 to 3.5 pcf.

If the optimum moisture content is plotted vs maximum dry unit weight for each of the three compaction efforts for each of the three conditions of compaction, three "lines of optimums" result. This method quickly reveals the variation in optimum moisture content. At no time did the values of optimum moisture content differ by more than 1 percentage unit. That extreme value was for the lowest compaction effort. Values of optimum moisture content were practically identical for the median compaction effort and did not differ by more than ¾ percentage unit for the highest compaction effort.

TABLE 9

EFFECT OF AIR DRYING AND RECOMPACTING ON THE DRY UNIT WEIGHT OF A LEAN CLAY (89)

Layer	Compactive Effort: Blow per Layer	Compactive Effort: Weight of Rammer (lb)	Compactive Effort: Drop of Rammer (in.)	Soil Treatment: Air-Dried, Water Added, Compacted First Time (pcf)	Soil Treatment: Reprocessed, Recompacted Immediately at Same Moist. Cont. (pcf)	Soil Treatment: Reprocessed, Air-Dried, Water Added, Recompacted Second Time (pcf)
5	12	10	18	102.2	102.7	105.7
	26	10	18	109.5	110.2	111.0
	55	10	18	114.3	115.7	116.9

Tamez (105) also performed tests to determine the differences in maximum dry unit weight and optimum moisture content that result from reusing the soil in the compaction test; he compared the results with unit weights obtained by using fresh samples for each point on the curve. His tests were made on three soils: (a) a highly plastic inorganic clay of the CH group (gravel, sand, silt, and clay according to MIT grain sizes were 6, 28, 40, and 26 percent; LL = 72, PI = 37, G_s = 2.71), (b) a well-graded clayey sand SC (gravel, sand, silt, and clay content of 29, 58, 11 and 2 percent; LL = 50, PI = 22, G_s = 2.68), and (c) an organic clayey silt OH (gravel, sand, silt, and clay content of 13, 18, 46 and 23 percent; LL = 66, PI = 24 and G_s = 2.72). The effect of recompaction was similar for the three materials, differing only in magnitude.

An example of his results is shown in Figure 22, which presents data for soil No. 1 (the highly plastic, inorganic clay). Comparing Curve III with Curve I, it may be seen that the values of dry unit weights (γ_d) for Curve III are greater than those for Curve I for the same moisture content. Curve III is the result of recompacting, for each point, the same portion of material used in the preceding one, whereas, a different portion was used for each point on Curve I. For each curve, the water content was increased by sprinkling, starting from the same initial conditions for each material.

By comparing Curve IV with Curve II a similar effect is observed. Curve IV is the result of recompacting the material, whereas, no recompacting was done for Curve II. In both cases the moisture content was allowed to vary by drying. Curve V shows the results at which one may arrive if, starting from the last point on Curve IV one continues to recompact the soil, increasing the water content. Comparison of the curves, particularly Curves I and III shows that recompaction affects the shape and position of the moisture content-unit weight relationship curve, resulting in higher dry unit weights for the same value of moisture content.

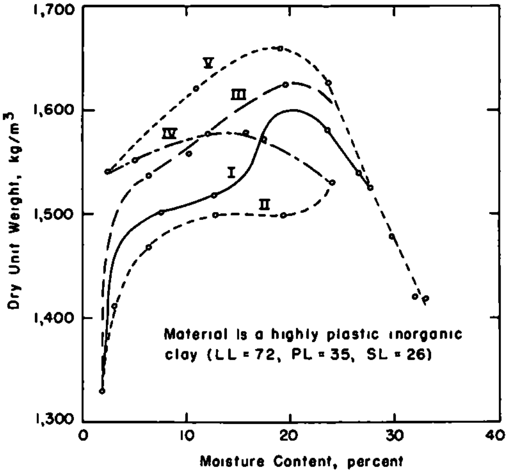


Figure 22. Moisture-unit weight curves, showing effect of recompaction and moisture distribution, obtained with the miniature mold and applying the same unit compaction energy as in the standard mold used by the Secretaria de Recursos Hidraulicos of Mexico (105). I. No recompaction, adding water. II. No recompaction drying. III. Recompaction curve, adding water. IV. Recompaction curve, drying. V. Recompaction curve, adding water.

Effect of Manipulation

It is evident from Figures 16 through 22 that physical manipulation of the soil like that applied in the compaction test has some influence on the maximum unit weight and optimum moisture content, particularly when the soil is subject to re-use as in the standard test. Few investigations have been made to measure the effects of manipulation on the workability of the soil. One of these, by Kersten and Krieger (108) employed two types of manipulation. One consisted of mixing soil and water in a Lancaster mixer. The other consisted of prolonged periods of tamping by a California kneading-type compactor. The influence of manipulation was not measured in terms of compactability but rather in terms of increase in plasticity index. Field tests were also made that consisted of observations of changes in plasticity index of subgrade soils under flexible-type pavements subject to moderately heavy traffic (3,400 vpd).

Six of the seven soils that were tested and that ranged from a nonplastic (PI = 0.2) sandy loam, through silt loams (PI = 1.3 to 5.1) to highly plastic clays (PI = 21.8 to 53.5) exhibited increase in plasticity index in both types of laboratory manipulation. All four soils tested in the field showed marked increases in plasticity index associated with strains resulting from traffic. Two silt loams exhibited very marked increases in plasticity index (5.0 to 12.7 and 1.3 to 8.0) in 5-hr manipulation. This high early rate of change was approximately enough to double the plasticity index in the time normally required to perform a compaction test reusing the soil. Field changes were smaller for the silts (5.1 to 6.4 and 1.3 to 1.5) but higher for the sandy loam (0.2 to 3.2) and the clay (25.3 to 30.3).

Although these experiments provide no measure of the effect of manipulation insofar as normal compaction is concerned, they do illustrate that physical manipulation has an influence on maximum unit weight, optimum moisture content, and plasticity index that may differ for various soils and test procedures.

Effect of Drying in Storage

Tests were made by Grady of the Bureau of Public Roads (47) after different periods of storage of the same soil sample. It was observed that significant variations can be obtained for the same soil and that these variations appear to be related to the amount of the original natural soil water content that the sample contained before the start of

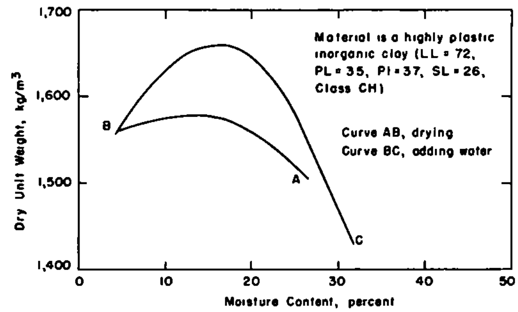


Figure 23. Effect of moisture control on the moisture-unit weight relations for a heavy clay soil (105).

compaction tests. The optimum moisture content varies directly and the maximum dry unit weight varies inversely with the initial moisture content at the start of the compaction test. The relationship holds for both Standard and Modified AASHO methods.

A similar condition holds for similar soils from a test pit. Data show (47) that when the initial moisture content of the soil in the pit is low the maximum dry unit weight is high and when the moisture content in the pit is high the maximum dry unit weight is low. An example is given of a laterite soil from Hawaii in which this effect of initial moisture content influenced maximum unit weight by as much as 12 pcf and optimum moisture content by as much as 7 percent.

Ray and Chapman (78), in their special studies of factors affecting test results in the compaction test, found that for a plastic soil, performing the test immediately after mixing in the water resulted in different values of maximum unit weight and optimum moisture content than if the moistened soil were allowed to "mature." Errors of 1 to 1½ pcf in unit weight and ½ to 1½ percentage units in the optimum moisture content were attributable to insufficient "maturing" of the soil after adding water. For soils having plasticity indices greater than 20 it is necessary to allow a maturing period.

Effect of Mixing Time and Method on Moisture Distribution

Tamez (105) held that the usual method of expressing the moisture content of the soil does not explain how the water is distributed within the soil particles or clusters. The different conditions of distribution may influence the shape and position of the moisture content-unit weight curve, especially for fine-grained soils. An indication of such influences is given by a series of tests performed on a highly plastic inorganic clay of the CH group (gravel, sand, silt, and clay are 6, 28, 40, and 26 percent, respectively; LL = 72, PI = 37, $G_s = 2.71$) with the results shown in Figure 23.

Curve AB in Figure 23 was started at point A, corresponding to the natural moisture content of the soil. Other points on the curve were obtained by allowing the soil to dry at room conditions, decreasing the moisture content until point B was reached. The successive points on Curve BC were obtained by adding water and recompacting the soil used in the preceding point.

Comparing Curves AB and BC it may be seen that Curve BC yields higher dry unit weights than does Curve AB, for the same moisture content. Tamez holds that the differences in dry unit weight, for the same moisture content, are attributed to differences in the distribution of the water within the soil clusters. When adding water, the outside of the clusters is more damp than the inside, whereas on drying, the situation is reversed. Thus, the lubricating effect of the water is greater in the first case and produces higher dry unit weights for the same compaction energy.

This if of practical importance in construction. If the existing soil has insufficient moisture, water is added and a relatively high unit weight is attainable. If, on the contrary, the existing moisture content exceeds that desired and the soil must be dried before compaction, a lower unit weight may be expected for the same compaction effort. Hence, lift thickness and compaction effort must be adjusted to provide the unit weights specified.

Effect of the Compaction Process

The various factors involved in the compacting process, including the size and shape of the mold, the means for delivering the compaction effort, the magnitude of the compaction effort, as well as other facets of the compacting process have been discussed previously or are discussed later under other appropriate subject matter.

TYPE, MAGNITUDE, AND DISTRIBUTION OF COMPACTION EFFORT

The nature of the compaction effort and the distribution of the effort have marked effects on the unit weight obtained in the compaction test. Results differ with type of compaction effort (impact, kneading, vibration, and static compression) and the elements that constitute the individual types of compaction effort. These effects are presented here according to type of compaction effort.

The Impact Compaction Test

The effect of the compaction effort in the impact type of test varies according to the type and dimensions of the rammer and rammer guide; the weight, velocity, energy, and momentum of the rammer; the percent of total compaction energy applied in each tamp; and the total energy applied to the soil.

Type and Dimensions of Rammer and Rammer Guide. —In the impact test, the nature of the rammer and its use determine the maximum unit weight attained in the test. Several investigators have studied the characteristics of the different designs and uses of rammers and reported on their influence on the maximum dry unit weight and optimum content obtained in the laboratory compaction test.

The original Proctor rammer (2) weighed 5.5 lb and had a striking face 2 in. in diameter. Proctor later (34) increased the weight to 5.75 lb. Proctor's originally described method read "12-in. firm blows" with a 5.5-lb tamper; when published, the 12-in. firm blows had been changed to "12-in. firm strokes" (34). This inadvertent substitution evidently led some to believe that Proctor intended the tamper should be dropped a distance of 12 in. in free fall and resulted in the requirement that all rammers specified in standard methods of test be equipped with suitable arrangement to control the height of drop to a free fall of 12 in., (AASHO T 99-57, ASTM D 698-57 T) or 18 in. (AASHO T 180-57) as the case may be.

Standard methods of test do not include requirements for the method of guiding the free fall of the tamper. The conventional rammer consists of a cylindrical metal weight attached to a rod that is allowed to fall in a guide tube of internal diameter slightly greater than the diameter of the weight. Some engineers believe that the tube

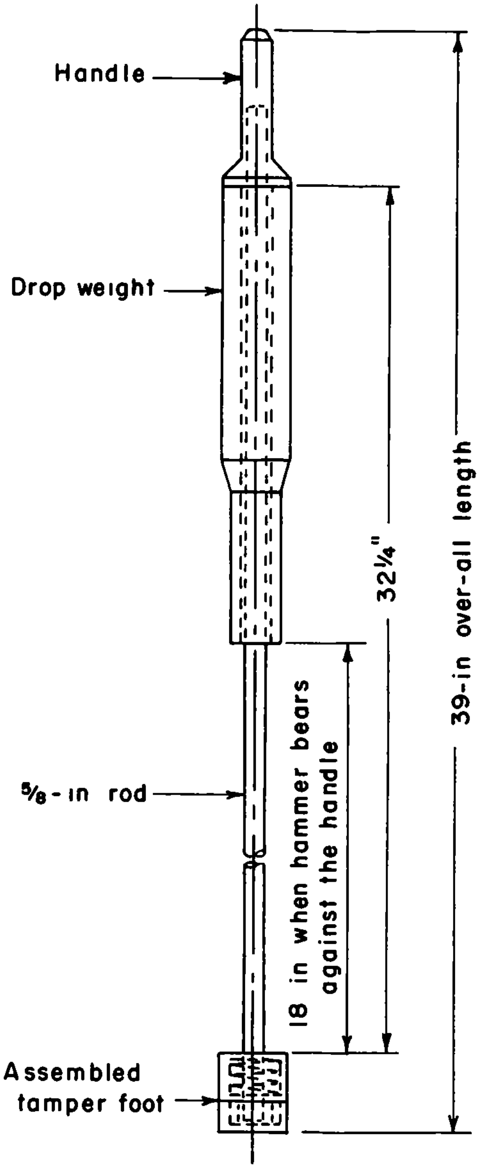


Figure 24. Compaction tamper of sliding weight type used by the U.S. Corps of Engineers in the Modified AASHO compaction method. Tamper foot equipped with a spring to absorb some of the hammer shock (117).

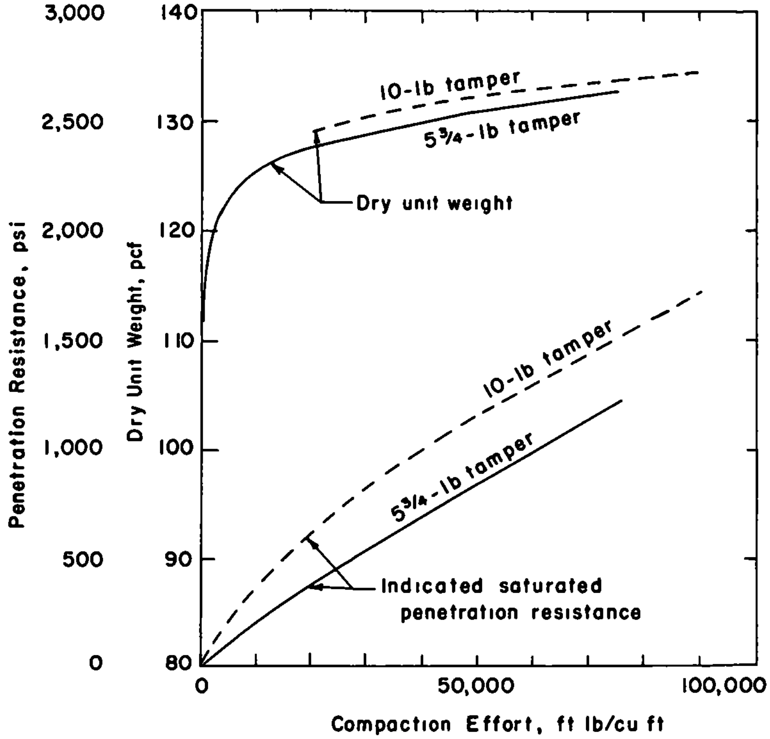


Figure 25. Maximum dry unit weights and indicated saturated penetration resistance for equivalent compaction efforts for 5 3/4- and 10-lb tampers; for a sandy soil having 27 percent passing No. 200 sieve, LL = 22.4, PI = 2.6, G_s = 2.70 (38).

prevents compaction of the soil immediately adjacent to the edge of the mold, although data have not been found to validate that belief. Another type of rammer, the Gawith type (29) employs three steel rods at 120 deg spacing to act as guides for the falling rammer. This device does permit packing immediately adjacent to the edges of the mold. A third type of rammer employs a weight sliding on a central guide rod attached to a tamping foot. This type is referred to as a hammer. An early version of this type was used in Kansas (7). A current version of the sliding weight type of hammer is that used by the Corps of Engineers in their modification of AASHO Method: T 180-57 (117). The hammer consists of a 2-in. diameter steel tamping foot, a $^{5}/_{8}$-in. steel rod, a weight with an $^{11}/_{16}$-in. hole through the center, and a handle. Construction of the tamping foot and weight is such that tamping blows can be applied adjacent to the sides of the mold. The rod is attached to the tamping foot with a spring cushion. The maximum allowable weight of the assembled hammer is $17\frac{1}{2}$ lb. A sketch of the hammer is shown in Figure 24 (117).

Experience in Kansas with the early designs showed that without the use of a spring cushion the foot worked loose from the rod. Inexperienced operators sometimes held the device so that the falling weight struck the collar of the mold as the layers of soil were added. This type of hammer needs to be calibrated so that the tamping foot gives the desired compaction effort.

The Dietert test described under "Principal Compaction Test Method—Impact Type—Manual Operation," is another example of the sliding weight type of laboratory compaction device (25, 31, 49, 54, 60).

Weight, Velocity, Energy and Momentum of the Rammer.—Several investigators have sought to determine the effect of the dead weight and the dynamic effects of the rammer on the maximum dry unit weight and optimum moisture content as well as on the physical properties of compacted soils. This has been done by using rammers of different weights but holding the compaction effort per unit volume constant by controlling the height of drop of the rammer, the number of blows, and/or the number of layers constant, or by holding the momentum constant.

Proctor (38) performed a series of compaction tests at various compaction efforts with a 5¾-lb rammer. Similar tests at a number of compaction efforts were also made with a 10-lb rammer. The resulting maximum dry unit weights are compared in Figure 25 to indicate the difference in maximum dry unit weight for the two weights of rammers for a range of compaction efforts. The investigation, made on two soils (one a plastic clayey soil, the other a slightly plastic sandy soil), shows that the variance in unit weight attributable to the weight of the rammer is small (of the order of 1 pcf) when the compaction effort per unit volume is constant. Proctor found a similar variance in the indicated saturated penetration resistance (ISPR) due to the rammer weight; the 10-lb rammer producing higher values of ISPR than did the 5¾-lb rammer although the compaction efforts were held constant.

Sowers and Kennedy (74) used rammers weighing 5.5, 10, and 25 lb with heights of fall ranging from 3 to 18 in. in their study of factors that influence the effectiveness of compaction. Their results indicate that the velocity of the rammer had no discernible influence on the effectiveness of compaction. They also found that neither the weight nor the momentum of the rammer had discernible effect.

Maclean and Williams (31) and the Road Research Laboratory of Great Britain (60) reported the results of an investigation carried out to determine if the maximum dry unit weight and optimum moisture content obtained with the Modified AASHO test could be obtained if the procedure were altered by using a heavier rammer falling through only 12 in. They used a 15-lb rammer (falling 12 in.) that yielded the same amount of applied energy (180 in.-lb) as the 10-lb rammer falling 18 in. They also used a 12¼-lb rammer falling 12 in. and giving the same momentum as the 10-lb rammer. The dry unit weight-moisture content curves for the two methods yielding the same applied energy are shown in Figure 26. The point of maximum unit weight and optimum moisture content for

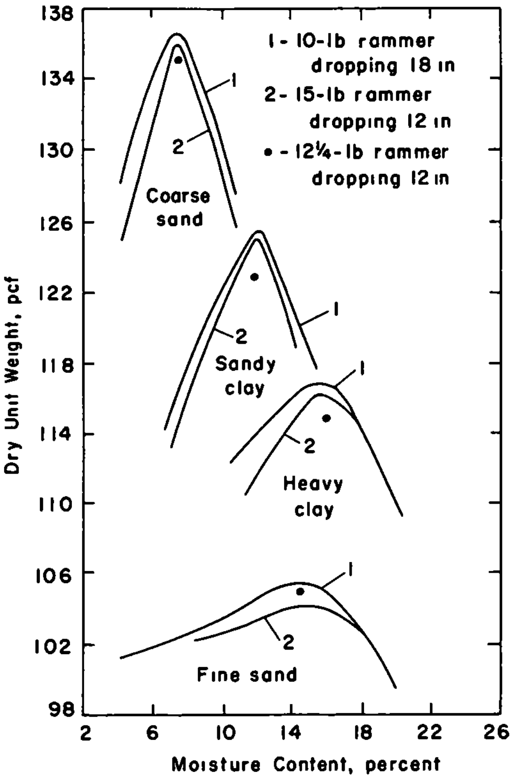


Figure 26. Dry unit weight vs moisture content relationships for four soil types using rammers of different weights dropping through different heights (60).

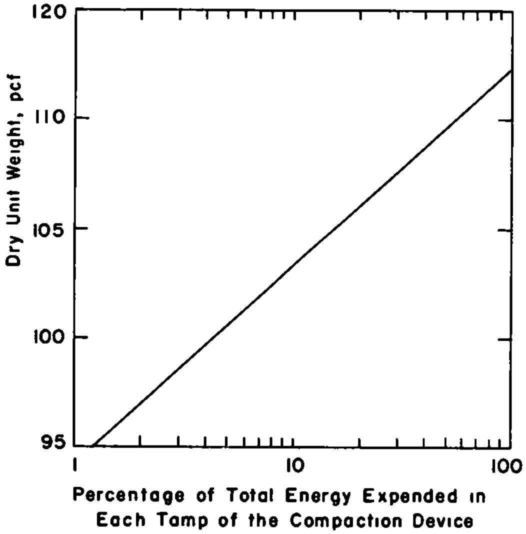


Figure 27. An example of the relationship between compacted unit weight of a soil (a low plasticity clay, AASHO Class. A-6) and percentage of total energy exerted by each tamp of the compaction device (74).

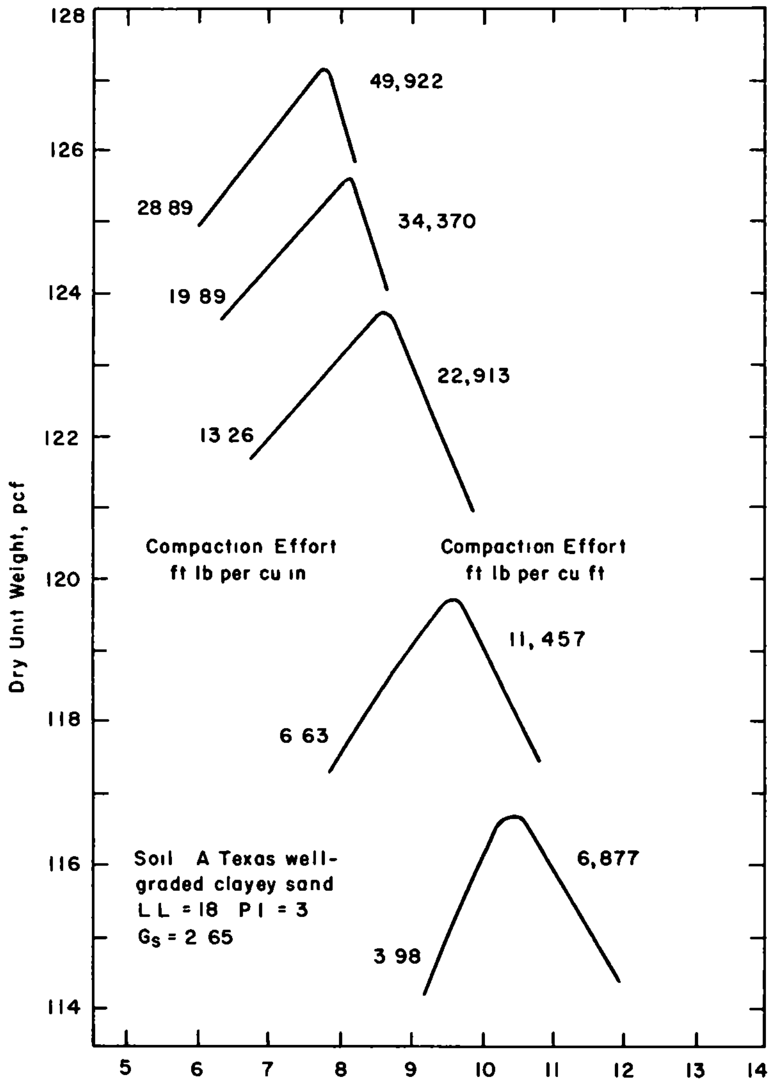


Figure 28. Effect of compaction effort on moisture content vs dry unit weight relationship for a clayey sand. Compaction effort for AASHO Designations: T99 = 12,375 and T180 = 54,986 ft-lb per cu ft (94).

the 12¼-lb rammer is indicated for each soil by the dot in the vicinity of the peak of each of the moisture content-unit weight curves.

For constant applied energy (compaction effort), the maximum dry unit weights attained by the two procedures, differed by less than 1 pcf and the optimum moisture content by less than ½ percentage unit. When momentum was kept constant, the difference was slightly greater but not completely beyond the limit of experimental error for reproducibility.

Percent of Total Compaction Energy Applied in Each Tamp. —Sowers and Kennedy (74) found that the most important factor influencing the effectiveness of compaction was the percentage of total energy that was applied in each tamp. The greatest unit weight in every case was produced when all the energy was utilized in a single application. The greater the number of tamps or blows required to apply the same amount of energy the smaller the resulting unit weight. This is brought out in the graph in Figure 27. The authors also expressed the effectiveness of compaction in terms of compaction ratio, the ratio of the amount of compaction to the work done in producing it. The compaction ratio is normally highest for the first pressure application and becomes less with each successive pressure application until it eventually approaches zero.

Diameter of the Rammer. —Sowers and Kennedy (74) found that the ratio of diameter of the rammer to the thickness of the soil layer is an important factor influencing the effectiveness of laboratory compaction. This may in some instances explain the differences in maximum dry unit weight obtained in different sizes of molds where the diameter of the rammer and its relationship to the layer thickness were also variables.

Jackson (132) compacted a sandy clayey silt into a ⅙-cu ft mold using different sizes of rammers and a constant compaction effort and found that increasing the diameter of the rammer foot from 2 to 3 in. increased the maximum dry unit weight of the soil from 98 to 100 pcf. With 4- and 5-in. diameter rammers he obtained a maximum unit weight of 98 pcf. The optimum moisture content in each case was about the same.

The ratio of diameter of the rammer to the diameter of the mold has been discussed with regard to the California Impact test (95) under "The Size and Shape of the Mold."

Total Energy Applied to the Soil. —The total energy applied to the soil, referred to here as compaction effort is the greatest single factor influencing the maximum unit weight and optimum moisture content in the compaction test. The degree of its influence has been described under the section "The Moisture—Unit Weight—Compactive Effort Relationship" in HRB Bull. 272 and in discussion of several subjects here that precede this paragraph. In addition, and because it is sometimes impractical to present data on other items without also including data on compaction effort, the subject of compaction effort is included in several discussions throughout the text.

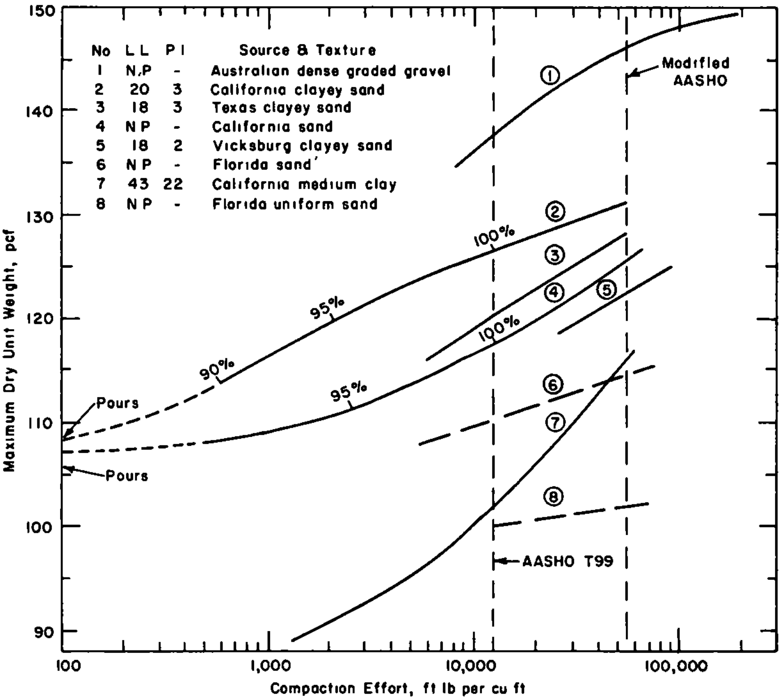


Figure 29. Relationships between compaction effort and the corresponding maximum dry unit weights, at optimum moisture contents, for each compaction effort. Sources of data for curves in the order shown are (85, 34, 95, 34, 48, 61, 34, 61).

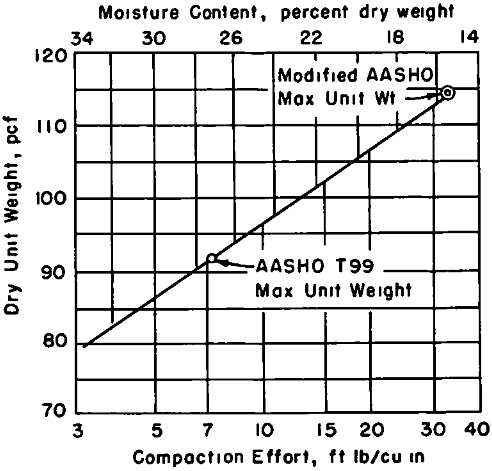


Figure 30. Compaction effort and moisture content vs unit weight at optimum conditions for various compaction efforts for a heavy clay soil (59).

Data presented in preceding sections has been limited to the influence of compaction effort on the maximum unit weight of the soil, although some evidence has been included relative to its influence on optimum moisture content. Figure 28 shows the maximum dry unit weights that result from the application of five different compaction efforts on a well-graded slightly plastic sand. The relationships between compaction effort and maximum dry unit weight for eight soils, for relatively wide ranges of compaction effort, are given in Figure 29.

That increasing the compaction effort increases the maximum unit weight and decreases the optimum moisture content has been stated as a general relationship governing compaction. The exact nature of this relationship is shown in Figure 30 from Dubose (59) based on data on a Texas Taylor Marl heavy clay soil (LL = about 70, PI = about 50, γ_d = 92 and OMC = 27). This figure shows how the optimum moisture content bears a direct relationship to compaction effort and the resulting maximum unit weight for this soil.

It is of further interest to observe the relative effects of compaction effort on a given soil at a number of different moisture contents as found by Dhawan (99). Figure 31 shows the rapid increase in unit weight for all moisture contents at the lower compaction efforts. For the values tested, the greatest effect of compaction effort occurs at a moisture content of 11 percent (1 percentage unit less than OMC) at which moisture content the unit weight continues to increase throughout the full range of compaction effort used in the tests. Slightly less effect of compaction effort occurs at a moisture content of 11 percent, and even less at 7 and 5 percent. On the wet side of optimum, the peak unit weight occurs at rather low compaction effort, and no further increase in unit weight occurs on application of greater compaction effort. Figure 32 shows the relationship between moisture content and compaction effort for given values of unit weight. Here, as in Figure 31, it is evident that for any given unit weight, the compaction effort required to obtain that unit weight decreases with increase in moisture content.

For those who may wish to study sources of data regarding compaction effort, the following references are suggested:

1. Compaction effort expressed in terms of number of blows per layer (see Fig. 33 as an example.) (7, 15, 19, 25, 43, 48, 85, 95).
2. Compaction effort expressed in terms of inch-pounds per cubic inch or foot-pounds per cubic foot (34, 35, 36, 51, 59, 61, 79, 84, 94, 95, 98, 104).
3. Compaction effort expressed in terms of moisture content-unit weight curves for two or more compaction test procedures (40, 41, 49, 60, 61, 62, 65, 66, 75, 77, 82, 86, 89, 100, 101, 103, 105, 113, 118, 119).

The Kneading-Type Compaction Test

The nature of the mechanically and manually operated types of kneading compactors is described under "Compaction by Mechanical Kneading-Type Compactors" and "Compaction by Manual Kneading-Type Compactors." All of these compactors operate on the principle that in any individual tamp, the pressure is gradually built up, then allowed to dwell on the sample for a brief period of time before being gradually released. The nature of this time vs pressure relationship may influence the resulting values of maximum dry unit weight and optimum moisture content.

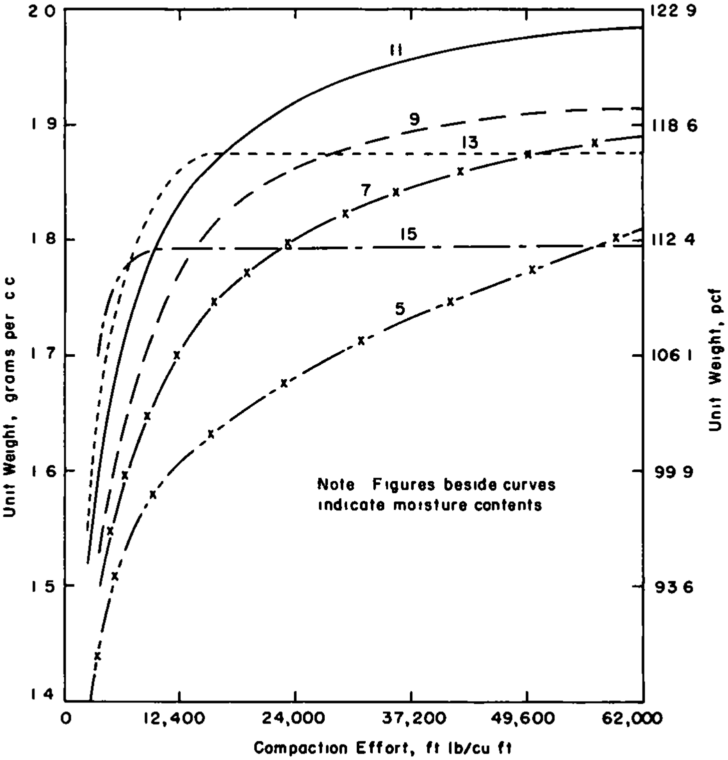


Figure 31. Relation between compaction effort and unit weight at various moisture contents. Soil contains 64 percent sand, 18 percent silt, and 18 percent clay. Maximum standard unit weight γ_d 116.4, OMC = 12 (99).

In the mechanically-operated compactors of either the pneumatic type (62) or the type employing a toggle-press mechanical system in conjunction with a hydraulic-pneumatic control system (52), the total time and pressure of the load application can be controlled except for minor differences in the shape of the time vs pressure relationship as is indicated by the time vs pressure traces in Figure 34. The degree in which these small differences in time vs pressure influence the maximum unit weight and optimum moisture content is not known. In any instance, it is possible that the machines can be calibrated and small differences in maximum unit weight and optimum moisture content can be adjusted as desired by small adjustments of the time vs pressure relationships, if standard test requirements are set up for the kneading-type compactor.

The hand-operated University of California compactor (Fig. 34 d) produced a time vs pressure trace almost identical

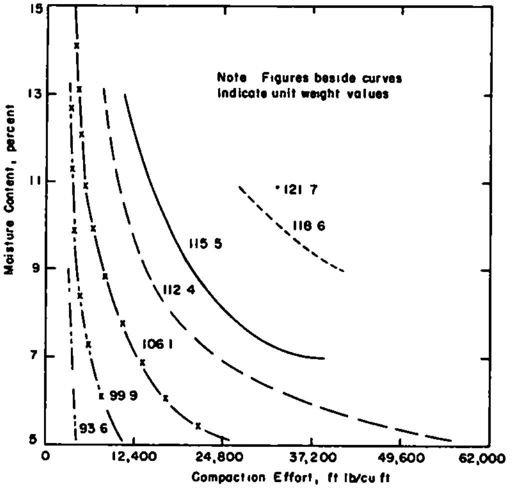


Figure 32. The relation between moisture content and compaction effort for given values of unit weight. Soil contains 64 percent sand, 18 percent silt, and 18 percent clay. Maximum standard unit weight γ_d = 116.4, OMC = 12 (99).

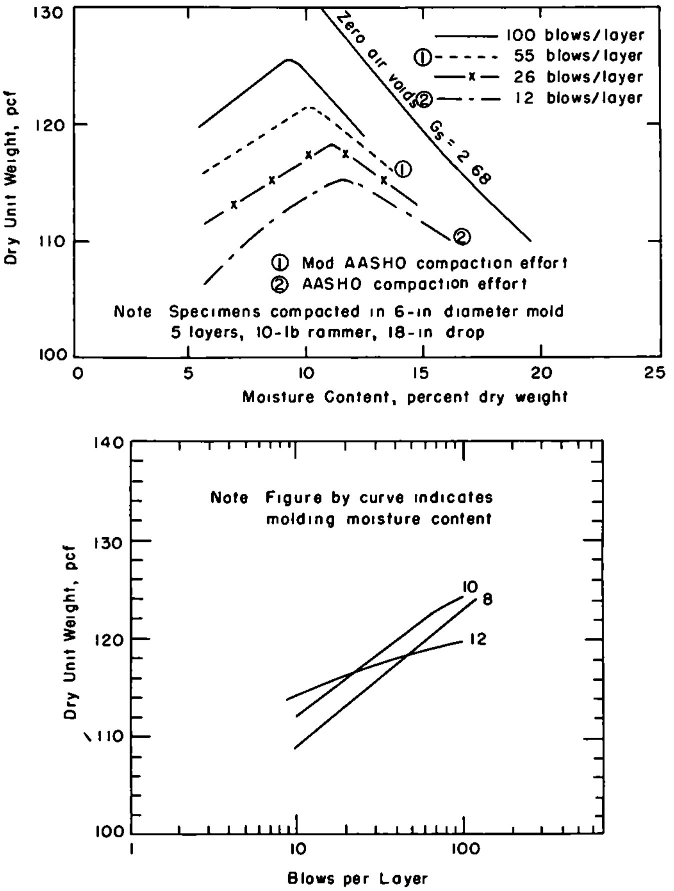


Figure 33. Laboratory compaction data. Soil is uniformly graded between sieves Nos. 30 and 80 and has 82 percent sand, 2 percent silt, 16 percent clay, LL = 18, PI = 2, G_s = 2.68 (48).

with that of the mechanically-operated kneading compactor from the same laboratory (Fig. 34 b). Examples of compaction curves for each of seven different compaction efforts for the Triaxial Institute compactor are shown in Figure 35.

McRae and Rutledge (62) found from tests with their Northwestern University air-operated kneading compactor that the position of the optimum moisture content could be shifted toward or away from the zero air voids curve; that is, the percentage of saturation could be increased or decreased by increasing or decreasing the time that the foot pressure acts on the soil. As the period of time of application of foot pressure was increased, the unit weight and the optimum moisture content increased slightly, moving nearer to the zero air voids curve, as is shown in Figure 36. Wilson (53) also found a similar tendency of moving the line of optimum moisture contents (on increasing the compaction effort) nearer to the zero air voids line. Wilson's tests were made on a Clinton, Miss., clayey sand (40) (LL = 18, PI = 2) and on a Vicksburg silty clay (41) (LL = 37, PI = 14) with a Harvard miniature kneading compactor. The McRae-Rutledge tests were also made on a Vicksburg silty clay. The effect of this change in position of the optimum moisture content with respect to the degree of saturation on the properties of compacted soils, and comparison with results from impact compaction is discussed under "Standard AASHO-ASTM Methods vs Kneading-Type Compaction."

In the Harvard miniature compactor, the operator may vary the optimum moisture content and the maximum unit weight by changing the number of layers, the number of tamps per layer or by changing the spring pressure. The spring pressure may be controlled by loosening or tightening the nut that controls the compression of the spring, or by using different springs. Examples of the range in maximum unit weights that may be expected on the Clinton, Miss., clayey sand by varying the individual components (number of layers, tamps per layer, and spring) are shown in Figure 37. The effect of the small end area of the tamp or the effect of sidewall friction of the small mold for all soil types on the maximum unit weight and optimum moisture content are not known. Also data on the reproducibility of the test are not available.

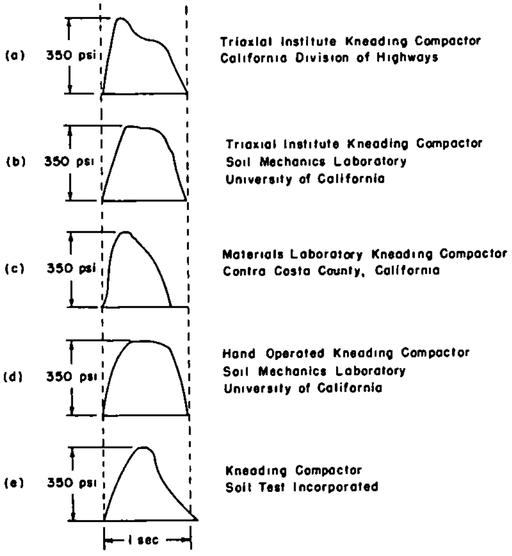


Figure 34. Typical pressure vs time relationships for five kneading compactors (91).

At the present time there is no standard test method for determining maximum unit weight and optimum moisture content that applies to the kneading-type compactor nor is there a specification governing the form of the pressure vs time relationship. A standard test method, AASHO Designation: T 173-56 is available for compacting soil specimens for the expansion pressure test (AASHO Designation: T 174-56) and for the Hveem Stabilometer test (T 175-56).

The Vibration Compaction Test

As far as is known, only two organized investigations have been made to compare the results of laboratory vibratory compaction test methods (51, 120). In the ASTM investigation, (120) several organizations cooperated in testing compaction test procedures, which included six methods involving sustained vibration. Information on apparatus and procedures for those six methods is given in Table 3 to the right of lines 1, 2, 3, 4, 9, and 10. The second column gives the type of test and the number used by Felt (120) in his report of the cooperative investigation.

Six soils were tested by each of the cooperators. All soils were of nonplastic nature. Grain size distribution curves for the six soils are shown in Figure 38. Each cooperator investigated a different method of vibratory compaction, although it may be seen from Table 3 that in some instances only small differences were involved.

The ranges of maximum unit weight obtained by the various cooperators using different laboratory apparatus and procedures for placing and vibrating the material are shown in Figure 39. For the fine and medium sands, test methods 7 through 10 attained maximum unit weights that fall within a rather narrow range but there exists a wide spread in unit weights for the coarser materials.

Various factors may influence the results of vibratory compaction:

1. Moisture content;
2. Frequency;
3. Surcharge;
4. Period of time vibrated;
5. Amplitude (displacement); and
6. Soil type.

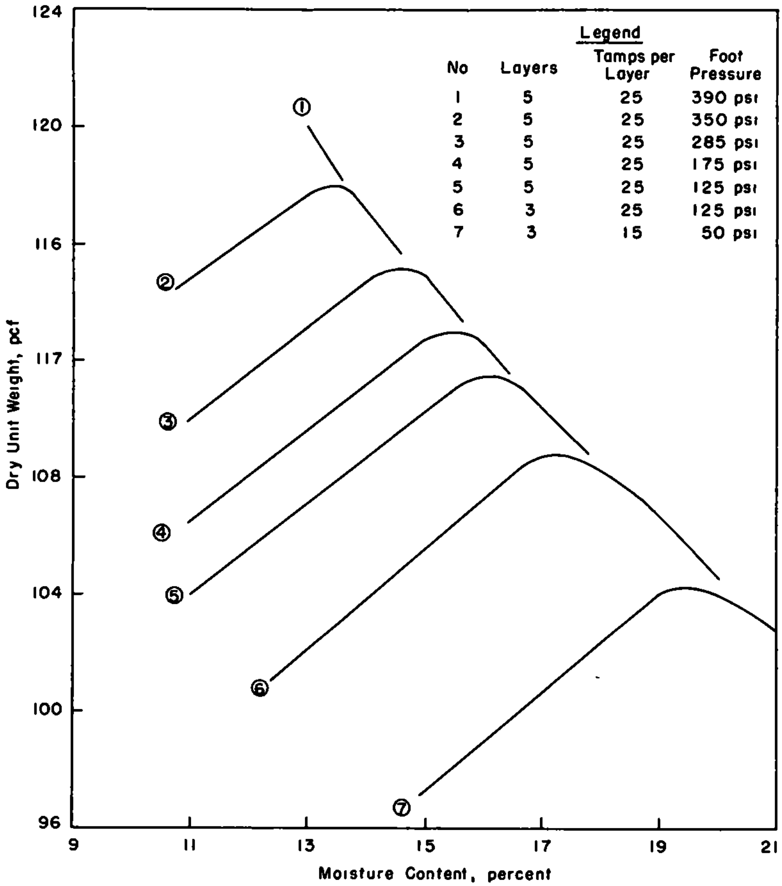


Figure 35. Relationship between moisure content and dry unit weight for several compaction efforts of a kneading compactor. Soil is a Vicksburg silty clay with LL = 37, PI = 14 (73).

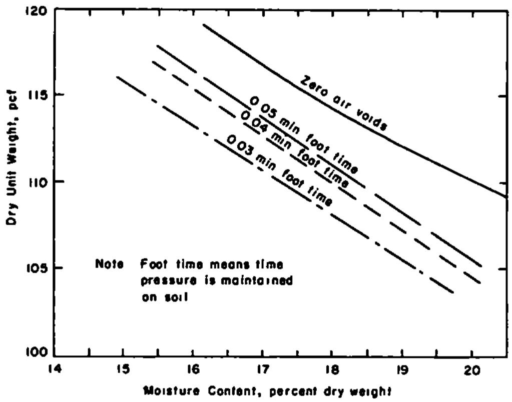


Figure 36. Effect of foot time on the position of the optimum moisture content for Northwestern University kneading compactor. Soil is a Vicksburg silty clay LL = 37, PI = 14, G_s = 2.72 (62).

Data available on the compaction results and the factors influencing the vibratory tests used in the ASTM investigation are given in Table 10. An analysis of the data in Table 10 shows that the order of maximum unit weights from highest to the lowest were associated with the following conditions:

1. (137.0 pcf) compacted wet, second longest period of vibration, low surcharge, moderately high frequency;
2. (132.6 pcf) compacted wet and dry, (highest value given), longest period of vibration, low surcharge, moderately high frequency;
3. (131.8 pcf) compacted dry, moderate period of vibration, low surcharge, high frequency;
4. (127.5 pcf) compacted dry, relatively short period of vibration, low surcharge,

moderately high frequency;

5. (127.3 pcf) compacted wet, moderate period of vibration, high surcharge, low frequency (exact range of frequencies of vibrations induced by horizontal blows on mold not known);

6. (115.3 pcf) compacted dry, time period of vibration not known, because this is a vibrating tamper, surcharge weight not known.

The amplitude is given in Table 10 for only two of the six methods.

Analysis of the data fails to show that any one of the several potential factors of influence included under compaction effort has a marked effect on the unit weights attained. The size of the mold or manner of placement of material may also have had some influence on the vibrated unit weight. Molds ranged from 2 to 6 in. in diameter.

In addition to the ASTM tests (120), the Corps of Engineers (51), in June 1945, proposed that a laboratory compaction device developed by the Barber-Greene Company be used in one phase for its study of compaction. The Barber-Greene laboratory vibratory compactor consists essentially of two counter-rotating shafts fitted with eccentric weights. The vibrator is shown in Figure 40. The compaction effort may be varied in three ways: (a) by changing the magnitude of the eccentric weights, (b) by varying the frequency by changing the sizes of the driving and driven pulleys, thus altering the speed of rotation, and (c) by applying surcharge weights to the platform mounted above the helical springs. The machine is equipped with a recording arrangement so that an approximate measure of the amplitude of vibration is traced on a tape. Recordings showed that an increase in surcharge weight tends to decrease the amplitude of vibration and an increase in eccentric weight tends to increase the amplitude of vibration. Traces were obtained for 0-, 20-, 60-, and 100-lb surcharge weights and for 1.54-, 2.57-, and 3.59-lb eccentric weights.

Ten soils were employed in the Corps of Engineers tests (51) with the Barber Greene vibrator. These soils consisted of eight cohesionless sands, a clayey sand (40) and a silty clay (41); the latter two having been used in full-scale rolling

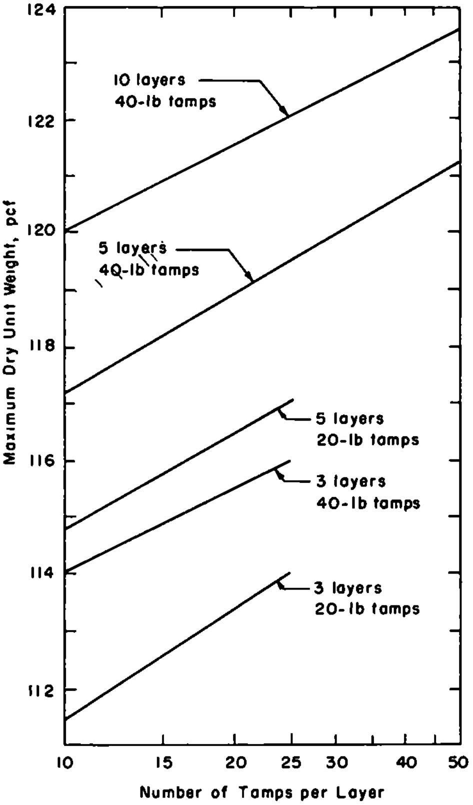


Figure 37. Effect of varying spring, number of layers, and number of tamps per layer in Harvard miniature compaction. Soil is clayey sand from Clinton, Miss., LL = 18, PI = 2, G_s = 2.68 (53).

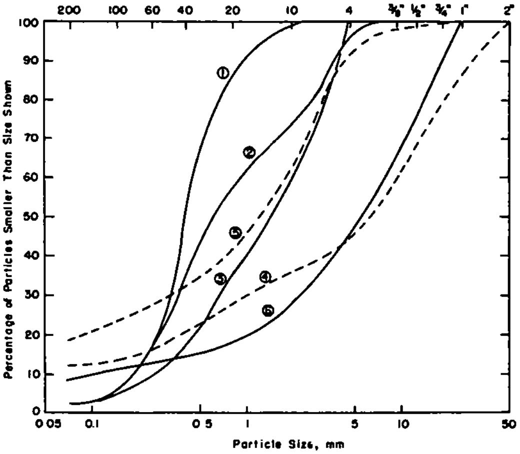


Figure 38. Average gradation curves of the six granular soils used in the cooperative studies of laboratory compaction methods (120).

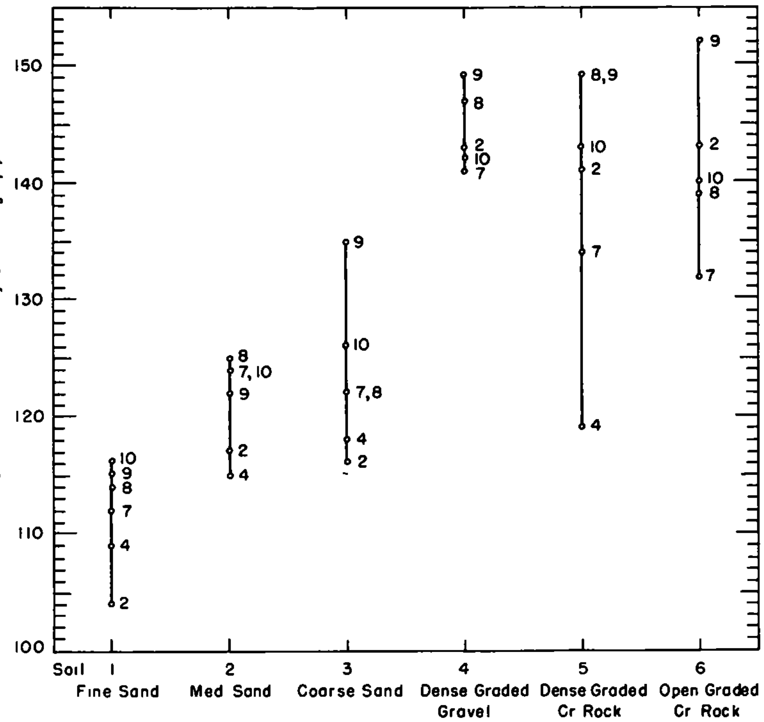


Figure 39. Maximum dry unit weights attained by six different methods of vibratory compaction of six non-cohesive granular soils (see Fig. 37 for grain size distribution of soils). Numbers beside bar graph are Felt's test method numbers (120).

TABLE 10

COMPARISON OF RESULTS OF SEVERAL LABORATORY VIBRATORY COMPACTION TEST METHODS (120)

Method[a]	Felt (121) Method	Average Max Unit Wt for All Soils (pcf)	Order of Magnitude of Avg Max Unit Weight	Moisture Content[b] (%) Always Dry	Always Wet	Sometimes Wet Sometimes Dry	Frequency (cpm)	Surcharge (psi)	Period of Time Vibrated (min)	Amp (in)	Source Refer
8	2	127 3	5		100 8 7		1,000	70	16	Not known	102
10	4	115 3	6	100			14,000	Not known	Not known	Not known	120 121
1	7	127 5	4	100			3,600	1	8 or more	0 012	120
3	8	132 7	2			100 7 3	3,500	3	30	Not known	120
2	9	137 0	1		100 9 7		3,600	1 75	20 or more	Not known	120 121
4	10	131 8	3	100			7,200	1 75	-c	1/32	120

[a] From Table 3

[b] Values are averages for the tests made using moisture

[c] Vibration until change in height is less than 0 001 in in 2 min

tests. All except two of the sands were uniformly graded, one being moderately well graded, the other being a well-graded gravelly sand. The grain size distributions of the soils are shown in Figures 41 and 42.

All soils were tested through the normal range of moisture contents in the Modified and Standard AASHO tests. Moisture contents on some of the soils were observed before and after compaction. For the lower values of initial (before compaction) moisture content, the values before and after compaction were in agreement. However, for the cohesionless sands, a moisture content was reached where drainage occurred and the water content after compaction was markedly lower. The magnitude of the retained

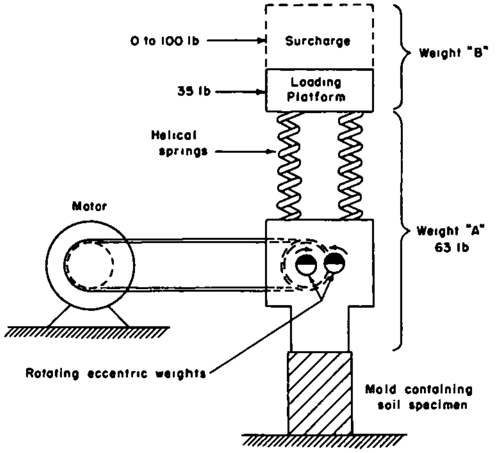


Figure 40. Barber-Greene vibratory compactor (51).

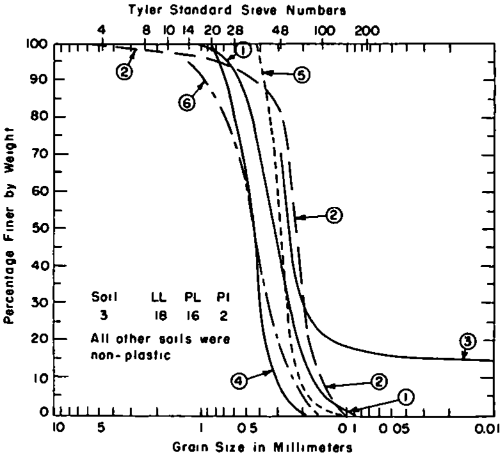


Figure 41. Grain-size distribution for six of the soils tested with the Barber-Greene laboratory vibrating-type compactor (51).

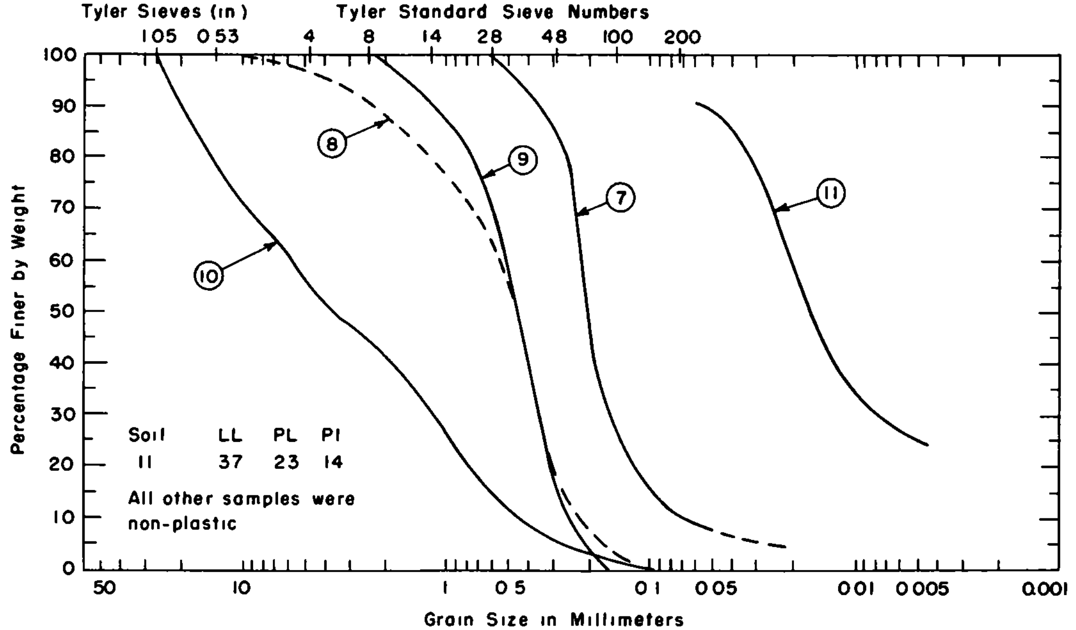


Figure 42. Grain-size distribution for soils tested with the Barber-Greene laboratory vibrating-type compactor (51).

water content bore a relationship to the mixing water content, being greatest for the greatest initial water contents. This is shown in Table 11 for soils 1, 2, and 9.

All soils were tested dry in the vibration test except for sand 2 (see Fig. 41) which was also tested submerged; a clayey sand (soil 3) tested at approximately Modified AASHO optimum moisture content; and, a silty clay (soil 11) tested at a water content

TABLE 11

RELATIONSHIP BETWEEN MIXING WATER CONTENTS AND WATER CONTENT AFTER THE STANDARD AASHO COMPACTION TEST FOR THREE COHESIONLESS SANDS (51)

Sample No.	Mixing Water Content (%)	Standard AASHO Test	
		Water Content After Compaction (%)	Saturation After Compaction (%)
1	10	9.9	42
	14	13.6	60
	20[a]	16.9	75
	25[a]	18.4	88
2	10	9.7	38
	20[a]	18.0	73
	25[a]	19.8	83
9	10	9.9	53
	14[a]	12.1	67
	20[a]	13.6	82

[a] Visibly saturated before compaction.

between optimum for the Modified and Standard AASHO tests. Soils 3 (40) and 11 (41) are similar to those employed in full-scale rolling tests.

Data on unit weights attained in the Modified and Standard AASHO tests and in the vibration test are compared in Table 12. These results were obtained with the machine operating at 2,020 rpm and using an eccentric weight of 2.57 lb and surcharge weights of 0, 20, 40, 60, and 100 lb. The surcharge weight appeared to bear no well-defined relationship to maximum vibrated unit weight in some of the tests. Therefore, only the surcharge weights corresponding to the maximum vibrated unit weights are given in the table.

It may be seen that small differences occur between the maximum dry unit weights of the Standard and Modified AASHO tests for sands. In fact, Standard AASHO maximum unit weight is greater than Modified AASHO maximum unit weight for three of the seven soils where data for comparison are available. Maximum vibrated dry unit weights were greater than those for the two impact compaction methods (Standard and Modified AASHO) for six of the eight cohesionless sands (102 to 105 percent of Modified AASHO) for which comparable data are available.

Table 13 gives dry unit weights obtained for soils 1 and 3 for different magnitudes of eccentric weights. Soil 3 was tested dry and at a moisture content of 14.3 percent. The amplitude of vibration of weight A is also shown in the table.

The Static Compression Compaction Test

Data are not available showing the effect of certain variables in the test apparatus and procedure on the maximum unit weight and optimum moisture content obtained in the static compaction test. It is believed that the following factors influence compaction and should be borne in mind in performing the test:

1. Type of soil. Granular soil with tendency to segregate should be placed carefully if results are to be reproducible.

2. Thickness of specimen. The greater the thickness of the specimen the greater the possibility of nonuniformity in unit weight from top to bottom of mold, if compacted from one end only, or from end to center if compressed simultaneously from both ends.

TABLE 12

SUMMARY OF DATA COMPARING MAXIMUM DRY UNIT WEIGHTS FROM STANDARD AND MODIFIED AASHO COMPACTION TESTS WITH RESULTS FROM BARBER-GREENE LABORATORY VIBRATING-TYPE COMPACTOR (51)

Soil No.	Maximum Dry Unit Weights from Tests				
	Modified AASHO (pcf)	Standard AASHO (pcf)	Barber-Greene Compactor		
			Surcharge Weight (lb)	Water Content (%)	Dry Weight (pcf)
1	103.8	106.8	0	0	109.1
2	102.5	101.1	0	0	106.6
3[a]	122.0	116.2	100	0	100.7
			40	10.1[b]	112.9
4	107.4	108.1	0	0	107.2
5	105.1	104.4	0	0	105.3
6	108.4	-	0	0	110.1
7	110.1	107.6	0	0	114.6
8	112.1	113.7	0	0	116.4
9	116.4	115.7	60	0	116.2
10	124.5	-	-	-	-
11[c]	114.0	104.2	100	15.4[d]	95.4

[a] A clayey sand used in full-scale rolling tests (40).

[b] Approximately Modified AASHO optimum moisture content.

[c] A silty clay used in full-scale rolling tests (41).

[d] Between Modified and Standard AASHO optimum moisture content.

3. Distribution of soil in the mold. Soil needs to be carefully distributed in mold and preferably should be tamped lightly to insure uniform compression.
4. The nature of compression. Compression from both ends simultaneously tends toward higher unit weight, and better uniformity. The rate of compression and time of load application may affect the value of maximum unit weight. Prolonged application of the static load at or above optimum may squeeze water out of the soil and yield an excessively high maximum unit weight and a nonrealistic optimum moisture content. The magnitude of the unit pressure may be too high or too low depending on the soil type and the purpose for which the moisture content-unit weight relationship is being determined.
5. The moisture content bears a relationship to maximum unit weight in static compaction that is quite similar to the relationships for impact and kneading compaction.

Static compaction does influence the physical properties of soils in that the properties obtained under static compaction differ slightly from those obtained on specimens compacted under the impact or the kneading-type methods.

EFFECT OF SOIL TEMPERATURE

Increasing the soil temperature tends to increase the maximum unit weight and decrease the optimum moisture content. Lowering the temperature makes the water in the soil more viscous and thereby reduces the workability of the soil. Hogentogler (6) reported the results of compacting three different soils at 35, 75, and 115 F. The compaction curves are shown in Figure 43. The index properties of the three soils are given in Table 14.

The Arlington soil is a slightly plastic silt loam; the Iredell and red clay soils have high plasticity and volume change characteristics. The differences in maximum unit weight due to temperature at which the soils were compacted was 2.0 pcf for the Iredell, 2.8 pcf for the Arlington and 3.6 pcf for the red clay soil.

TABLE 13

EFFECT OF ECCENTRIC WEIGHTS ON DRY UNIT WEIGHTS OF COHESIONLESS SANDS (51)
(Barber-Greene Vibratory Compactor)

Soil No.	Surcharge (lb)	1.54-Lb Eccentric Weight[a] Dry Weight (pcf)	1.54-Lb Eccentric Weight[a] Water Content (%)	1.54-Lb Eccentric Weight[a] Amplitude (Wt. A) (in.)	2.57-Lb Eccentric Weight[a] Dry Weight (pcf)	2.57-Lb Eccentric Weight[a] Water Content (%)	2.57-Lb Eccentric Weight[a] Amplitude (Wt. A) (in.)	3.59-Lb Eccentric Weight[a] Dry Weight (pcf)	3.59-Lb Eccentric Weight[a] Water Content (%)	3.59-Lb Eccentric Weight[a] Amplitude (Wt. A) (in.)
1	0	102.6	0	0.08	110.5	0	0.26	109.8	0	0.25
	20	103.4	0	0.06	107.1	0	0.22	109.7	0	0.30
	60	101.5	0	0.05	106.4	0	0.20	109.4	0	0.26
	100	101.5	0	0.05	104.1	0	0.06	107.8	0	0.24
3	0	92.2	0	0.16	94.6	0	0.24	95.2	0	0.40
	20	92.5	0	0.14	97.6	0	0.20	97.1	0	0.36
	60	90.9	0	0.03	98.6	0	0.20	98.9	0	0.28
	100	88.2	0	0.02	99.3	0	0.24	100.3	0	0.28
3	0	108.8	14.3	0.20	111.7	13.6	0.24	113.4	14.2	0.40
	20	110.0	14.3	0.18	112.7	13.6	0.28	113.3	14.2	0.35
	60	112.4	14.3	0.16	114.2	13.6	0.20	113.5	14.2	0.28
	100	103.8	14.3	0.04	115.1	13.6	0.20	114.8	14.2	0.20

[a] Sum of both rotating eccentric weights.

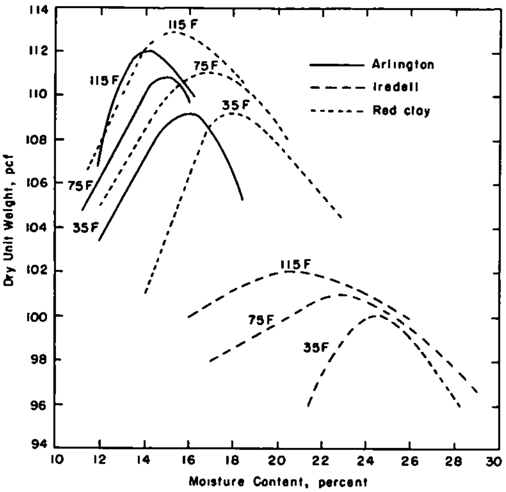


Figure 43. Effect of temperature on unit weight of different soils (6).

Somewhat similar tests were performed by Belcher (14) on two soils: one a sandy soil, the other a silty clay soil. Standard AASHO Method: T 99 compaction tests were performed at temperatures of 35 and 75 F. The differences obtained, shown in Figure 44, were somewhat greater than from the Hogentogler tests (6), the sandy soil showing a difference in unit weight of 2.3 pcf for a temperature difference of 40 F and the silty clay a difference of 10.5 pcf for the 40 F temperature difference.

The effects of low temperatures have been investigated by the New York State Department of Public Works (131). Figure 45 shows Standard AASHO and Modified AASHO compaction curves for a fine sand, compacted at 74, 30, 20, and 10 F. Figure 46 shows similar curves for a gravelly sand. The data in Figures 45 and 46 show that low temperatures have a very marked influence in reducing unit weights obtained under given compaction efforts.

EFFECT OF METHOD FOR DETERMINING SOIL MOISTURE CONTENT

The procedures for the standard compaction tests (AASHO Designation T 99-57 and T 180-57, and ASTM D 698-57T) require the use of a thermostatically controlled drying oven capable of maintaining a temperature of 110+ 5 C (230 ± 9 F) for drying moisture samples. Although some very special clays (44) may display drying curves (curves of moisture content vs temperature) that show a variation of approximately 1 percentage unit of moisture ± within the permissible temperature limits, all soils

TABLE 14

INDEX PROPERTIES OF SOILS USED IN STUDY OF EFFECT OF TEMPERATURE

Soil	Particle Size (mm)			Physical Characteristics		
	Sand 2.0 to 0.05	Silt 0.05 to 0.005	Clay less than 0.005	LL	PI	SL
Arlington	33	36	31	27	7	19
Iredell	22	20	58	78	55	12
Red clay	12	20	68	65	47	10

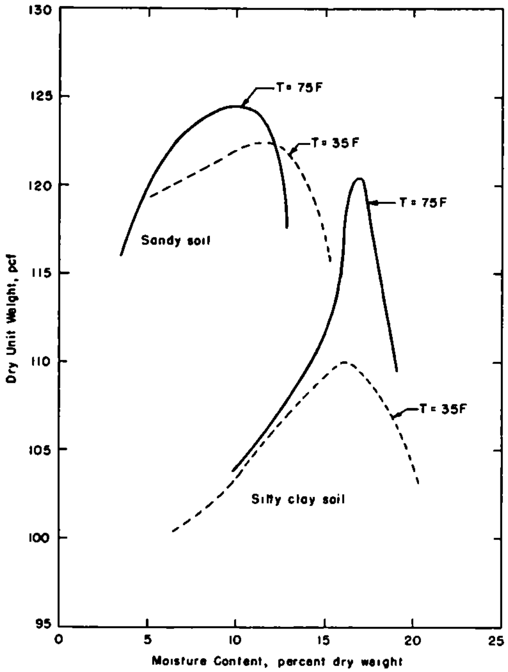


Figure 44. Effect of temperature on Proctor (AASHO Method: T99-38) maximum dry weight (14).

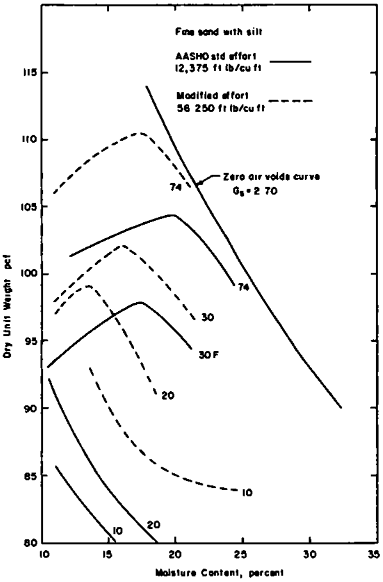


Figure 45. Effect of freezing temperatures on compaction of a silty fine sand (131).

normally suitable for use in subgrade and embankment construction should display drying curves showing a maximum of about ½ percentage unit of moisture ± for the permissible temperature range of ± 5 C (± 9 F).

Thus if drying is by oven, the accuracy of the moisture content and therefore also the dry unit weight, depends in the main on the accuracy of the oven temperature control. Carefully conducted tests (44) on non heat-distributing ovens have revealed that the temperatures in the oven chamber have varied, in a typical case, from 99.6 to 146.7 C, a variation of 47.1 C. Those temperatures were obtained from observations of thermometers placed on shelves of ovens supposedly "controlled" at 105 C. Search has not been made for comparable data on heat-distributing (forced draft) ovens. It may be well also to investigate their accuracy in temperature control under study conditions.

From this it may be concluded that the accuracy of the unit weights and moisture con-

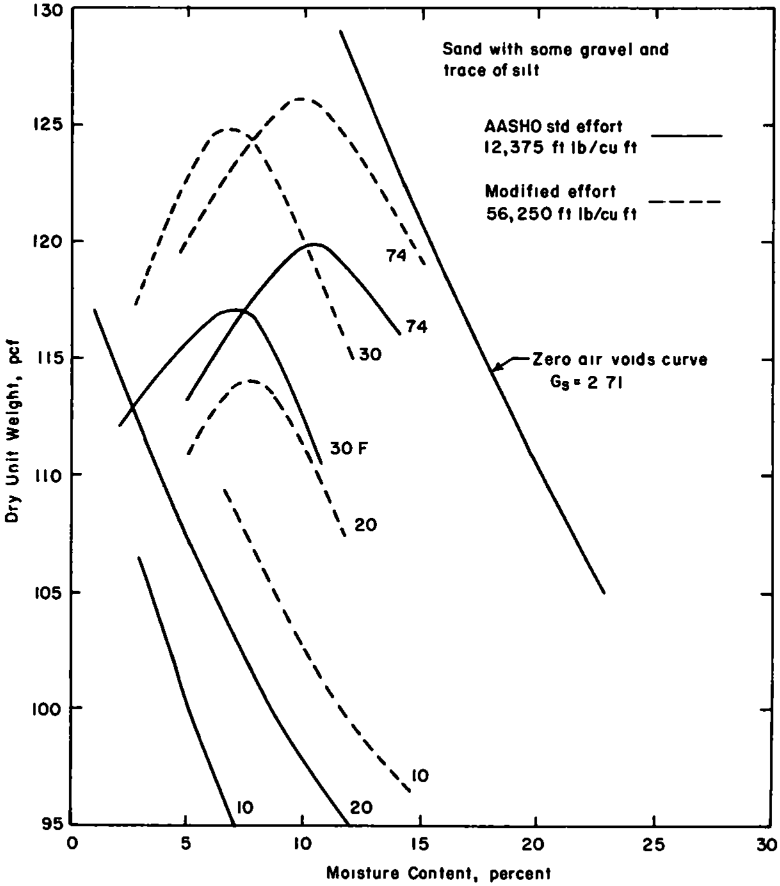


Figure 46. Effect of freezing temperatures on compaction of a gravelly sand (131).

tents observed in the compaction test are dependent in large measure on the apparatus and methods used in drying. If accuracy is desired the engineer should examine carefully the temperature ranges found in the various parts of the oven he uses for drying the soils to constant weight.

When the compaction test is performed in the field laboratory the moisture content may be determined by drying over an open fire or heating over a sand bath; by hot air, use of the Proctor needle, or alcohol dilution; by electrical, nuclear, or some other of the many known methods. Each method needs to be carefully checked against results obtained by oven-drying under satisfactorily controlled conditions.

EFFECT OF METHOD FOR DETERMINING VOLUME OF SOIL COMPACTED IN MOLD

A possible source of error in determining unit weights of soils compacted in the compaction mold is in determining the volume of the compacted specimens. This source of error does not exist for fine grain soils which can be "struck-off" accurately, leaving the top of the compacted soil flush with the top of the mold. However, for soils containing appreciable proportions of aggregates, the difficulty of accurately striking off the top of the specimen, to result in a specimen having a volume equal to that of the mold, becomes apparent.

Campen suggests the use of the sand-funnel (sand cone) apparatus of the type described in his work (121, p. 422) for measuring the volume of the unfilled portion of the mold extension (collar) instead of removing the extension and striking off the excess soil as prescribed in AASHO Designation T 99-57 and ASTM Designation D 698-57 T. An ASTM "Suggested Test Method for Measuring Volume of Compacted Samples in the Moisture-Density Relations Test" is available for preventing this possible source of error in determining the correct volume of the compacted soil. A similar device consisting of an appropriate size sand-funnel apparatus could be constructed for use with AASHO Designation: T 180-57.

DEPTH OF COMPACTED SOIL IN MOLD

Studies reported by Maclean and Williams (31) showed that in the Standard AASHO test (T 99), especially when a test is being made on a heavy clay, it is important that the three compacted layers should "only just more than fill the mold leaving little excess soil to be struck off." The tests showed that lack of care in following this precaution could affect the maximum dry unit weight by as much as 6 pcf and the optimum moisture content by as much as 4 percent.

EFFECT OF SOIL TYPE

Inasmuch as soils differ in "type" because they have different properties, it is axiomatic that the nature of the soil determines in large measure the value of maximum dry unit weight and optimum moisture content obtained in the compaction test. The influence of soil type has been discussed in general terms in HRB Bull. 272 under "The Moisture Content-Unit Weight-Compaction Effort Relationship—Effect of Soil Type." Eight compaction curves representing different types of soils are shown in Figure 47 to indicate the wide range of maximum dry unit weights and optimum moisture contents that can be expected for a wide range of "normal" soil types. In addition, the influence of gravel content on the unit weight of the total mix and on the unit weight of the soil mortar is shown in Figure 48, and on the unit weight of gravel soil mixtures in Figure 49. Further discussions have been included pertaining to the effect of soil type under the size and shape of the mold (Figs. 13 and 14), the effect of the rammer (Fig. 26), the effect of compaction effort (Fig. 29), and comparison of methods of compaction. All of these previous discussions, in some manner, indicate some effect of soil type. In fact, it is difficult to classify and discuss some variables that influence compaction without introducing data on soil type.

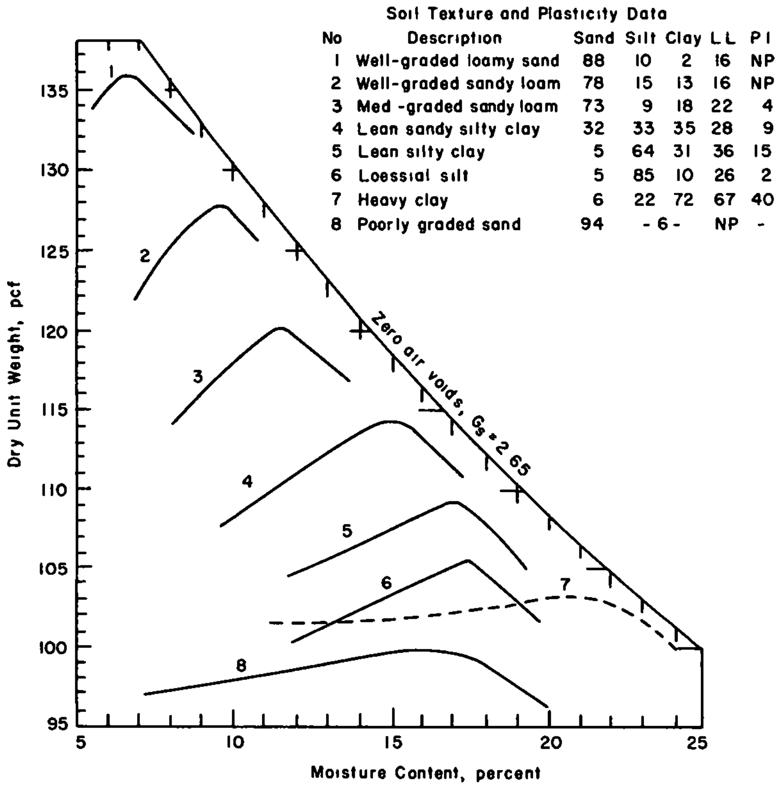
These previous discussions provide some information on the many facets of the effect of soil type but they fail to consider some of them as thoroughly as is desirable if the engineer is to appreciate their significance fully. Accordingly, there follows presentation of additional data that concerns the nature of the soil and includes some discussions of special soils and soils conditions that are not often encountered.

Effect of Coarse Aggregates

The task of performing the compaction test and applying its results as a means for control of compaction would be more simple if soils were composed entirely of particles passing a No. 10 sieve, for then the compaction mold could be relatively small in dimensions. However, because soils and shales often contain particles up to boulder size in dimensions, some size limitation must be placed on the size of the mold and on maximum size of particle included in the test. Also, some provision must be made for determining the influence of coarse particles on unit weight. The information pertinent to coarse aggregates and the compaction test that has been found in the literature, is summarized.

The Gradation and Type of Coarse Aggregates. —One of the early investigations of the effect of content of coarse aggregate on the unit weight of the total mix and of the soil mortar was that of Maddison (17). Maddison admixed single-size aggregates of hard cubical crushed rock of three sizes ($\frac{3}{8}$ to $\frac{1}{2}$ in., $\frac{1}{2}$ to $\frac{3}{4}$ in., and $\frac{3}{4}$ to 1 in.) to a silty clay (sand, silt, and clay contents of 58, 18, and 24 percent, respectively, LL = 26, PI = 5). The results of his tests are shown in Figure 48. In later work (60), an aggregate graded between $\frac{3}{4}$ in. and the No. 7 British standard sieve was used.

Maddison found that the admixture of up to about 25 percent single-size aggregate



Soil Texture and Plasticity Data

No	Description	Sand	Silt	Clay	L L	P I
1	Well-graded loamy sand	88	10	2	16	NP
2	Well-graded sandy loam	78	15	13	16	NP
3	Med -graded sandy loam	73	9	18	22	4
4	Lean sandy silty clay	32	33	35	28	9
5	Lean silty clay	5	64	31	36	15
6	Loessial silt	5	85	10	26	2
7	Heavy clay	6	22	72	67	40
8	Poorly graded sand	94	- 6 -		NP	-

Figure 47. Moisture content vs dry unit weight relationships for eight soils compacted according to AASHO Method: T99.

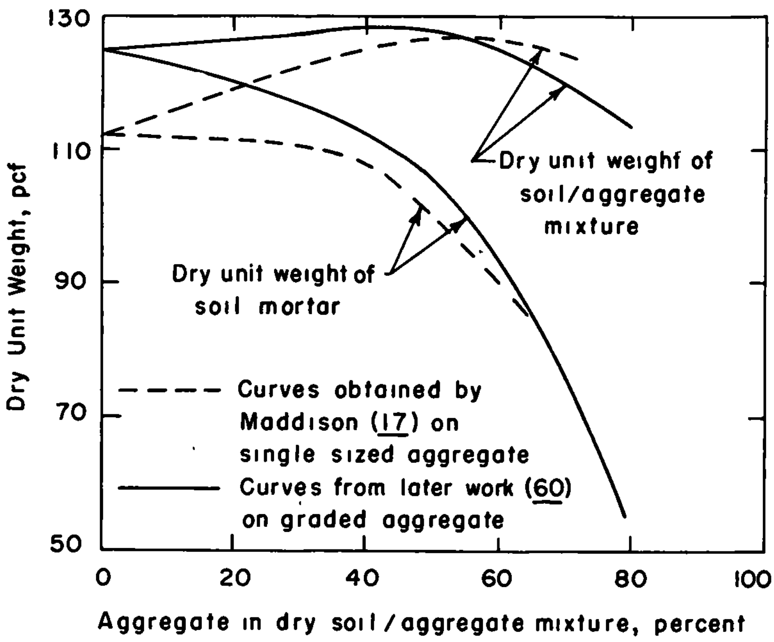


Figure 48. Compaction of soil mortar at optimum moisture content with different percentages of aggregate (17, 60).

of any of the three sizes stated above had little effect on the compaction of the soil mortar. The coarse aggregate merely acted as a displacer. At higher coarse aggregate contents, the dry unit weight of the soil mortar decreased rapidly. At a coarse aggregate content of 65 percent the unit weight decreased to about 75 percent of the unit weight of the soil when compacted alone. However, the dry unit weight of the total mix (soil plus coarse aggregate) continued to increase up to a coarse aggregate content of about 50 percent. At coarse aggregate contents of more than about 70 percent, contact between coarse aggregates prevented compaction of the soil mortar.

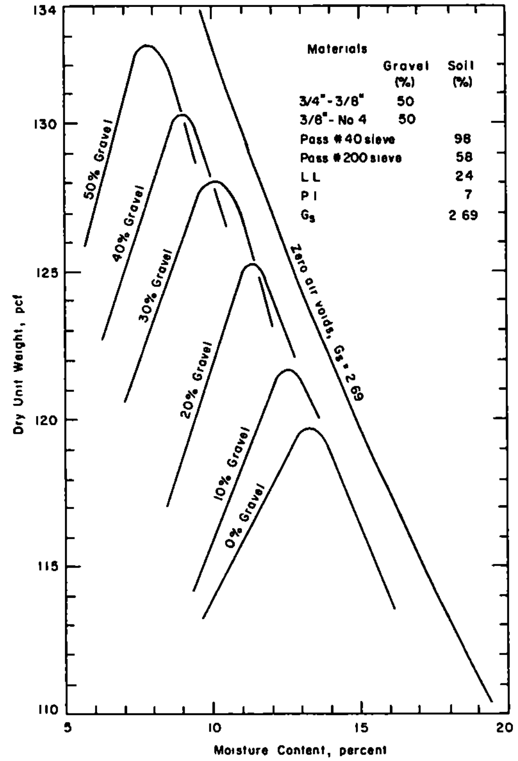


Figure 49. Effect of gravel content on moisture content vs unit weight relationship. Compaction according to AASHO Method: T99 (28).

The addition of a graded coarse aggregate yielded results somewhat similar to those obtained previously but the dry unit weight of the soil mortar decreased on the addition of even small proportions of the aggregate, as indicated in Figure 48. However, this decrease was of small magnitude until more than 45 percent of the aggregate had been added.

Zeigler's efforts (28) were directed toward developing a means for accurately computing the effect of coarse aggregate on unit weight of the total mix and then making actual determinations of maximum unit weight for gravel admixtures from 0 to 50 percent, in 10 percent increments. The index properties of the soil and the individual compaction curves of soil plus aggregate are shown in Figure 49. The methods used for computing the effect of the addition of coarse aggregate on maximum unit weight and optimum moisture content and the accuracy obtained are discussed under "Methods of Determining Maximum Dry Unit Weight and Optimum Moisture Content for Materials Containing Coarse Aggregates" for purpose of comparison. Although not drawn to the identical scale of those by Maddison, it is evident that the work of Zeigler shows a greater effect of gravel content on the unit weight of the total mixture. Zeigler's work was not carried to a gravel content sufficiently high to indicate a point of maximum unit weight for the total mixture, and beyond which additional gravel would cause a reduction in maximum unit weight of the total mix.

Maclean and William's test (31) showed that the maximum dry unit weights and optimum moisture contents did not vary considerably with the maximum size aggregate used in the standard laboratory test and except for samples containing 1½-in. size material, the test was performed without difficulty and test results were closely reproducible. Therefore the British standard test specified early the use of a maximum size of ¾-in. material.

Turnbull (32) held that it was not possible to compact particles having a maximum dimension greater than ⅜ in. into a standard cylinder.

The work of Mainfort and Lawton (64, 67) was essentially a study to determine the applicability of the Standard AASHO and Modified AASHO test apparatus and procedures for the compaction of prepared aggregate consisting of sand and gravel, crushed limestone and slag, although their studies did include observations of degradation of aggregates during compaction. They used total aggregates of each material consisting of

Size A (minus No. 4 sieve material); Size B (No. 4 to ¾-in. material); and Size C (¾-in. to 1½-in. material). The Minus No. 4 sieve material constituted the matrix. The materials were not admixed to a soil; each material existed or was crushed to furnish the full gradation used. Both 4- and 6-in. diameter molds were used. Volumes were 0.0333 and 0.075 cu ft. The Modified AASHO compaction effort was used in all tests. Several gradations were tested. These included mixtures of A + B, A + C and A + B + C for each of the main types of aggregates. Within each group, combinations were usually in terms of increments of 10 percent.

The essential part of their findings that are of interest here is the effect of gradation. Inasmuch as most aggregate gradings used in highway base course construction are continuous (not skip gradings) data summarized from the report and presented here

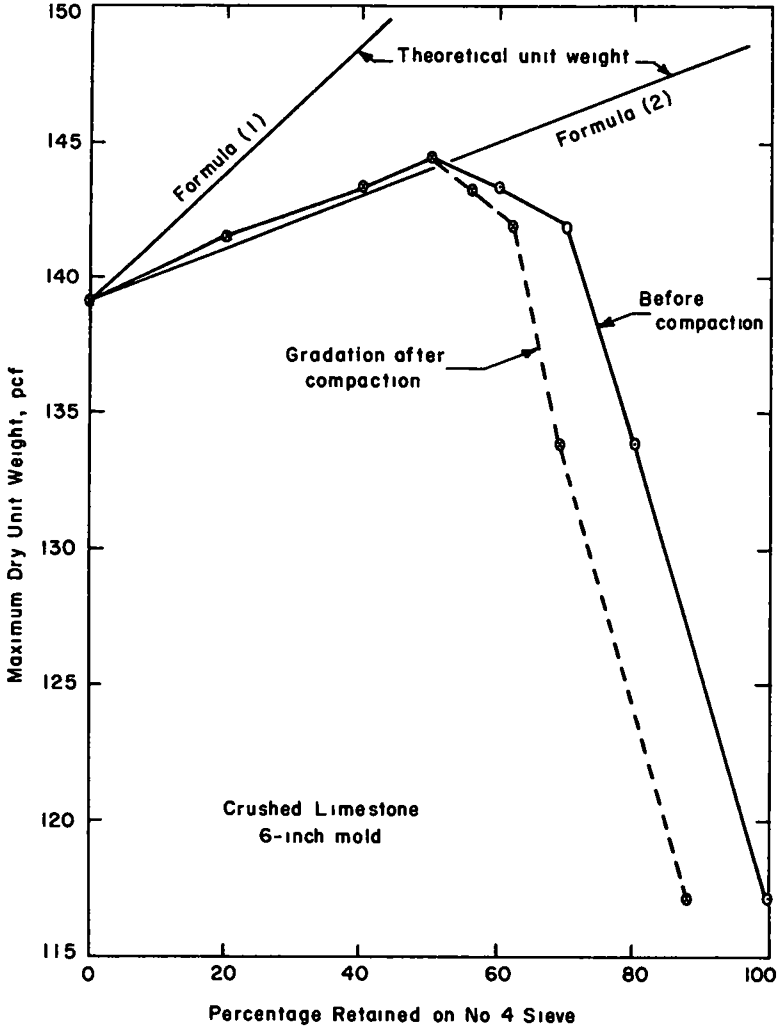


Figure 50. Gradation-unit weight relationships for a crushed limestone composed of fractions of minus No. 4, No. 4 to 3/4-in., and 3/4-in. to 1 1/2-in. sizes. The percentage retained on the No. 4 sieve, prior to compaction, consisted of equal portions of No. 4 to 3/4-in. and 3/4-in. to 1 1/2-in. material. Theoretical unit weight formulas (1) and (2) are discussed under "Correcting Maximum Dry Unit Weight for Coarse Aggregate Content by Computations" (64, 67).

are for the A + B + C gradings; that is, they include the minus No. 4 (Size A); the plus No. 4 to ¾-in. (Size B); and, the plus ¾-in. to 1½-in. (Size C) materials. All data are presented on the basis of dry unit weight vs percent retained on the No. 4 sieve. The effect of gradation is brought out in Figures 50 and 51. These figures show the maximum dry unit vs gradation in terms of percent retained on the No. 4 sieve. The figures also show the theoretical unit weight of the whole material vs the percentage re-

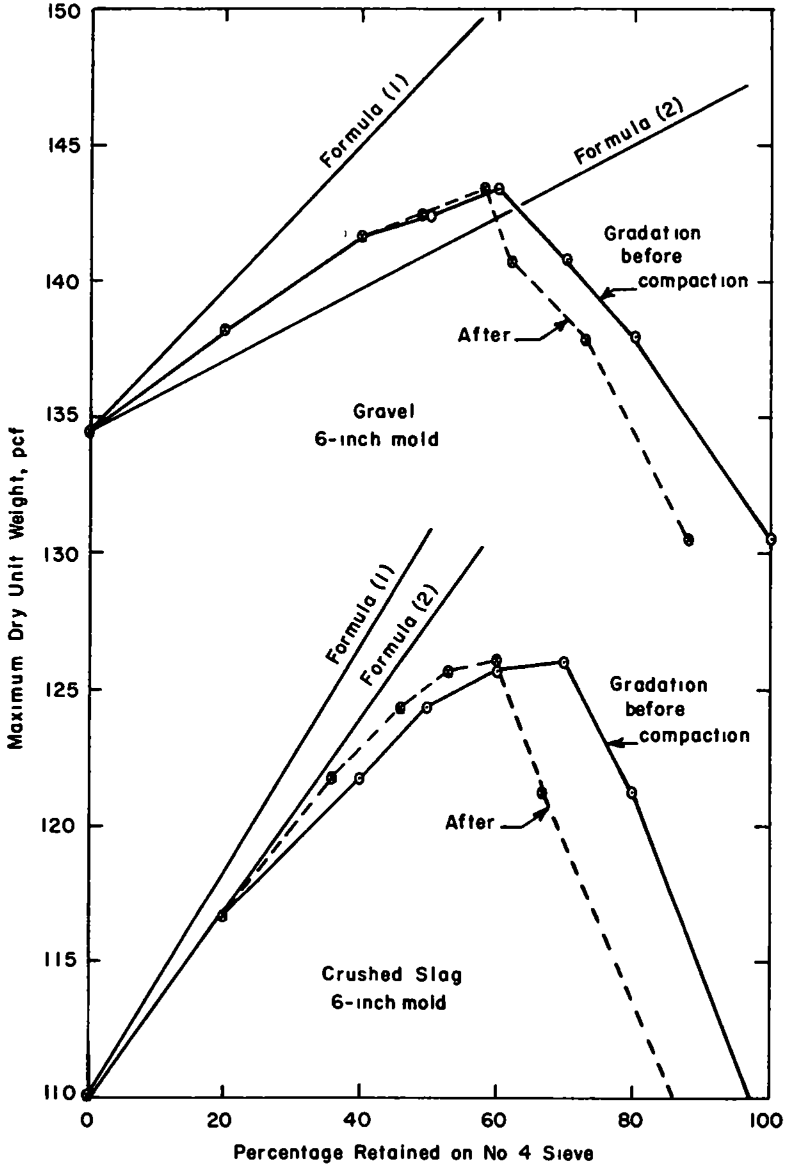


Figure 51. Gradation-unit weight relationships for a gravel and a crushed slag, each composed of fractions of minus No. 4, No. 4 to 3/4-in., and 3/4-in. to 1 1/2-in. sizes. The percentage retained on the No. 4 sieve prior to compaction, consisted of equal portions of No. 4 to 3/4-in. and 3/4-in. to 1 1/2-in. material. Formula (1) and (2) lines are discussed under "Correcting Maximum Dry Unit Weight for Coarse Aggregate Content by Computations (64, 67).

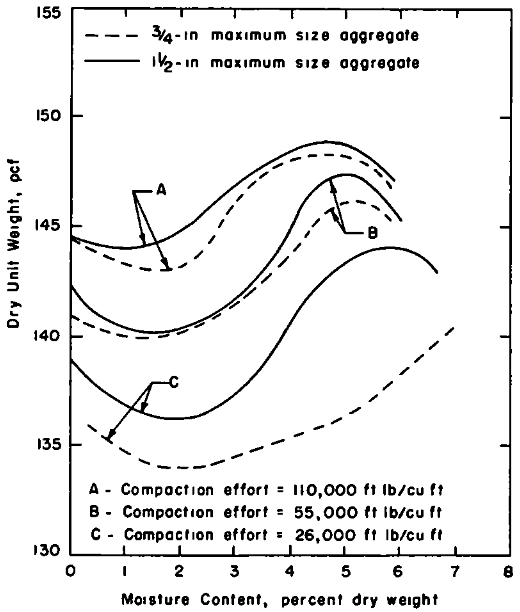


Figure 52. Comparison of results of laboratory compaction of graded crushed limestone with maximum size of 3/4 in. and 1 1/2 in. under three compaction efforts. Effort of 55,000 ft-lb per cu ft is approximately equivalent to that for Modified AASHO method (100).

tained on the No. 4 sieve as computed by two different equations. These computations are discussed later under "Correcting Maximum Dry Unit Weight for Coarse Aggregate Content by Computations." Figure 50 shows the variation in unit weight with plus No. 4 material for a crushed limestone; Figure 51 shows similar data for gravel and a crushed slag; all as compacted in the 6-in. mold. Similar curves were obtained for mixtures compacted in the 4-in. mold (see Fig. 14).

The effect of gradation on the maximum unit weight is clearly shown in the graphs. Except for combinations of very coarse fractions, all of the textures yielded an increase in dry unit weight with increasing coarse aggregate content up to an optimum gradation beyond which the unit weights decreased rapidly with increased amounts of coarse material. The optimum combination varied for the individual materials and with the particular fractions used to form the sample. In general, optimum unit weight was reached when the samples contained 40 to 60 percent plus No. 4 material. All samples exhibited degradation during the test.

The tests also showed that for normally graded materials, the size of the coarsest particle does not significantly affect the maximum unit weight at the optimum gradation. This indicates that smaller aggregate can be substituted for the larger without erroneous results in cases where it is desirable to limit the top size of the coarse fraction. All of the findings showing the effects of gradation on unit weight were consistent. The optimum point occurs at approximately the same gradation, regardless of mold size, indicating that the decrease in unit weight beyond this point is a function of gradation and is not due to arching or restriction in the mold.

Walker and Holtz (57) indicate that when soil and rock are compacted, unit weights start to fall below theoretical laboratory unit weight when the total material contains about 30 percent rock, the percentage causing interference may be as low as 25 percent in some materials. In some cases, theoretical unit weights were maintained for rock contents as high as 50 percent in extremely well-graded material. Individual measurements show an increment scattering in the zone beyond 40 percent rock content.

Turnbull and Foster (100) performed both field and laboratory compaction on graded crushed limestone base courses having ¾- and 1½-in. maximum size aggregates. The two aggregates were well graded and differed in gradation only above the No. 4 sieve (1½-in. maximum size had 100, 76, 55, 41, 32, 15, 10, and 9 percent passing the 1½-in., ¾-in., ⅜-in., No.'s 4, 10, 40, 100, and 200 sieves respectively). The results of the laboratory tests are shown in Figure 52 which shows that at low compaction effort the 1½-in. maximum size aggregate resulted in markedly higher maximum unit weight. At compaction efforts equivalent to or greater than that of the Modified AASHO the effect of the maximum size aggregate on maximum unit weight and optimum moisture content was relatively small.

Holtz and Lowitz (106) conducted an extensive series of tests to determine the compaction characteristics of gravelly soils. They performed the standard Bureau of Reclamation test (1/20-cu ft mold, 5.5-lb rammer, 18-in. drop, 3 layers, 25 blows per layer, 12,375-ft-lb per cu ft compaction effort) on three soils and on gravel-soil mixtures in

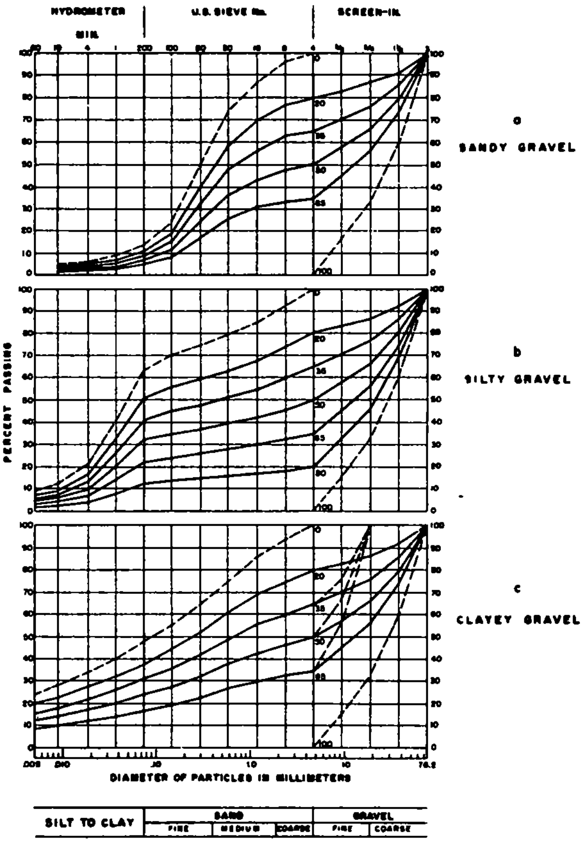


Figure 53. Gradation of the numerous mixtures used in investigation of compaction characteristics of gravelly soils (106).

TABLE 15

INDEX PROPERTIES OF SOILS USED IN COMPACTION TESTS (106)

Soil	Grain Size Fractions (%)					Unified Classification	G_s	Bureau of Reclamation	
	Sand 0.074mm-No.4	Silt 0.074-0.005mm	Clay -0.005mm	LL	PI			Max. Dry Unit Wt. (pcf)	OMC (%)
Sandy soil	86	10	4	NP	NP	SW-SM	2.67	116.1	-
Silty soil	35	56	9	26	4	ML	2.67	120.0	-
Clayey soil	52	24	24	49	28	CL-CH	2.70	105.9	-
$^3/_4$ in. max. size gravel	100[a]	100[a]	100[a]	-	-	-	2.66	107.1[a]	-
3 in. max. size gravel	100[b]	100[b]	100[b]	-	-	-	2.66	113.6[c]	-

[a] Between No. 4 and 3/4-in. sieves.
[b] Between No. 4 and 3-in. sieves.
[c] Large scale compaction test.

which the minus $^3/_4$-in. maximum size was used. They also performed large-scale compaction tests with a specially constructed mechanical compactor employing a mold of 291 sq in. by 9 in. deep (about $1\frac{1}{2}$ cu ft) a 185.7-lb rammer of 70.9-sq in. area, dropping 18 in. in a total number of 22 blows per layer on each of three layers and applying a compaction effort of 12,135 ft-lb per cu ft. The large apparatus was used to compact mixtures containing up to 3-in. maximum size gravel. Some results from the investigation have been discussed under "The Size and Shape of the Mold" (see

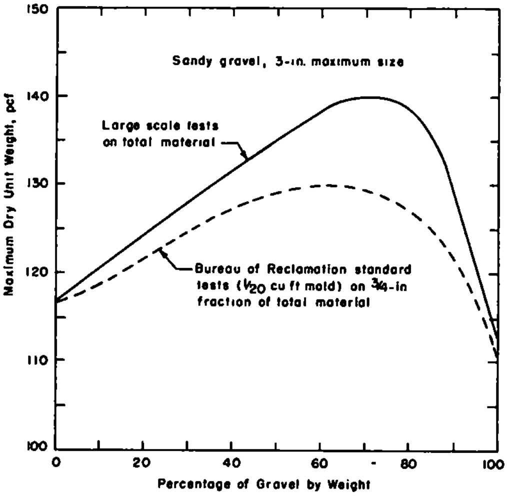


Figure 54. Relationship between maximum dry unit weight and gravel content. Fine soil fraction is nonplastic sandy soil of SW-SM group (106).

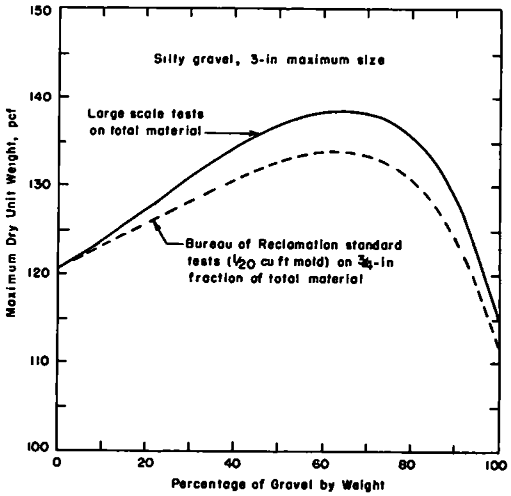


Figure 55. Relationship between maximum dry unit weight and gravel content. Fine soil fraction is silty soil of ML group with LL = 26, PI = 4 (106).

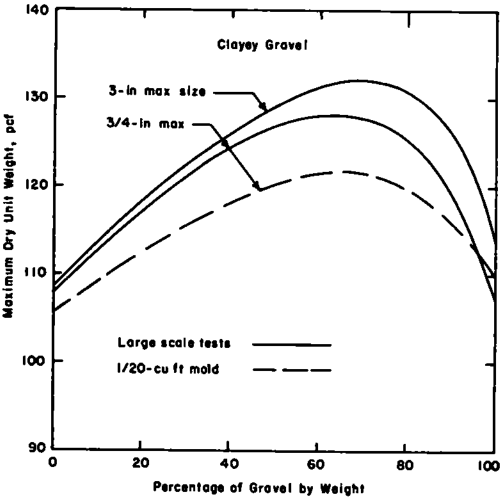


Figure 56. Relationship between maximum dry unit weight and gravel content. Fine soil fraction is clay of CL-CH group with LL = 49, PI = 28 (106).

Table 6) to bring out the effect of mold size on maximum dry unit weight and optimum moisture content of the minus No. 4 fraction.

The fine soils forming the matrix for the gravel mixtures consisted of a sandy soil, a silty soil and a clayey soil. The index properties of the soils are given in Table 15. The gradations of the mixtures of gravel and soil used for the compaction tests are shown in Figure 53.

The results of the compaction of the 3-in. maximum size gravel soil mixtures and the $^{3}/_{4}$-in. maximum size mixture with the large compactor are shown by the solid lines in Figures 54, 55, and 56. For all materials tested, the 3-in. maximum size, as well as for the $^{3}/_{4}$-in. maximum size, there occurred an increase in unit weight of the total material, as the percentage of gravel increased. The resulting unit weight reached a maximum at 65 to 70 percent gravel content. When the gravel content exceeds this amount there are insufficient fines to fill the voids within the gravel and the unit weight decreases rapidly with increase in gravel content.

A special study of the effect of maximum particle size was made for the clayey gravel. The results are indicated in Figure 56 which shows the maximum unit weights obtained in the large-scale tests for the 3-in. maximum size and the $^{3}/_{4}$-in. maximum size. The unit weights obtained for the $^{3}/_{4}$-in. maximum size gravel were somewhat lower than that obtained for the clayey gravel with the 3-in. maximum size gravel. This may be due to the gradation characteristics of the materials. The difference between the two materials increases as the gravel content increases becoming a maximum (6.5 pcf) at the 100 percent gravel content when the gradation effects are most pronounced. The calculated maximum unit weights for the fine fractions (minus No. 4 sieve material) are lower for the ¾-in. maximum size clayey gravel than for the 3-in. maximum size. Approximate values scaled from computed curves (106) are given in Table 16. Thus, the size and gradation of the gravel has an effect on the compaction of the fine fraction. Possibly the finer gravel, being less well-graded, has greater particle interference and, also, because the particles are smaller, does not transmit the compaction effort to the fine fraction as effectively as the coarser material.

Another special study was made to determine the effect of using material up to ¾-in. maximum size in the small mold (1/20 cu ft). In this test the soils were separated on the No. 4, ¾-in., and 2-in. sieves. Sufficient No. 4 to ¾-in. material is then added back to the fine fraction to produce a gravel content by weight equal to that determined for the No. 4 to 2-in. fraction.

Some engineers have questioned if this procedure produces comparative results equivalent to what would be obtained by testing the total material with larger equipment. For this reason, the dashed line curves in Figures 54, 55, and 56 show wherein compaction tests were performed with the Bureau of Reclamation 1/20-cu ft mold on the fraction of the total material passing the ¾-in. sieve. These may be compared directly with the results of compaction tests made with the large-scale apparatus on the 3-in. maximum size material.

Though the shapes of the curves are generally similar, lower unit weights were obtained for all three materials on the minus ¾-in. gravel in the smaller mold, the differences increase with increasing gravel content. A direct comparison between the results of the large-scale and small-scale tests is made in Figure 56, which shows that lower unit weights were obtained with the smaller mold and lighter tamping equipment. This has been discussed under "The Size and Shape of the Mold."

The writers (106) concluded from data of the nature given in Figures 54, 55, and 56 that the lower unit weight obtained for the ¾-in. maximum size material compacted in the 1/20-cu ft mold as compared with the 3-in. maximum size material compacted with the large scale apparatus was due to "(a) improved gradation characteristics for the total material, and (b) improved compaction of the fine fraction." The writers made comparison between actual and computed unit weights and found that the unit weight of the total material began to become less than the theoretical unit weight (and thus the unit weight of the fine material may be expected to decrease) when gravel contents of 28, 36, and 44 percent by weight respectively are exceeded for the sandy, silty and clayey gravels of 3-in. maximum size. Apparently, as the fine fraction becomes finer and more plastic, interference occurs at higher gravel contents. In comparing

TABLE 16

COMPUTED MAXIMUM UNIT WEIGHTS OF THE MINUS NO. 4 FRACTION IN LARGE-SCALE COMPACTION TEST FOR 3-IN. AND ¾-IN. MAXIMUM SIZES OF GRAVEL AND DIFFERENT GRAVEL CONTENTS[a] (106)

Percent Gravel	Max. Dry Unit Wt. of Minus No. 4 Fraction in 3-In. Max. Size Clayey Gravel	Percent Gravel	Max. Dry Unit Wt. Minus No. 4 Fraction in ¾-In. Max. Size Clayey Gravel
65	99.0	65	95.4
50	106.3	50	100.3
35	108.8	35	108.5
20	111.0	--	--

[a] Approximate values scaled from graphs.

the compaction curves for the 3- and ¾-in. maximum size materials, the greatest differences between the two methods are about 11.5 pcf for the sandy gravel at about 80 percent gravel content; 4.5 pcf for the silty gravel at about 65 percent gravel content; and, about 11 pcf for the clayey gravel at about 70 percent gravel.

Humphres (102) performed a large number of compaction tests on gravelly soils while developing his method of establishing maximum unit weight vs gradation curves for granular materials. He applied his method (107) to determine the relationship between maximum dry unit weight vs percent passing the No. 4 sieve for each of the aggregates tested by Holtz and Lowitz (106). To plot the derived curves, Humphres used the maximum unit weight values derived by Holtz and Lowitz with their vibrator test. The results of the Humphres determinations are given in Table 17. They are approximate in that they are taken from charted data.

There is good agreement between the two methods for the sandy gravel, and fair agreement for the silty gravel and the 3-in. maximum size clayey gravel. Significant difference occurs for the ¾-in. maximum size clayey gravel.

In summarizing, Maddison (17) found only small increases in the maximum unit weight of the total mix on the addition of the one-size coarse aggregate. Later work (60) with the addition of graded coarse aggregate showed a greater increase in maximum unit weight with increase in coarse aggregate content up to at least 40 percent. Zeigler's (28) tests showed a strong increase in maximum unit weight and almost a linear relationship between maximum unit weight and percent coarse aggregate up to the maximum (50 percent) that he used in his tests. Mainfort and Lawton (64) made similar findings except that their unit weights diminished at a more rapid rate after reaching the peak value. The Holtz and Lowitz (106) investigation also showed sharp breaks in the curves of maximum unit weight vs percent of gravel and showed those peaks at higher gravel contents than found by others. There is no apparent explanation for the differences in the data obtained by the different investigators. No doubt the differences in soil matrix, the size of the mold and nature of compacting equipment, as well as the nature of the coarse aggregate can account for the differences in results obtained. The effect of the maximum size of the coarsest aggregate was generally insignificant when the materials were compacted in the same mold; when larger molds were necessary to accomodate the coarsest materials, the difference was significant with the coarsest materials being compacted to the greatest unit weights.

The Shape of Coarse Aggregates.—Few data are available that show the effect of shape of coarse particles on the maximum unit weight and optimum moisture content. Holtz and Lowitz (106) reported the results of a single test performed on a soil aggregate that consisted of 50 percent silty soil and 50 percent very angular crushed quarry rock. The crushed rock had the same gradation as used for the 3-in. maximum size gravel mixed with 50 percent silty soil as shown in Figure 53.

The single test provided a maximum unit weight of 135.1 pcf and an optimum moisture content of 6.8 percent compared to similarly derived values for the subround to subangular gravel mixture of 135.3 pcf and 7.3 percent. The fines in the angular material had a unit weight of 116.7 pcf and an optimum moisture content of 12.1 percent compared to similarly derived values for the gravel of 113.8 pcf and 13.8 percent. The reasons for the differences are not brought out.

TABLE 17

HUMPHRES DETERMINATIONS (107)

Soil	Max. Size (in.)	Max. Unit Wt. (pcf)
Sandy gravel	3	142.4
Silty gravel	3	142.7
Clayey gravel	3	136.2
	¾	137.2

The experience of Humphres (107) regarding the effect of shape of coarse particles has been the opposite of that of Holtz and Lowitz in that a reduction in compactability occurs with an increase in fracture.

Optimum Moisture Content of Relatively Free Draining Materials. —Relatively free draining materials may exhibit no normal optimum moisture content. They may show no consistent relationship between moisture content and dry unit weight or they may continue to show an increase in dry unit weight with increase in moisture content to the maximum used. That maximum may constitute a saturated condition on compaction. Spencer, Allen, and Smith (87) reported compaction tests of that nature for an "open-graded" crushed rock base (specification limits in terms of percent passing sieves were 1-in., 90-100; ½-in., 60-90; No. 4, 30-70; No. 30, 10-30; and, No. 200, 0-3 percent). They found that in performing the standard compaction test (on the material passing the ¾-in. sieve) that the material either exhibited no distinct optimum at any water content or yielded the highest dry unit weight at the maximum moisture content used. Turnbull and Foster (100) also found that the maximum moisture content used yielded the greatest dry unit weight when a relatively low compaction effort (26,000 ft-lb per cu ft) (see Figure 52) was used in the test. The material was a graded crushed limestone having approximate values of 32, 15, 10 and 9 percent passing sieves Nos. 10, 40, 100 and 200. For higher compaction efforts (55,000 and 110,000 ft-lb per cu ft) optimum moisture contents slightly below the maximum moisture content were developed in the laboratory test. Field-compacted dry unit weights continued to increase to a condition of saturation that the authors referred to as a "flushed" condition.

Effect of Fines on Compaction of Granular Materials. —The addition of fine grain materials to aggregates does not result merely in increasing the dry unit weight by increasing the amount of material in the voids of the coarser material. It may or may not facilitate compaction of the coarser material depending on its nature. Thus it may have a much more pronounced effect on the maximum dry unit weight of one coarse grained material then on another, making it difficult to predict the unit weights that may be anticipated by compacting different materials of types normally used in base courses when they include fines.

Effect of Fines on Compaction of Predominantly Granular Materials

This section deals primarily with (a) the influence of clays in aggregate-soil mixtures, and (b) the effect of the fine sand fraction in noncohesive to lightly cohesive granular materials on the moisture-unit weight relationships. The behavior of cohesionless granular materials, in general, is discussed under "The Vibration Compaction Test" and "Standard AASHO-ASTM Methods vs Vibratory Compaction."

Effect of Clays in Aggregate-Soil Mixtures. —Studies have been conducted that included measurement of the effect of soil content on compaction and wet-strength characteristics of four types of aggregate-soil mixtures (23). Three were of coarse aggregate type: (a) a ¾-in. maximum size gravel-soil mixture, (b) a ¾-in. maximum size crusher-run limestone-soil mixture; and (c) a ⅜-in. maximum size graded sand-soil mixture. The fourth was a No. 30 mesh maximum size dune sand-soil mixture. The admixed soil was a silty clay having a liquid limit of 27 and a plastic index of 5. Each of the coarser materials were admixed with the clayey soil in six to eight mixtures in which the final grading contained from 0.4 to 21 percent passing the No. 200 sieve. The dune sand mixtures were six in number, but contained up to 50 percent passing the No. 200 sieve. Materials were compacted in a 6-in. diameter mold 4⅝ in. deep ($^1/_{14.6}$ cu ft) and compacted by various numbers of blows per layer of a 10.4-lb rammer dropping 12 in. For purpose of comparison, test data were selected from those made with 25 blows per layer because it produced a compaction effort of 12,843 ft-lb per cu ft, the nearest to the standard AASHO effort (12,375 ft-lb per cu ft), even though comparative tests showed that the applied energy yielded maximum dry unit weights of about 2 pcf greater than that produced by the standard method. Comparative data for the four types of aggregate-soil mixtures showing the relationship between maximum dry unit weight and percent finer than the No. 200 sieve are shown in Figure

57. It may be seen that the rate of increase in maximum dry unit weight was about the same for the three coarser aggregates but somewhat less for the dune sand-soil mixture. Inasmuch as both the total volume of voids and the size of the pore spaces differed, the greatest maximum dry unit weight occurred at markedly different percentages of fines. Although a sharp peak of maximum dry unit weight vs percentage minus No. 200 material occurred for the coarse materials and especially the coarse-graded sand, the effect on the dune sand was one of gradual increase in unit weight to a maximum of 40 percent admixture. The greatest wet strength occurred at fine contents of less than those that produced maximum dry unit weight.

In another study (111), two natural materials were combined. One was a coarse to medium graded, angular to subangular, nonplastic sand (having approximately 100, 87, 50, 15, and 0 percent passing sieves Nos. 4, 10, 20, 40, and 200 respectively, $G_s = 2.71$); the other, a well-graded inorganic B-horizon sandy clay (having approxi-

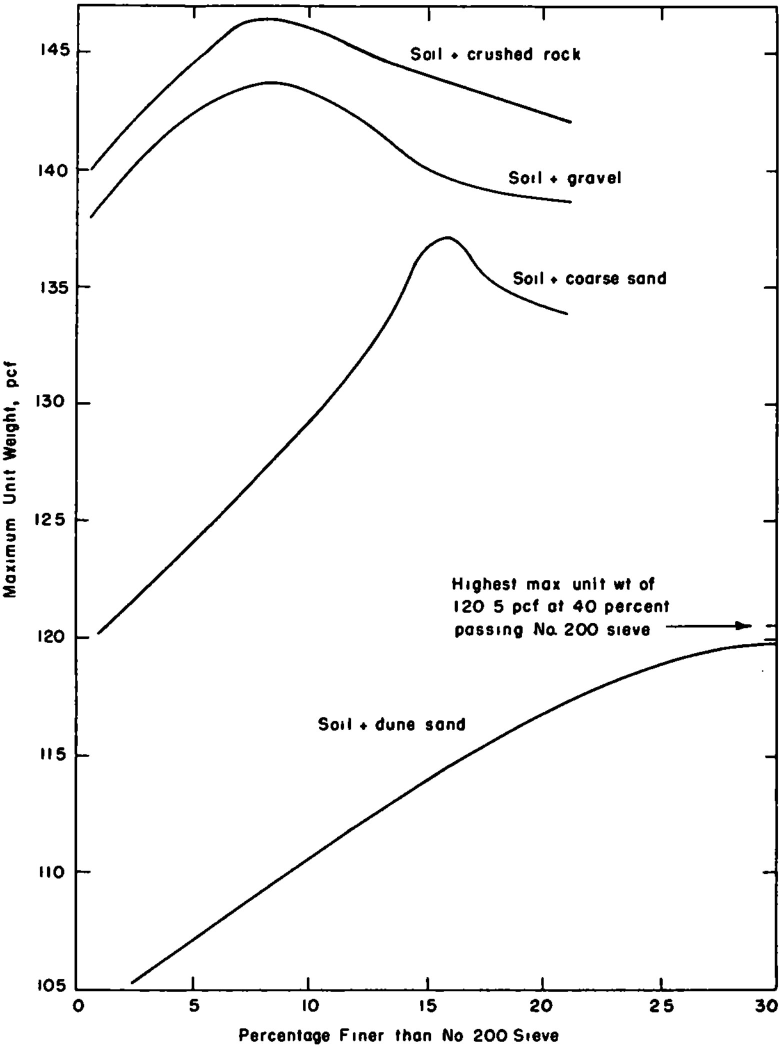


Figure 57. Variation in maximum unit weight of aggregate-clayey soil mixtures with percent passing the No. 200 sieve. The silty clay soil admixed to aggregate had LL of 27, and PI of 6 (23).

mately 99, 88, and 59 percent passing sieves Nos. 10, 40, and 200 respectively and a liquid limit of 31, a plastic index of 6, $G_S = 2.68$). Various mixtures of the two soils were made ranging from 100 percent aggregate (sand) to 100 percent admix soil. Compaction test method AASHO T 99 (ASTM D 698) was employed except that separate portions of soil were used for each determination of moisture content-dry unit weight relationship. The maximum dry unit weights and corresponding optimum moisture contents resulting from the tests are shown in Figure 58. The peak maximum dry unit weight was produced at 26 percent admix. The figure also shows the percentage compaction of the soil admix at various proportions of the admix indicating that it did not receive enough compaction to attain near 100 percent relative compaction until the peak unit weight was reached for the mixture.

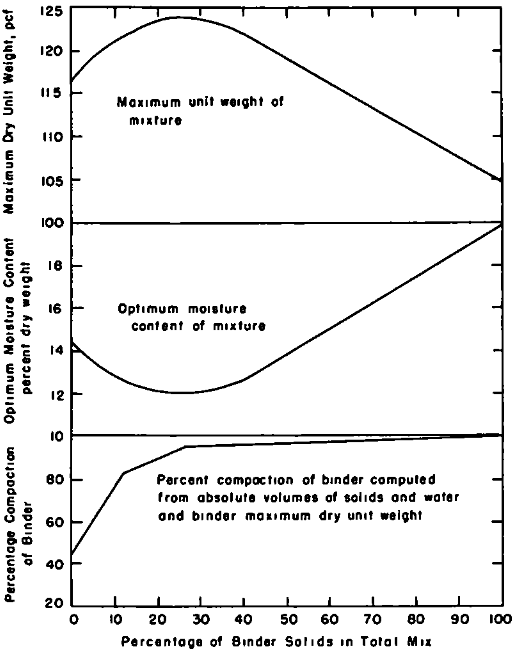


Figure 58. Maximum dry unit weight, optimum moisture content, and percentage of compaction of binder for various proportions of binder soil and aggregate (111).

Effect of Fine Sand Fraction In Granular Materials.—Any improvement in grain-size distribution, especially when it is in the sand sizes will, within limits, result in an increase in maximum dry unit weight. The addition of or subtraction of fine sands of various sizes may have marked influence on the maximum dry unit weight. These factors are evident in many examples in the text and are discussed in part in HRB Bull. 272 under "The Moisture-Unit Weight-Compactive Effort Relationships—Effect of Soil Type." It is also discussed in the bulletin under "Control of Compaction During Construction—The Humphres Method for Granular Soils.'

Investigation of compaction of sand subgrade at Eglin Field, Fla., by the Corps of Engineers (42) showed that the sand was uniformly graded ("one-size") but varied through a small range for each of the various sieves. The sieve numbers and ranges in percent passing for the sand are given in Table 18.

TABLE 18

GRADATION OF EGLIN FIELD SAND (42)

Tyler Standard Sieve No.	Range in Percent Passing
10	100
28	87-93
48	30-51
100	3-10
200	1.5-7

Examination of data on gradation and on maximum unit weight showed that a relationship existed between the modified AASHO maximum dry unit weight and the percent passing the No. 200 sieve. The average relationship is indicated by the solid line in Figure 59. The dashed lines representing values of maximum dry unit weight 2 pcf greater and 2 pcf smaller than the average included all except 2 of the 40 test results on the sands at Auxiliary Field 2, Eglin Field, Fla.

Spencer, Allen, and Smith (87) found a somewhat similar relationship in observing gradation and compaction data on an open-graded crushed stone rock course, except that the significant sieve size was the No. 30 mesh sieve. Their results are shown in Figure 60. The specification limits and the average percents passing the control sieves for the crushed rock base course are given in Table 19. The relationship between the maximum dry unit weight and the percent passing the No. 30 sieve was so strong that it permitted the chart in the figure to be used in field compaction control.

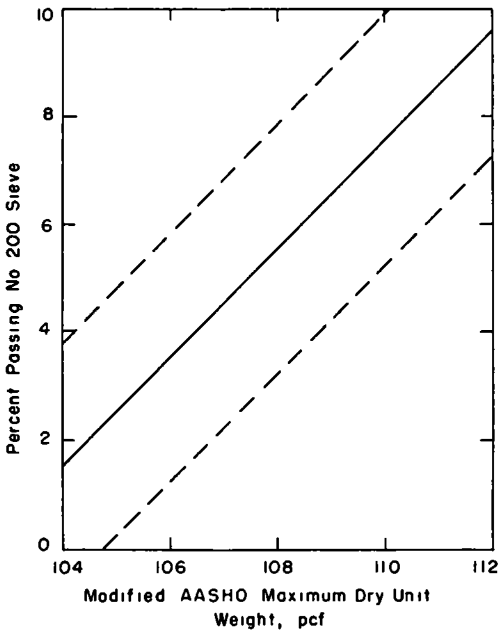


Figure 59. General relationship between modified AASHO maximum dry unit weight and percent passing the No. 200 mesh sieve for 40 different gradations of a non plastic uniformly graded Florida fine sand (42). The dashed lines enclose 38 of the 40 test results.

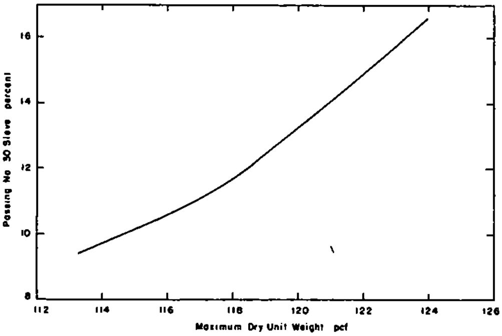


Figure 60. Relation between percent passing the No. 30 sieve and maximum dry unit weight obtained in laboratory compaction test (87).

Soils Having Special Properties

Some soils may appear from limited test data, to be normally reacting soils and may not be suspected of having characteristics that make them behave, in service, different than normal soils. Among these are thixotropic clays.

Thixotropic Clays. —Thixotropy is a process of softening and reduction in strength caused by manipulation, followed by a gradual return to the original strength when the material is allowed to rest. The process is completely reversible in a thixotropic soil (96). It is a property found in many natural (residual and sedimentary) deposits of clay and is also a property of many compacted clays at moisture contents well below that of saturation. There is evidence that some measure of thixotropy is caused by a non-uniform moisture content and that redistribution of nonuniformly distributed moisture, as in a compaction test, may account for some strength increase (109). Because it is a function of both moisture content and unit weight and because in some soils it may determine the method of compaction, it is discussed here.

Seed and Chan (96) observed some thixotropic effects on a Vicksburg silty clay (LL = 37, PI = 14) subjected to repeated applications of a constant axial stress on specimens having a water content of 18 percent, a dry unit weight of 112 pcf, and a degree of saturation of 95 percent. (A Standard AASHO compaction effort yields a maximum dry unit weight of 105 pcf at an optimum moisture content of 18 percent. The value for Modified AASHO maximum dry unit weight is about 116.7 percent and 14.5 percent (41).) However, this silty clay soil is normally reacting and there was no evidence that the thixotropic properties should influence the method of performing the compaction test.

Among the most active of thixotropic soils are some laterite clays, red tropical soils developed by laterization of volcanic ash in Hawaii. Where it was encountered on the Papaikou-Pepeekeo section of the Belt Highway on the Island of Hawaii (22). The rainfall for the area exceeds 200 in. per year. When first encountered, these soils have a granular, friable structure and the favorable engineering characteristics of relatively free internal drainage and high bearing capacity. Remolding and manipulating them, in the degree necessary to excavate and move them from cut to fill, transforms them into soft clay-like soils of low strength. An example of the influence of manipulation and drying is indicated in the index properties obtained under three different methods of preparing samples of the same soil for the standard tests (Table 20). The three methods used were (a) air drying, (b) partial air drying with subsequent separation on the No. 40 sieve, and (c) washing the sample on the No. 40 sieve.

Compaction tests, using standard equipment and compaction effort were performed on this and similar soils (37). The test was begun by compacting the soil at its initial field moisture content of about 180 percent, drying it for 24 to 48 hr, performing another compaction test, and repeating the process to produce Curve A (Fig. 61). After allowing the soil to air dry in the test (for example, to 75 percent), it was rewetted in increments and compacted in accordance with the accepted procedure. This resulted in Curve B, a curve that is concave downwards. The soil was further air dried, and again rewetted and compacted in increments. This produced a second curve concave downwards, Curve C.

Thus, the optimum moisture content and maximum dry unit weight of this extremely active soil are dependent on the amount of drying that took place before wetting. Table 20 showed that drying to a low moisture content produced an irreversible and extreme change in soil properties. No doubt each increment of drying in the compaction test produced some slight irreversible change in the character of the soil. Experience has shown that Curve A furnishes a reasonable close estimate of the dry unit weight that can be expected in field rolling for the full range of moisture content given. A value of 50 pcf has been arbitrarily adopted as standard maximum dry unit weight. It is the lower of the two maxima (Curve B) in Figure 61.

Barber (110) provides additional data on compaction test data on two laterite clays

TABLE 19

GRADATION OF INDIANA CRUSHED STONE SUBBASE (27)

	Percent Passing				
	1-In. Sieve	½-In. Sieve	No. 4 Sieve	No. 30 Sieve	No. 200 Sieve
Avg. all samples	100	87	55	15	3.3
Spec. limits	90-100	60-90	30-70	10-30	0-3

TABLE 20

INDEX PROPERTIES OF A HAWAIIAN LATERITE CLAY SOIL (22)

Property	Method of Preparation		
	1	2	3
Sand, 2 to 0.05 mm	86	42	34
Silt	11	17	10
Clay	3	41	56
Colloids	-	25	33
Liquid Limit	NP	217	245
Plastic Index	NP	71	110
Shrinkage Limit	-	44	44
Shrinkage Ratio	-	1.17	1.17
Specific Gravity, G_s	2.84	-	-

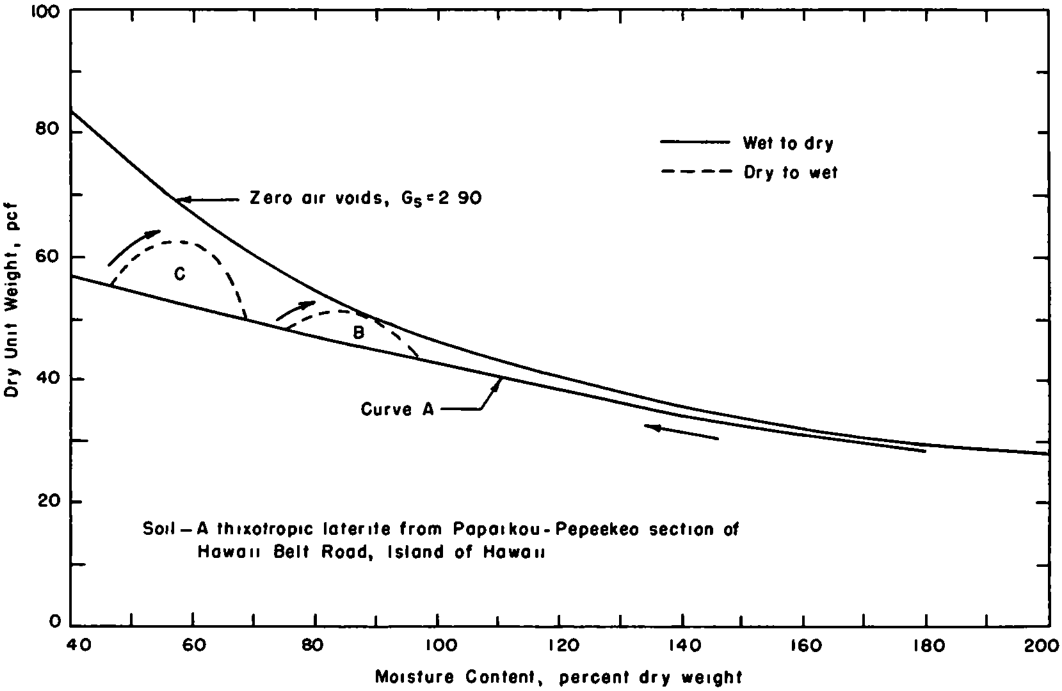


Figure 61. Results of compaction tests using Standard AASHO Method: T99 compaction effort on Hawaiian laterite soil exhibiting thixotropic properties. Curve A was obtained by drying and compacting; Curves B and C by increasing moisture and compacting (37).

from Costa Rica and Panama. Two clay laterite soils (LL = 59 and 54, PI = 32 and 41) had values of Standard AASHO Method T 99 maximum dry unit weights of 77 and 88 pcf and optimum moisture contents of 41 and 29 percent respectively. Comparative values for the Modified AASHO test were 86 and 89 pcf and 36 and 24 percent respectively.

Very Heavy Clays and Uniformly Graded Sands. —Very heavy (fat) clay soils that are often highly structured may result in irregular compaction curves when tested under Standard AASHO Method: T 99-57 Methods A, B, C, or D that apply compaction efforts of either 12,375 ft-lb per cu ft (Methods A and C), or 12,317 ft-lb per cu ft (Methods B and D). An example of a compaction curve for this type of clay is shown in Figure 62 (Curve 4). Increasing the compaction effort by three times resulted in a marked change in the shape of the moisture content—dry unit weight curve. Some of the index properties for this heavy clay are listed in Table 21.

Sands may also exhibit oddly shaped compaction curves; for example, Curves 1 and 2 in Figure 62. This fine sand is a uniformly graded nonplastic Florida coastal plain parent material. Sands of this nature may be affected so little by the magnitude of an impact type of compaction effort that curves for the widely different compaction efforts of AASHO Methods: T 99-57 and T 180-57 differ by only 1 to 3 pcf. Some sands display compaction curves throughout the range from dry to saturated that are, for practical purposes, straight lines. Those sands, like most nonplastic sands containing little or no silt and clay, respond poorly to impact compaction but respond very well to vibratory compaction. An indication of the index properties of the sand represented by compaction Curves 1 and 2 in Figure 62 are given in Table 21.

DEGRADATION DURING COMPACTION

It is generally known that all types of equipment and procedures for compaction, in both field and laboratory, produce breakage of (a) soil aggregates; (b) mineral aggregates composed of crushed rock, natural sands, and gravels; and (c) crushed slag. It is generally believed that compaction of granular soils by vibratory methods, either in the field or in the laboratory, results in less degradation of mineral aggregates than by other methods of compaction. Several studies have been conducted yielding data on degrada-

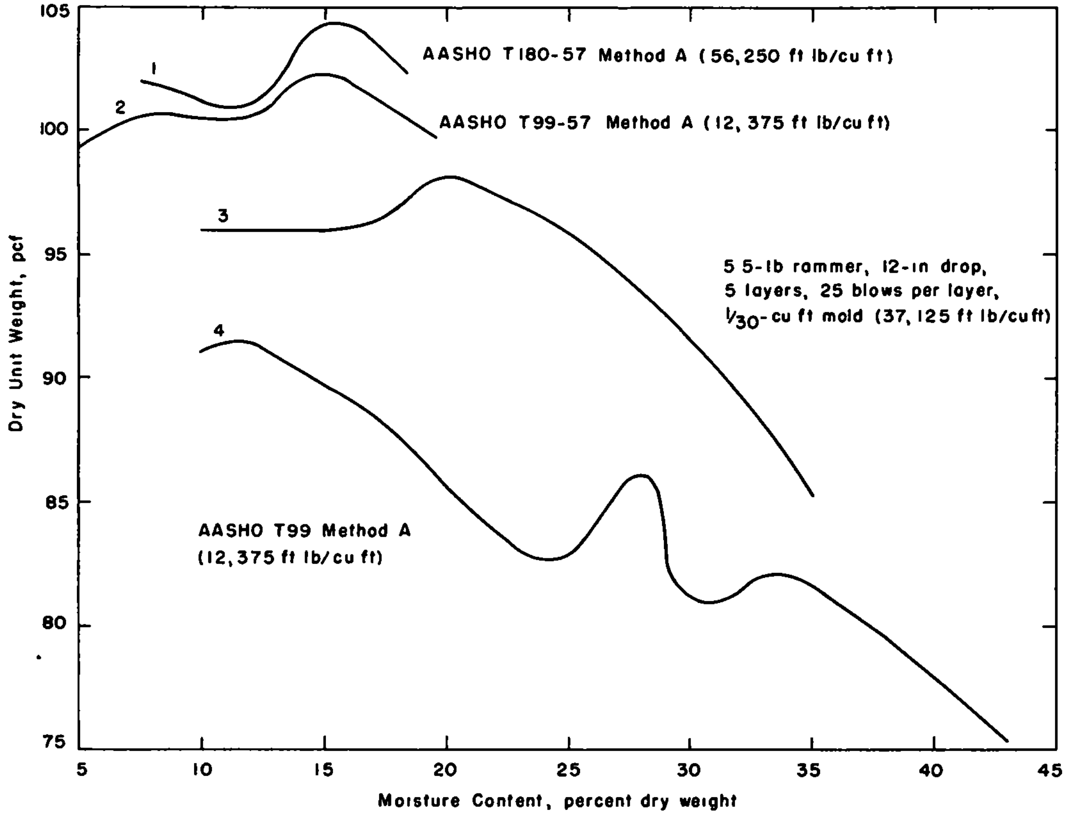


Figure 62. Examples of irregular compaction curves for a non plastic fine sand (Curve 2) and a heavy clay (Curve 4) when compacted with a low compaction effort. Increasing the effort yielded a more nearly normal curve for the clay (125, 126).

TABLE 21

INDEX PROPERTIES OF SOILS PRODUCING IRREGULAR COMPACTION CURVES (125, 126)

Soil Compaction Curve No.	LL	PI	SL	Sand 0.05 mm (%)	Silt 0.05-0.005 mm (%)	Clay 0.005 mm (%)	Spec. Grav., G_s	Source of Soil
1 and 2	NP	NP	NP	98	1	1	2.68	Fla. coastal plain parent material
3 and 4	118	83	14	14	18	68	2.76	Jackson, Miss., subsoil

TABLE 22

PHYSICAL CHARACTERISTICS OF DIFFERENT FRACTIONS OF THE TEST MATERIALS (64)

Fraction Identification	Specific Gravity		Percent Absorption	Percentage of Wear Los Angeles Abrasion Test			Percent Passing Sieve							
	Bulk	Apparent		Whole Sample	¾ to ⅜ In.	⅜ In. to No 4	1 ½ In.	1 In.	¾ In.	⅜ In.	No. 4	No. 10	No. 40	No 200
Fraction of a dense-graded gravel -4	--	2.76	--	--	--	--	--	--	--	--	100	76	37	12
Fraction of a washed gravel. +4 to -¾ in	2.56	2.74	2.7	33	30	38	--	--	100	31	2	0	0	0
+¾ to -1 ½ in	2.70	2.79	1.3	22	--	--	100	86	2	0	0	0	0	0
Fraction of a crushed limestone -4	--	2.75	--	--	--	--	--	--	--	--	100	71	42	19
+4 to -¾ in	2.65	2 69	0 9	38	34	49	--	--	100	26	3	0	0	0
+¾ to -1 ½ in	2.66	2.69	0.6	22	--	--	100	40	3	0	0	0	0	0
Fraction of a crushed slag -4	--	2.72	--	--	--	--	--	--	--	--	100	52	13	2
+4 to -¾ in	2 58	2.69	1.2	29	30	25	--	--	100	5	0	0	0	0
+¾ to 1 ½ in	2.58	2.68	0.8	20	--	--	100	80	10	0	0	0	0	0

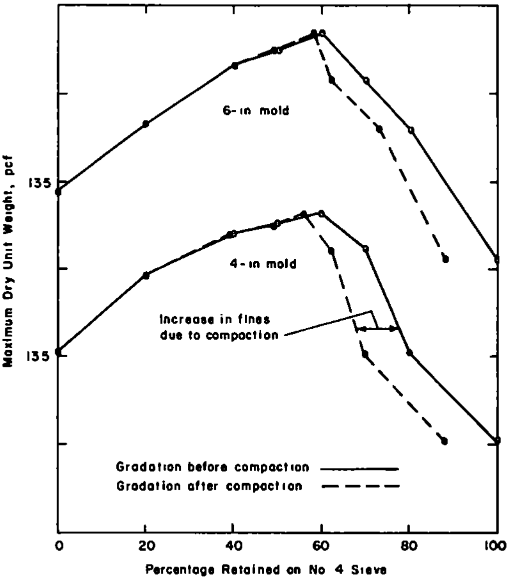


Figure 63. Effect of gradation on maximum dry unit weights of a sand-gravel compacted in 4- and 6-in. diameter molds, and on degradation of plus No. 4 material (64, 67).

tion in construction compaction and/or in the laboratory compaction test. Insufficient data are available for correlation of degradation in the various laboratory compaction test procedures with degradation in construction by various types of compaction equipment and compaction efforts. Also, sufficient data are not available for correlation of degradation in the various laboratory compaction test procedures (and compaction efforts) with other laboratory tests, such as the Los Angeles Abrasion Test (AASHO Designation: T 96-56; ASTM Designation: C 131-55). Therefore, an attempt is made here only (a) to show that degradation does occur and (b) to indicate its effect on the results (and the interpretation of the results) of the laboratory compaction test. Only degradation of mineral aggregates is discussed here. Degradation of aggregates due to weathering under service conditions is not considered.

Several investigations have provided evidence of degradation of mineral aggregates in laboratory compaction tests (12, 13, 21, 64, 67, 127).

In a very comprehensive study (64, 67), degradation of sandy gravel, crushed limestone, and crushed slag was examined to determine the effect of particle-size distribution, type of material, and size of mold. Each material was separated into three fractions, designated A, B, and C, and several combinations of the fractions were compacted. Fraction A consisted of Minus No. 4 sieve material; fraction B, plus No. 4 sieve to ¾-in. material; fraction C, plus ¾- to 1½-in. material. Physical characteristics of the fractions of the three materials are shown in Table 22.

The compaction equipment consisted of a Rainhart automatic tamper No. 62 modified by the addition of a motor drive and a counter for recording number of blows. To compact the material into 4- and 6-in. diameter molds 10- and 22.5-lb rammers were used. The inside depth of each mold was 4.6 in.

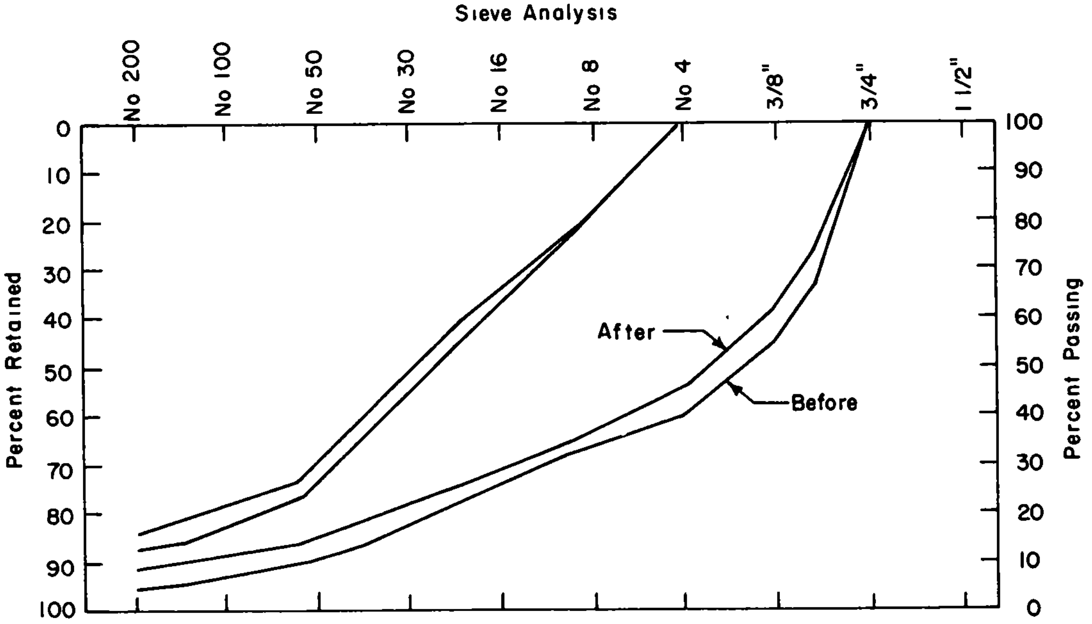


Figure 64. Gradation curves for different gradings of sand gravel before and after compaction in 4-in. diameter mold. Modified AASHO compaction effort (64).

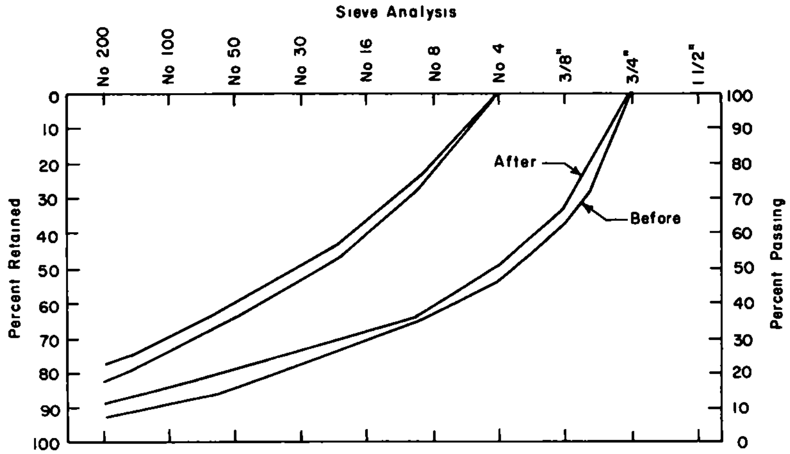


Figure 65. Gradation curves for different gradings of crushed limestone before and after compaction in 4-in. diameter mold. Modified AASHO compaction effort (64).

The compaction effort for all tests was equal to the Modified AASHO compaction effort. To accomodate the large-size aggregate, the material was compacted in three layers, instead of five, with 42 blows per layer.

The effect of particle-size distribution or gradation on degradation is shown in Figures 50, 51, 63, 64, 65, 66 and 67. Generally, degradation of coarse aggregate (plus No. 4 sieve material) increased with increasing percentages of coarse aggregate. Breakage in the 4-in. mold was negligible when the plus 4 material was less than 30 percent. Inasmuch as the Standard laboratory tests (AASHO Designations: T 99 and T 180; ASTM Designations: D 698 and D 1557) are normally performed on the minus No. 4 sieve or the minus $^{3}/_{4}$-in. size material, it is of interest to compare "before"

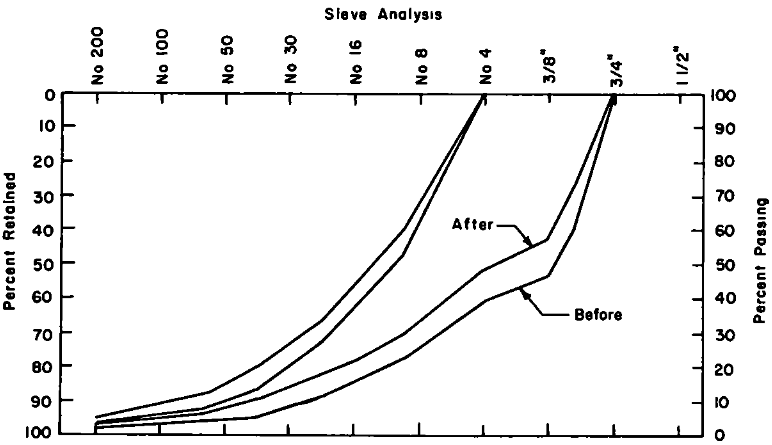


Figure 66. Gradation curves for different gradings of crushed slag before and after compaction in 4-in. diameter mold. Modified AASHO compaction effort (64).

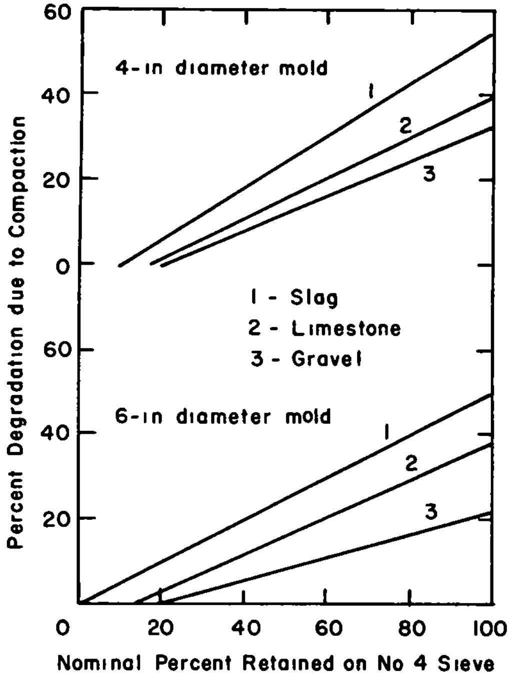


Figure 67. Degradation as a function of the plus No. 4 material (64).

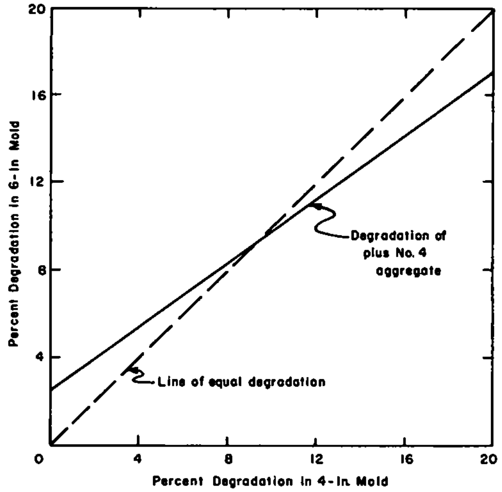


Figure 68. Degradation of the plus No. 4 sieve material as a function of mold size. The line expresses the average degradation of gravel, crushed limestone, and slag coarse aggregates (64).

and "after" particle-size distribution curves for those limiting sizes for the three materials. These results are shown in Figure 64, 65, and 66. The curves indicate the relative effect of maximum size for the three materials inasmuch as tests were all made in 4-in. diameter molds. The influence of the proportions of coarse aggregate is brought out more clearly in the graphs of percent degradation vs nominal percent retained on the No. 4 sieve shown in Figure 67.

The effect of type of material on degradation is shown in Figures 50, 51, and 67. Sand and gravel degraded least for all mixtures; crushed slag degraded most, with measurable breakage in mixtures with small percentages of coarse aggregate.

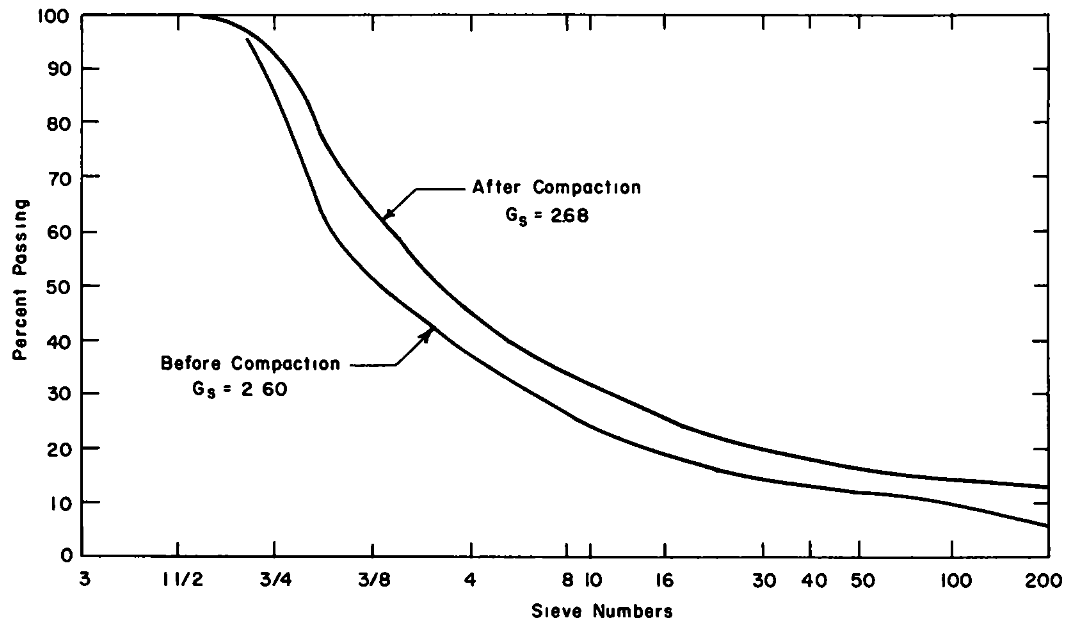


Figure 69. Particle size distributions of a blend of slag, crushed chert gravel, sand, and limestone dust before and after compaction (128) according to Modified AASHO compaction procedure.

The effect of mold size on degradation is slight. The general relationship for all the tests is shown in Figure 68. For lower percentages of breaking (fine material predominating) the greater degradation occurred in the large mold. At higher values of breakage (coarse material predominating) the greater degradation occurred in the smaller mold.

Further evidence of the degradation of materials in compaction is seen from tests performed on materials used in the Proof-Test Section of the Columbus (Miss.) Air Force Base (128), where the crushed aggregate base course consisted of a blend of slag, crushed chert gravel*, sand, and limestone dust. Most of the material larger than ½ in. in size consisted of slag. Modified AASHO compaction tests were performed on the material. Appreciable degradation occurred during the test as shown by the "before" and "after" particle-size distribution curves in Figure 69.

A significant feature of degradation is that it not only influences maximum dry unit weight directly by producing a particle-size distribution that results in a greater unit weight (unless the material contains more fines than required to produce maximum weight) due to the factor of degradation but also results in a change in specific gravity of the total aggregate. This is the result of exposing a greater number of previously

---

*The gravel used was produced from alluvial deposits on the Columbus AFB reservation, probably representing reworked cretaceous gravels derived from cherty limestone of Paleozoic Age. Test data on gravels from Columbus Sand and Gravel Co. and from Fleming Gravel Co. workings are described in "Test Data, Concrete Aggregates in Continental U.S." WES Tech. Memo. 6-370, Vol 4, Area 33-88, Indices 1 and 3.

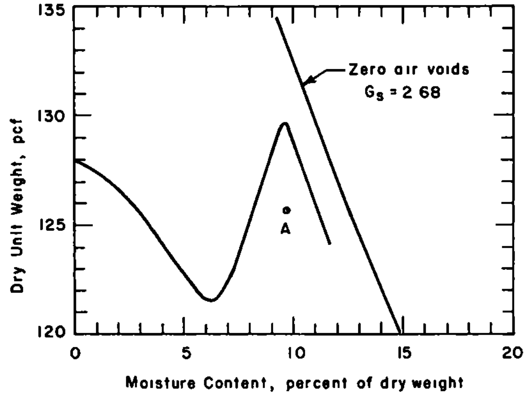


Figure 70. Modified AASHO compaction data for a blend of slag, crushed chert gravel, sand, and limestone dust (128).

TABLE 23

EFFECT OF DEGRADATION OF SLAG ON APPARENT SPECIFIC GRAVITY (128)

Description	Apparent Sp. Gravity, G
¾-in. to 1-in. size slag	2.384
Crushed to ½- to ¾-in. sizes	2.477
Crushed to No. 4 to ½-in. sizes	2.518
Crushed to minus No. 4 sizes	2.806

impervious voids (closed pores in rock that cannot be filled by absorption) and thus increasing the apparent specific gravity as the particle size is reduced. The change in specific gravity accompanying the degradation shown in Figure 69 is exemplary for easily crushed material high in impervious voids. The Modified AASHO compaction curve for this material is shown in Figure 70. Point A in Figure 70 illustrates the "corrected" laboratory maximum dry unit weight when the ratio of specific gravities

$$\frac{\text{apparent sp. gravity before compaction}}{\text{apparent sp. gravity after compaction}} = .97$$

is applied to the maximum unit weight of 129.6 pcf (after compaction) at 9.6 percent moisture content. The corrected or reduced maximum dry unit weight value is necessary for field use when degradation in the field is not expected. To illustrate further the influence of increase in apparent specific gravity, a sample containing only particle sizes between ¾ and 1 in. was degraded. Specific gravity determinations were made on fractions containing ½- to ¾-in., No. 4 to ½-in., and minus No. 4 particle sizes. The results are given in Table 23.

The increase in apparent specific gravity with degradation of slag emphasizes the need for recognizing that degradation (a) is a factor in laboratory (and construction) compaction, (b) should be considered in evaluating the significance of the increased unit weight as related to decrease in porosity in the compaction of mineral aggregates of various types and particle-size distributions, and (c) may be affected by the type of laboratory apparatus and test procedures.

EFFECT OF CHEMICAL ADMIXTURES

The reaction of a soil to the energy applied during compaction can be changed some by the use of certain types of admixtures. These additives may include sodium salts, detergents, dispersants, and wetting agents. However, except for the results of three investigations concerning the effectiveness of calcium chloride as a compaction aid, a special study of the effect of additives in aiding vibratory compaction of cohesive soils, and limited field trials of proprietary compounds, the influence of additives has received little attention from researchers either in the field or in the laboratory.

The use of calcium chloride as a compaction aid has received the most attention from researchers. Johnson (20) performed laboratory tests on six soils of the A-2 group. Three were of a plastic nature and three of a friable nature; one of each type came from Alabama, North Carolina, and Virginia. Compaction tests were made on each soil using 0, 0.5, 1, 2, and 3 percent calcium chloride. Three compaction efforts were used: (a) a 6-in. drop with the 5.5-lb rammer, (b) a 12-in. drop with the 5.5-lb rammer (Standard AASHO Method: T 99 compaction effort), and (c) an 18-in. drop with the 10-lb rammer (Modified AASHO test). This resulted in a compaction test for each soil at each calcium chloride content for each compaction effort, or a total of 30 tests for each compaction effort; 90 tests in all.

The soils fall into a comparatively narrow gradation band; except for the Virginia friable soil, which contained more sand in place of the gravel by the others. The results of the compaction tests also fall within a small range. For example, for the 6-in. drop compaction effort, the range of maximum dry unit weight for all six soils for 0 calcium chloride content is from 114.4 to 121.0 pcf; for the 12-in. drop, the range is from 121.2 to 125.6 pcf; and for the 18-in. drop (10-lb rammer) the range is 127.3 to 132.9 pcf.

Because of this small range in maximum dry unit weights, these data are analyzed in terms of average dry unit weights. Table 24 gives the effect of calcium chloride on the average maximum dry unit weights of the mixtures (including the weight of the calcium chloride) for all six soils for the different compaction efforts. Table 25 gives the average maximum dry unit weights of the soils (not including the weight of the calcium chloride) for all six soils for the different compaction efforts.

Table 24 shows a gain in maximum dry unit weight for each increment of increase

TABLE 24

MAXIMUM DRY UNIT WEIGHTS[a] OF SOIL-CALCIUM CHLORIDE MIXTURES (20)

Calcium Chloride Added (%)	Dry Unit Weight (pcf)					
	6-In. Drop of 5.5-Lb Rammer		12-In. Drop of 5.5-Lb Rammer		18-In. Drop of 10-Lb Rammer	
	Average	Net Gain	Average	Net Gain	Average	Net Gain
0	118.4	---	123.2	---	130.4	---
0.5	120.3	1.9	124.6	1.4	130.8	0.2
1	121.3	2.9	126.0	2.8	131.9	1.5
2	122.4	4.0	127.0	3.8	132.9	2.5
3	123.5	5.1	128.1	4.9	133.6	3.2

[a] Include weight of calcium chloride added.

TABLE 25

MAXIMUM DRY UNIT WEIGHTS[a] OF SOIL IN SOIL-CALCIUM CHLORIDE MIXTURES (20)

Calcium Chloride Added (%)	Maximum Dry Unit Weight (pcf)					
	6-In. Drop of 5.5-Lb Rammer		12-In. Drop of 5.5-Lb Rammer		18-In. Drop of 10-Lb Rammer	
	Average	Net Gain	Average	Net Gain	Average	Net Gain
0	118.4	---	123.2	---	130.4	---
0.5	119.7	1.3	124.2	1.0	130.2	-0.2
1	120.0	1.6	124.8	1.6	130.6	+0.2
2	120.0	1.6	124.5	1.3	130.3	-0.1
3	119.9	1.5	124.6	1.4	129.6	-0.8

[a] Of soil alone, after subtracting weight of calcium chloride added.

in the proportion of calcium chloride added. The gain is in excess of the weight of chloride added. Table 25 which gives the net unit weights of the soil alone (after subtracting the weight of the calcium chloride added) shows a maximum net gain of 1.6 pcf for each of the two lower compaction efforts. This gain occurs with the addition of 1 percent by weight of calcium chloride. No net gains in unit weight of compacted soil occurred when the Modified AASHO compaction effort was applied.

Yoder (24) reported results of laboratory testing on four fine-grain glacial drift soils obtained locally in Indiana, and in addition, limited test data on 21 soils from 9 southern states. These soils were also, in the main, fine-grain, and contained less than 40 percent aggregate which was mostly sand. Admixtures of calcium chloride ranged from ¼ to 1½ percent by dry weight of soil. Compaction efforts used were 5, 15, 45 and 90 blows per layer of 5.5-lb rammer on each of 3 layers. A total of 156 tests were made. Of these, 81 were made on raw soils and 75 on soil-calcium chloride mixtures. The four Indiana soils were tested at all four compaction efforts. Two southern soils were tested at only 15 and 45 blows per layer. The remaining soils were tested at only one compaction effort—15 blows per layer. Only the test data from the four soils tested at all compaction efforts are shown here for comparison.

The dry unit weights of the specimens tested with calcium chloride were corrected by deducting the weight of the calcium chloride. In most cases, the increase in maximum dry unit weight was more than the amount attributable to the weight of the admixture. Like Johnson (20), Yoder found that the greatest increases in weights of dry soils attributable to calcium chloride occurred at the lower compaction efforts used (5 blows per layer) for one soil, and at 15 blows per layer for two soils. One soil

TABLE 26

MAXIMUM DRY UNIT WEIGHTS[a] OF SOIL IN SOIL-CALCIUM CHLORIDE MIXTURES (24)

Calcium Chloride Added (%)	Dry Unit Weight (pcf)							
	5 Blows per Layer		15 Blows per Layer		45 Blows per Layer		90 Blows per Layer	
	Dry Weight	Increase	Dry Weight	Increase	Dry Weight	Increase	Dry Weight	Increase
(a) Soil No. 1945 S, Crosby, 10-In.								
0	99.5	-	106.2	-	114.5	-	117.2	-
0.25	100.5	1.0	106.5	0.3	114.7	0.2	116.2	-1.0
0.5	100.0	0.5	106.5	0.3	113.9	-0.6	117.4	0.2
1.5	99.5	0.0	106.3	0.1	111.8	-2.7	116.5	-0.7
(b) Soil No. 1946 S, Illinoian Drift, 6-In.								
0	91.2	-	95.0	-	102.5	-	104.8	-
0.25	88.7	-2.5	96.3	1.3	103.8	1.3	104.9	0.1
0.75	90.8	-0.4	97.1	2.1	105.9	3.4	107.5	2.7
1.5	87.9	-3.3	97.0	2.0	103.6	1.1	105.2	0.4
(c) Soil No. 1947 S, Illinoian Drift, 60-In.								
0	88.0	-	97.8	-	106.4	-	110.0	-
0.25	89.9	1.9	98.2	0.4	107.7	1.3	111.4	1.4
0.75	89.8	1.8	99.0	1.2	105.6	-0.8	112.2	2.2
1.5	90.7	2.7	99.7	1.9	107.9	1.5	110.3	0.3
(d) Soil No. 1948 S, Illinoian Drift, 120-In.								
0	108.0	-	115.2	-	120.6	-	122.0	-
0.25	109.2	1.2	116.2	1.0	121.1	0.5	123.9	1.9
0.75	109.1	1.1	115.1	-0.1	121.5	0.9	122.8	0.8
1.5	107.7	-0.3	115.0	-0.2	120.9	0.3	122.9	0.9

[a] Of soil alone, after subtracting weight of calcium chloride added.

showed the greatest increase in maximum dry unit weight at the highest compaction effort (90 blows per layer). The results are given in Table 26.

Several field experimental projects have been constructed to study the use of calcium chloride as an aid to compaction and to increase subgrade bearing capacity. Sections of these projects where calcium choloride has been used have, in the main, shown dry unit weights slightly greater than control sections where no chloride was used. The total tests on a given project were usually insufficient in number to permit use of statistical methods in analyzing the data.

Slate and Yalcin (80) used the Modified AASHO apparatus (6-in. diameter mold and 10-lb rammer) in testing to determine the effect of calcium chloride and compaction effort on dry unit weight. They used compaction efforts of 10, 25, and 55 blows per each of 5 layers. Tests were performed on an unwashed sample, and its washed equivalent, of a New York (Ithaca) gravel containing, in the unwashed state 62, 39, 24, 18, and 12 percent passing sieves Nos. 4, 14, 48, 100, and 200 respectively. After washing, only 5 percent passed the No. 200 sieve. The results of the tests made on the washed and unwashed gravel at calcium chloride contents of 0.1, 0.5, and 1.0 percent are shown in Figure 71 for the three compactive efforts used.

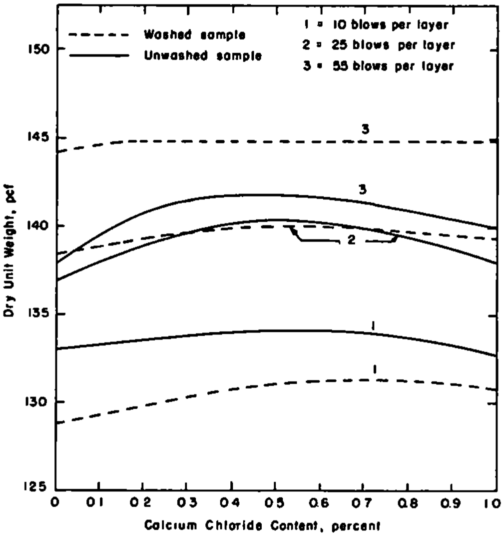


Figure 71. Maximum dry unit weights of washed and unwashed bank-run gravel of various percentages of calcium chloride for three compaction efforts using Modified AASHO apparatus, drop of rammer, and number of layers (80).

The addition of calcium chloride resulted in higher maximum dry unit weights of both washed and unwashed bank-run gravel. The greatest increases were obtained with 0.5 percent calcium chloride. Amounts smaller or larger than this gave unit weights intermediate between those for no chemical and for 0.5 percent chemical. The maximum increase was 3.5 pcf for unwashed gravel at the 25-blow compaction effort. It was concluded that the addition of an optimum amount of calcium chloride results in either a higher maximum dry unit weight or an equal dry unit weight at lower compaction effort. Calcium chloride is effective for increasing unit weight only on gravel containing an appreciable amount of material passing the No. 200 sieve. The effect is minor when the content of fines is below 5 percent.

To summarize the results of investigations, there is general agreement on the effect of calcium chloride on soils that are essentially granular. These soils have shown a consistent increase in dry unit weight (of the soil alone) due to the addition of the calcium chloride. The more limited results for fine-grain soils are erratic. One soil showed marked decreases in unit weight at all percentages of admixture for the two higher compaction efforts with little or no gain for the lower efforts; a second soil showed decrease in unit weight for all proportions of admixture for the lowest compaction effort and substantial increases in unit weight at other efforts; a third showed increases in unit weight for all but one effort and one proportion of admixture; and a fourth showed decreases for the two lower compaction efforts and very small increases for the two higher compaction efforts.

Although salts of sodium and magnesium have been used in soil stabilization, results of studies of their influence on soil compaction comparable to those described have not been found. Limited studies of the effectiveness of sodium chloride and sodium sulphate have been made as part of a larger investigation to determine the effects of chemicals as aids to the vibratory compaction of cohesive soils (81).

These studies, made by the California Institute of Technology, included theoretical studies of the nature of soil water in cohesive soils. Inasmuch as compaction of cohesive soils must overcome the shear strength furnished by cohesion, it was reasoned that any chemical additive that would reduce cohesion should aid compaction. It was concluded (81) that the cohesion between soil particles may be reduced by (a) reducing the surface tension of the liquid present in the soil mass, (b) reducing the concentration of swarm ions around the individual particles, (c) increasing the effective size of the soil particles, and (d) creating like and uniform electric fields on the soil particles.

This led to the investigation of 95 different chemicals as potential aids in compaction of cohesive soils by vibration. These included many anionic wetting agents (agents that depend on their acid radical for their wetting activity), several detergents, cationic wetting agents, organic wetting agents, nonionic wetting agents and many commonly known chemical compounds. It should be made clear that the action of these chemicals under impact compaction or under rolling in construction may not parallel results obtained in vibratory compaction either by the small Lazan Oscillator that was used or the large sled vibrator used in the tests.

It was concluded from these studies that the addition of chemicals to the soil can result in increased compaction, although this is not necessarily true for all chemicals nor for all soils. All of the most successful chemicals were sodium salts, and those that were wetting agents were all anionic. The most successful chemicals, in order of their success were as follows:

1. Sodium sulphate;
2. Darvan No. 1 (known also as Daxad 11) (polymerized sodium salt of alkyl naphtalene sulphonic acid);
3. Darvan No. 2 (Daxad 23) (polymerized sodium salt of substituted benzoid alkyl sulphonic acids);
4. Aerosol OT (di-octyl sodium sulphosuccinate, an anionic wetting agent);
5. Nopco 1067-A (an anionic wetting agent);
6. Victawet 35 B ($Na_5R_5(P_3O_{10})_2$ in which R is 2-ethylhexyl, an anionic wetting agent);
7. Sodium chloride;
8. Aerosol IB (di-iso-butyl sodium sulphosuccinate, an anionic wetting agent).

The maximum effect was obtained when these chemicals were added in the amount of about ⅓ percent by weight. The "spread" (that is, the range of maximum dry unit weight obtained by vibratory compaction with the equipment used with the aid of the chemicals) varied only within the range of 98.8 to 103.2 pcf and the optimum moisture content within the range 18 to 19.5 percent.

A commercial product known as SC-100, reported to be a liquid detergent that reduces the surface tension of water, was used experimentally on construction lifts on a section of the Kansas Turnpike (88, 90). The material was admixed in the proportion of 1 part to 8,000 parts water and the mixture applied to 6-in. loose construction lifts of clay soil. On a control section, water had penetrated 4½ in. during a 3-hr period, while the mixture had penetrated 6 in. The use of the admixture was reported to have resulted in a gain of 2 pcf in dry unit weight and to have aided materially in the mixing in of water. Another report (114) concerns the use of a regular "wash-day detergent" on extensive grading for a California housing subdivision. The soil was described as a very light-weight chalky shale, locally called "chalk." Difficulty was encountered in getting water to penetrate the fluffy excavated "chalk." Detergent in the proportion of 1 qt to 4,000 gal water was used on one project to permit sheepsfoot rollers to attain a unit weight of "95 percent."

Factors Influencing Absolute Maximum and Minimum Unit Weights of Cohesionless Materials

The use of density ratio (30), relative density (39) or compaction ratio (71) as specification values for the control of unit weight in construction compaction of sands, gravels, and crushed rock requires the determination of an "absolute" maximum that will not be exceeded in construction and an "absolute" minimum to serve as a reference point that is the lowest limit of unit weight at which the material can be placed.

ABSOLUTE MAXIMUM DRY UNIT WEIGHT OF GRANULAR MATERIALS

There is no known method for producing the absolute maximum dry unit weight of a cohesionless granular material. Attempts have been made to produce high dry unit weights by vibratory compaction. These methods have been described under "The Vibration Compaction Test." Additional data are not available to present here.

ABSOLUTE MINIMUM DRY UNIT WEIGHT OF GRANULAR MATERIALS

Several factors influence the "loose" or "minimum" dry unit weight of granular soil. The minimum unit weight is sensitive to the method of deposition or placement employed in the laboratory test. Method of deposition, although it employs a minimum of effort, is considered here as compaction effort.

Most engineers and technicians concerned with earthwork have measured a "loose density," particularly on sands used in the sand cone method for measuring in-place unit weight. However, the methods used in these tests and the results obtained have, in the main, been unrecorded. Also, the values have been for medium to fine sands and sand fractions. Of recorded studies, the Kansas Highway Department in 1939 performed investigations (10, 11) of the dry unit weights at which sands were deposited by various methods in cylinders up to 6 in. in diameter and from 6 in. to 16 ft in depth. The objectives of the tests were to study the following:

1. Several types of apparatus and methods used in depositing sand;
2. Effect of diameter and depth of hole (cylinder);
3. Effect of the grading of the sand; and
4. Magnitude of the effect of the personal element.

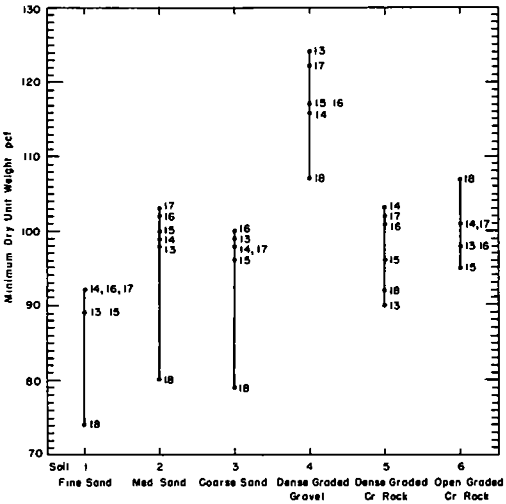


Figure 72. Minimum dry unit weights obtained on six soils by six different methods of depositing the soil into the container (see Fig. 38 for grain-size distribution of soils). Numbers beside bar graph are Felt's test method numbers (see Table 4) (120).

Ten different sands were used. They included four graded sands and six fractions. Results of significance here showed that, when using a funnel depositor from the top of the cylinder, differences in unit weight to 3 pcf occurred for the 12- to 36-in. depths. Differences of ¼ to ⅓ pcf occurred for the 6- and 12-in. depth in the 6-in. diameter mold. Pouring sand around the edge of the cylinder rather than in the center increased the density.

A committee of ASTM investigated six methods (Methods 3 to 9 in Table 4) for determining the minimum unit weight for each of six soils by each of the methods. Figure 38 shows the grain-size distribution for each of the six soils tested. The minimum unit weights in Figure 72 show that with the exception of one test method in the case of the sands (Soils 1, 2, and 3) the spread in minimum unit weight is not great (3 to 6 pcf), but that the spread for gravel and crushed rock is markedly greater.

These results show the need for determining the magnitude of the difference in minimum unit weight that can be attributed to apparatus and method of deposition, as well as to the other factors of soil type, diameter and depth of cylinder, and the personal element.

Methods of Determining Maximum Dry Unit Weight and Optimum Moisture Content for Materials Containing Coarse Aggregate

Whenever a soil contains coarse aggregates exceeding the maximum size permitted in obtaining dependable and reproducible results by the stndard apparatus and procedures, the tester must determine the correct maximum compacted dry unit weight of the total soil by adjustment of apparatus or procedure, by computations, or by a combination of methods. Performing a compaction test on the whole material is the most direct method for obtaining the maximum unit weight and optimum moisture content of the whole material. Unfortunately, the relatively small compaction molds used in the standard tests limit the maximum aggregate size. The tests specify $^3/_4$-in. maximum although larger sizes, up to $1^1/_2$ in., may be tested satisfactorily in the 6-in. mold.

If the entire sample cannot be tested, the best approach is to test as much of the material as possible. Methods C and D of the standard compaction tests provide for testing the soil material passing the $^3/_4$-in. sieve. These methods also provide for replacing the coarser material (retained on the $^3/_4$-in. and passing the 2-in. sieve) with an equal weight of material between the $^3/_4$-in. and the No. 4 sieves.

In cases where granular material from the same source is used extensively, it is often useful to conduct a series of compaction tests on mixtures containing different amounts of plus No. 4 material and thereby establish the relationship between compaction test results and amount of plus No. 4 material.

If compaction test data are available for the fine fraction of the soil-aggregate mixture, the maximum dry unit weight and optimum moisture content of the whole material may be estimated by one of several methods.

CORRECTING MAXIMUM DRY UNIT WEIGHT FOR COARSE AGGREGATE CONTENT BY COMPUTATIONS

Several experimental studies have been made that provide information on the effect of coarse aggregate on maximum dry unit weight as determined by the compaction tests. These studies were concerned in some manner with (a) the influence of the size and shape of the compaction mold (28, 34, 38, 51, 64, 67, 70, 105, 106,), (b) the effect of the method of determining the volume of the soil compacted in the mold (121), (c) degradation (12, 13, 21, 64, 67, 128), and (d) nature and content of coarse aggregate (17, 28, 31, 64, 67, 100, 106, 102). Some of the studies formed the basis for developing the formulas and computing the corrected maximum dry unit weight described here. Each of these sources should be studied if the reader desires a complete background for evaluating the various factors that may have some influence on the nature of the corrections that should be made to provide a representative value of calculated maximum dry unit weight for the total soil.

Theoretical Unit Weight Formula.—The authors have consulted a total of 16 engineering papers and discussions pertaining to formulas for computing the maximum dry unit weight of the total soil when aggregates that are larger than the maximum size permitted in the test are present. Of the 16 papers, 11 employed the theoretical density formula, one employed the formula altered to take into account the percent absorption of the "oversize" aggregate, (that is, material retained on the No. 4 or $^3/_4$-in. sieve; or other sieve if used to separate materials too large to be used in the compaction test), and two employed modifications of the theoretical formula. The theoretical density formula is as follows:

$$\gamma_d \text{ (calc)} = \frac{\gamma_{df} \; \gamma_{dc}}{\gamma_{df} \; P_c + \gamma_{dc} \; P_f} \qquad \text{(1a)}$$

in which

γ_d (calc) = the calculated maximum dry unit weight in pounds per cubic foot of the total sample;

γ_{df} = maximum dry unit weight in pounds per cu ft of the material passing the sieve used to separate the "oversize" aggregate;

γ_{dc} = the bulk specific gravity (oven-dry basis) of the "oversize" aggregate, multiplied by 62.4. The bulk specific gravity (oven-dry basis) may be determined by dividing the bulk specific gravity (saturated surface-dry basis) by 1 plus the absorption;

P_f = percent of material passing the No. 4 or the 3/4-in. sieve ÷ 100; and

P_c = percent of "oversize" material ÷ 100

The formula (26) taking into account the absorption of the coarse aggregate, is as follows:

$$\gamma_d \text{ (calc)} = \frac{\gamma_{df} \; \gamma'_{dc}}{\gamma_{df} P_c \; (1 + A) \; + \gamma'_{dc} \; P_f} \qquad \text{(1b)}$$

in which

A = percent absorption ÷ 100; and

γ'_{dc} = bulk specific gravity (saturated surface-dry basis) of the "oversize" aggregate multiplied by 62.4

Work by the U.S. Bureau of Reclamation.—Much discussion in the engineering literature concerns the accuracy and limitations of the "theoretical density curve" calculated by means of the previous formula. (Although termed "theoretical density curve" in the literature, the term is used hereafter as "theoretical dry unit weight" curve because the term unit weight has been standardized by engineering organizations.) For purpose of discussion, an example of the theoretical dry unit weight curve is represented by line ABCD in Figure 73 for a silty gravel soil. This soil was compacted in the laboratory with a 3-in. maximum size aggregate by means of the large scale Bureau of Reclamation compaction equipment described previously (1.5-cu ft mold, 185.7-lb rammer controlled to deliver a total compaction effort of 12,135 ft-lb per cu ft) and, with a 3/4-in. maximum size aggregate by means of the Bureau of Reclamation standard test using a 1/20-cu ft mold and a compaction effort of 12,375 ft-lb per cu ft. In addition, maximum dry unit weight determinations were also made for the minus No. 4 fraction by means of each of the two compaction procedures. The minus No. 4 fraction of the silty gravel had sand, silt, and clay contents of 35, 56, and 9 percent respectively, a liquid limit of 26, a plasticity index of 4, and a specific gravity of 2.67. The gravel had a specific gravity of 2.66. The maximum dry unit weight from the large-scale test was 113.6 pcf for the 3-in. maximum size. The maximum dry unit weight for the soil (minus No. 4 fraction) was 120.0 pcf for both the large-scale and Bureau of Reclamation standard test methods.

The original formula used for calculating data for line ABCD in Figure 73 appears above as formula No. 1 and is shown in the upper left of the figure. This formula is based on the assumption that the coarse aggregate in a compacted mixture acts as a displacer only. In other words, the theoretical dry unit weight curve in the figure represents the unit weight of the gravel-soil mixture when the compacted soil completely fills the space between the coarse aggregates and has a dry unit weight of 120 pcf.

The figure also shows the effect on the dry unit weight of the total material (containing soil and gravel) from 0 to 100 percent gravel content. First, the theoretical formula is valid only (92) if the dry weight of gravel per unit volume of total material

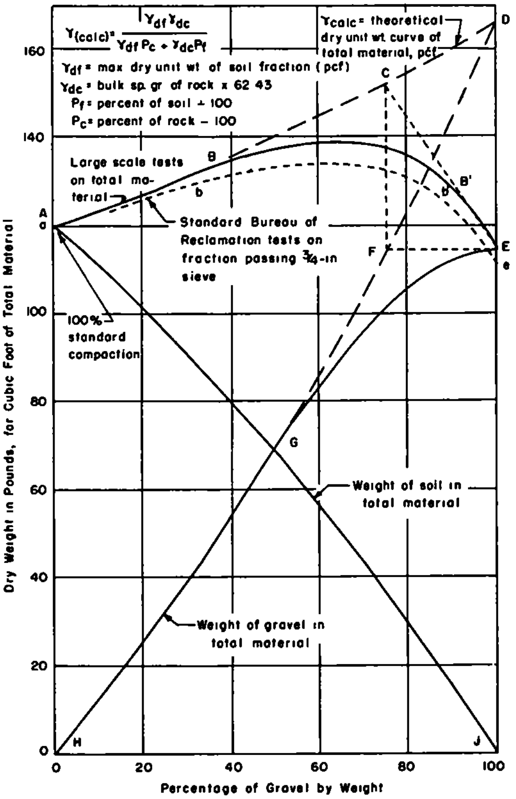


Figure 73. Maximum dry unit weight vs gravel content for silty gravel, 3-in. maximum size. Soil fraction has 35, 56, and 9 percent sand silt and clay; LL = 26, PI = 4 (106).

does not exceed the weight of gravel particles (generally taken as dry and rodded weight, but in this case is that obtained by the large scale compaction test on the gravel fraction only); this is shown as point E. If the material contains more than about 75 percent gravel particles by weight of the total material (point F), the relations as determined by the theoretical formula do not apply beyond point C. Second, as gravel is added to a fine soil, the soil unit weight (106) begins to be reduced because the coarse particles interfere with the compaction of the soil fraction; point B represents the percent gravel at which this begins to occur.

The percentages of gravel particles that a total material can contain and not exceed the physical limitations of the formula is called the upper theoretical limit of gravel. The weight of gravel and weight of soil in pounds per cubic foot of total compacted material are indicated in the figure as continuous heavy lines that cross beneath the theoretical density curve. In this case, the unit weight of gravel particles alone was found to be 113.6 pcf and the maximum dry unit weight of the soil fraction 120 pcf. Because the unit weight of the gravel cannot exceed 113.6 pcf the total material cannot theoretically contain more than 75 percent gravel, if the gravel voids are to be filled with compacted soil.

This example, representing a small part of the results of a study by the Bureau of Reclamation (106) on sandy, silty, and clayey gravel, is of particular interest because it also presents the relationship between maximum dry unit weight and gravel content for 3-in. maximum size silty gravel (Curve ABB'E) obtained with the large-scale compaction equipment and a similar relationship for the ¾-in. maximum size silty gravel (Curve abb'e) obtained with the standard Bureau of Reclamation compaction test apparatus (described in Table 1). It is also of interest because of the availability of distribution of coarse and fine materials by weight for

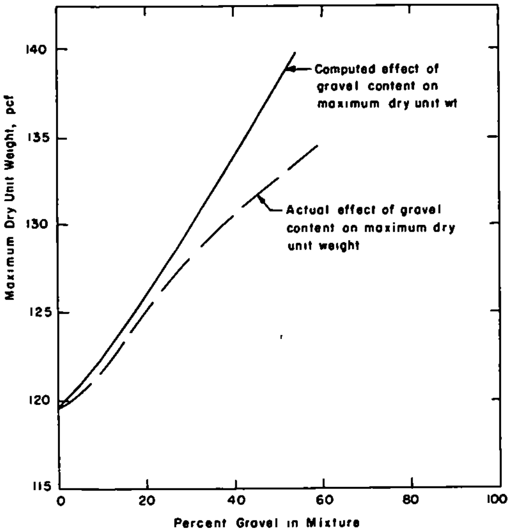


Figure 74. Comparison of maximum dry unit weights for various gravel contents with computed dry unit weights using Eq. 1 (28).

the full range of gravel contents as shown by curves HGE, HGD, and JA.

Curves JA and HGE show the weights of fine and coarse materials, respectively, in each cubic foot of total material, for various gravel contents (106). These curves were plotted from computed weights of the two materials as required to satisfy the requirements for the dry unit weights obtained by tests on the total material. Curve HGD is a theoretical curve showing the weight of gravel per cubic foot of total material required to satisfy the theoretical dry unit weight curve ABCD. The curve is not valid beyond point G for reasons mentioned previously. The curve does provide a means for locating point F. The gravel content at point F is the amount of gravel that can be contained in the total mixture without exceeding the physical limitations of the theoretical dry unit weight curve. Point C is located on the theoretical curve at the gravel content represented by F.

Dry unit weights of materials containing coarse aggregates and soil, whether compacted by field or laboratory methods, tend to fall below the theoretical dry unit weight curve with percentages of coarse material of approximately 30 percent. Actual coarse aggregate contents for the sandy, silty, and clayey soils in the Bureau of Reclamation tests (106) at which unit weights became less than theoretical were 28, 36, and 44 percent gravel respectively. The nature of the divergence for the silty soil (at 36 percent gravel) is also shown in Figure 73. The percentage causing the particle interference that results in dry unit weights less than theoretical may range from a low of 25 percent to a high of 50 percent for extremely well-graded material (92). Individual measurements show a scattering beyond 40 percent coarse material. In comparing the results for the sandy, silty, and clayey soils (106), the gravel fraction became effective in reducing the compaction of the fines at the lowest gravel content for the sandy soil. As the fines became smaller (the silty soil) and more plastic (the clayey soil), interference caused by the coarse particles was reduced as indicated by the gravel contents previously given.

Work by Zeigler, Mainfort and Lawton, and Krynine.—The authors either analyzed the theoretical dry unit weight formula mathematically or made direct comparisons between dry unit weights computed by means of the formula and actual laboratory compacted dry unit weights at various coarse aggregate contents. One of the early comparisons was made by Zeigler (28). His results are shown in Figure 74. The calculated dry unit weights exceed those obtained in laboratory tests.

Mainfort and Lawton (64) reported the results of a series of laboratory tests on a wide range of gradations of three materials: a gravel, a crushed limestone, and a slag. The results of their studies are discussed under "The Size and Shape of the Mold"; "The Nature of and Content of Coarse Aggregates"; and also under "Degradation During Compaction." None of the gradings had a soil matrix. The entire grading of each consisted of material from the same source to simulate materials used in base courses. They attempted to fit the theoretical dry unit weight formula to the charted results of their compaction tests. As a result, they modified the theoretical dry unit weight formula. The modified formula is as follows:

$$\gamma_{d\,(calc)} = \frac{P_f\ \gamma_{df}}{100} + \frac{0.9\gamma_{dc}\ P_c}{100} \qquad (2)$$

in which

$\gamma_{d\,(calc)}$ = the calculated maximum dry unit weight in pounds per cubic foot, of the total sample;

γ_{df} = the maximum dry unit weight, in pounds per cubic foot, of the material passing the sieve used to separate the "oversize" material;

γ_{dc} = the bulk specific gravity (see definitions, Appendix B) of the "oversize" aggregate multiplied by 62.4;

P_f = percentage of material passing the "oversize" sieve (No. 4 or ¾-in.); and

P_c = percentage of "oversize" material.

Comparisons of the calculated maximum dry unit weights of the total materials using the "theoretical dry unit weight" formula (Eq. 1a) and the modified Mainfort and Lawton formula (Eq. 2) with maximum laboratory compacted dry unit weights for the full range of "oversize" aggregate content (in this case, the material retained on the No. 4 sieve) are shown in Figures 50 and 51 for 1½-in. maximum size aggregate for the sand-gravel, the crushed limestone, and the slag. The modified formula results in closer agreement with the compacted maximum dry unit weights than does the original theoretical formula. Additional calculations (115) comparing the theoretical formula with the modified formula were made for an A-4 group silt loam to which had been added various percentages of materials retained on the No. 4 sieve. The results of those tests and calculations are shown in Figure 75.

Krynine (69) held that the theoretical dry unit weight formula gave exaggerated results for all percentages of "oversize" aggregate and discussed means for adjusting the formula to give a better correlation with dry unit weights obtained by compaction. He suggested that a simplified method of calculating the dry unit weight of the aggregate soil would be as follows:

Up to the value of $P_c = 0.6$

$$\gamma_{d\,(calc)} = \gamma_{df}\left[1 + P_c\left(1 - \frac{\gamma_{df}}{\gamma_{dc}}\right)\right] \qquad (3)$$

in which

$\gamma_{d\,(calc)}$ = the calculated maximum dry unit weight, in pounds per cubic foot, of the total sample;

γ_{df} = the maximum dry unit weight, in pounds per cubic foot of the material passing the sieve used to separate the "oversize" material (No. 4 or ¾-in. for standard tests);

γ_{dc} = the bulk specific gravity (see definitions, Appendix B) of the "oversize" aggregate multiplied by 62.4; and,

P_c = percentage of "oversize" material ÷ 100.

From $P_c = 0.6$ through $P_c = 0.8$, the value of $\gamma_{d\,(calc)}$ may be considered practically constant.

The writers performed computations to determine maximum dry unit weights of a crushed limestone for the purpose of comparing the results with those obtained by the use of Eqs. 1a, 2, and 3. The crushed limestone was 1½-in. maximum size and consisted wholly of crushed materials (no soil matrix); it had a bulk specific gravity of 2.69 and a maximum dry unit weight of the fraction passing the No. 4 sieve equal to 141 pcf. The results of the calculations compared to results of compacting the crushed limestone with various percentages of material retained on the No. 4 sieve are shown in Figure 76. The curve of maximum compacted dry unit weights represents test data obtained by the use of the ⅓₀-cu ft mold.

Charts and Nomographs.—Some authors have prepared charts or nomographs to facilitate the rapid determination of maximum dry unit weights of the total material from known values of compacted maximum dry unit weight of the fraction passing the No. 4 or the ¾-in. sieve. One form of chart prepared by the Corps of Engineers (26) based on Eq. 1b taking into account the absorption of the coarse aggregate is shown in Figure 77. This chart is prepared for a soil whose fraction passing the ¼-in. sieve has a specific gravity, G_s, of 2.46 and an absorption of 3 percent. The use of the chart is illustrated by the following example:

Given: Dry unit weight of material passing the ¼-in. sieve = 100 pcf. Percent retained on ¼-in. sieve = 40.

Problem: To determine the unit weight of the total material.

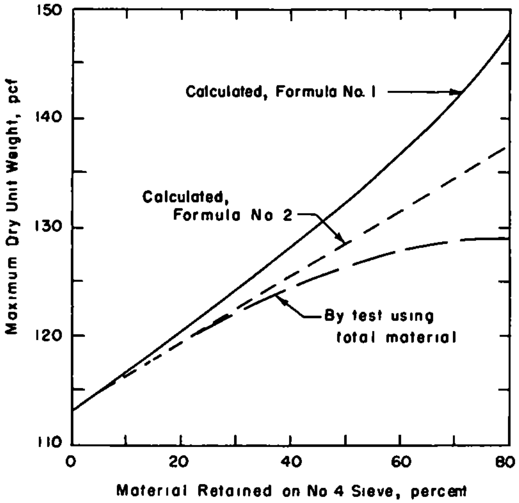


Figure 75. Comparison of compacted dry unit weights with unit weights calculated by means of the theoretical unit weight by means of Eqs. 1 and 2 (115).

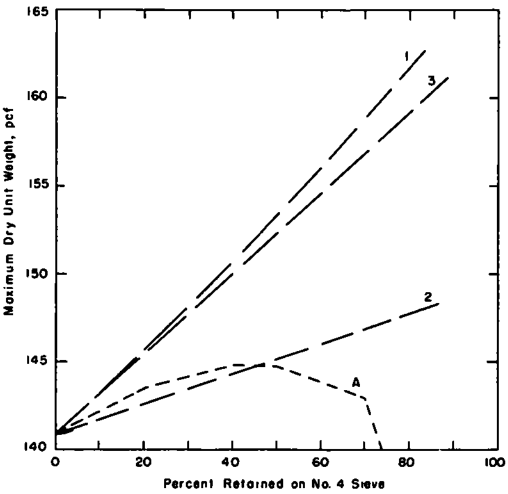


Figure 76. Comparison of actual maximum compacted dry unit weights (Curve A) for 1 ½-in. maximum size crushed limestone and unit weights calculated by use of Eqs. 1, 2 and 3.

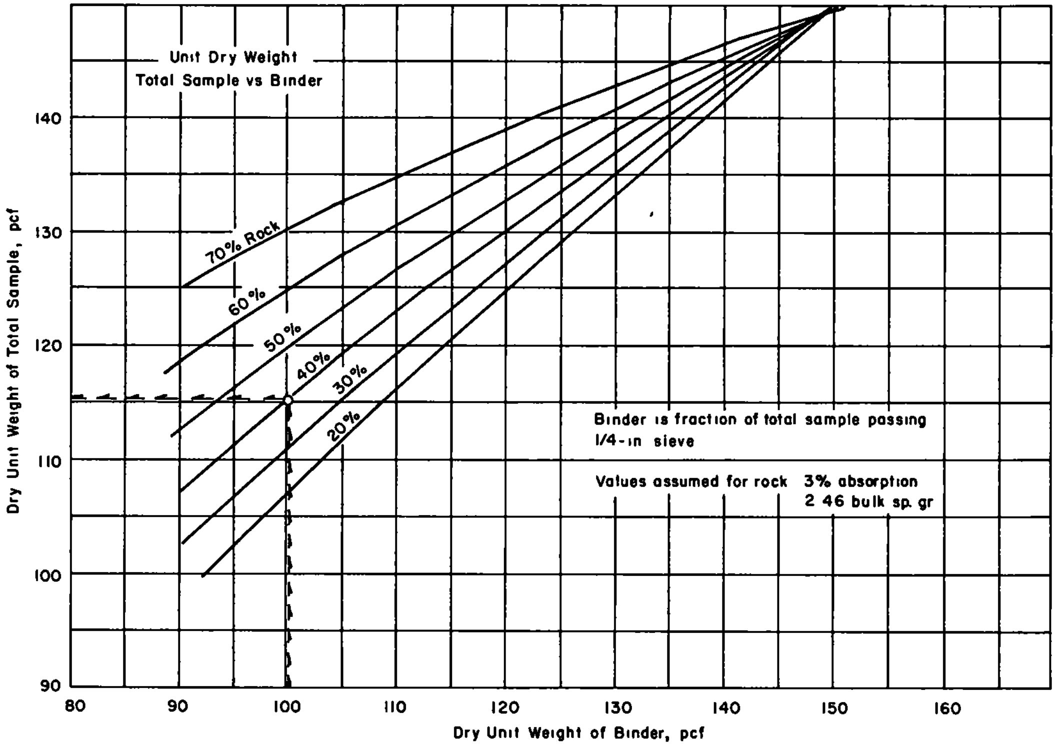


Figure 77. Chart for determining relationship between dry unit weight of fraction passing ¼-in. sieve and the total sample (26).

Enter Figure 77 on the scale at the base of the chart at 100 pcf and continue vertically to the intersection with the 40 percent rock line. From that point, read the dry unit weight of the total sample on the scale of values on the ordinate to the left. The appropriate value is about 115 pcf. The chart may also be used to determine the unit dry weight of the portion passing the ¼-in. sieve if the maximum dry unit weight of the total material and the percent passing the ¼-in. sieve are known.

Another chart, in the form of a nomograph, based on the theoretical formula, has been prepared by the Washington Department of Highways (56) and is shown in Figure 78. The same example, except for a specific gravity of 2.65, instead of 2.46, is employed to explain the use of the nomograph. Project a line from the point of 60 percent fines on the left-hand scale, across to the value of 100 pcf on the line representing the maximum dry unit weight of the portion passing the "oversize" sieve at the extreme right. The point of intersection with the line of corrected dry unit weight for a specific gravity of 2.65 is 118.5 pcf.

Another nomograph, based on the theoretical unit weight formula, has been prepared by the Virginia Department of Highways and is shown in Figure 79. Using the data given in the Washington example, the maximum dry unit weight of the total material (with 40 percent coarse aggregate) is 118.7 pcf.

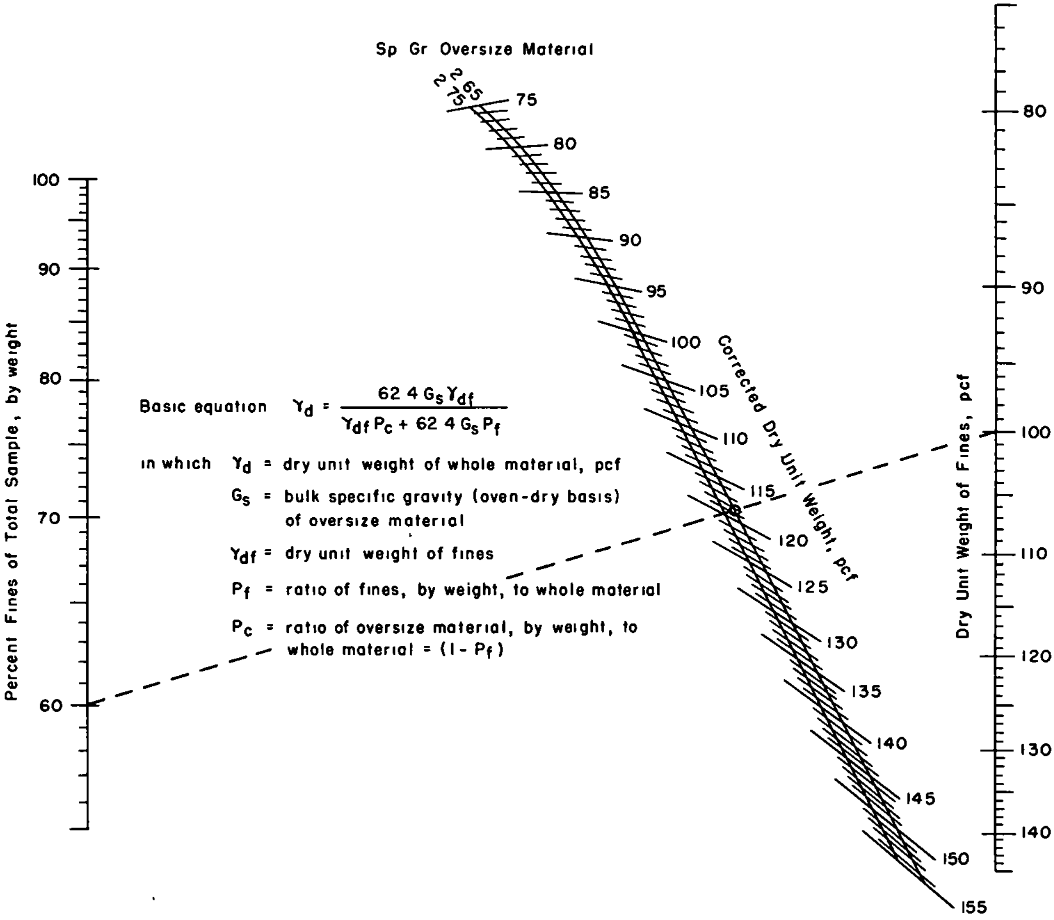
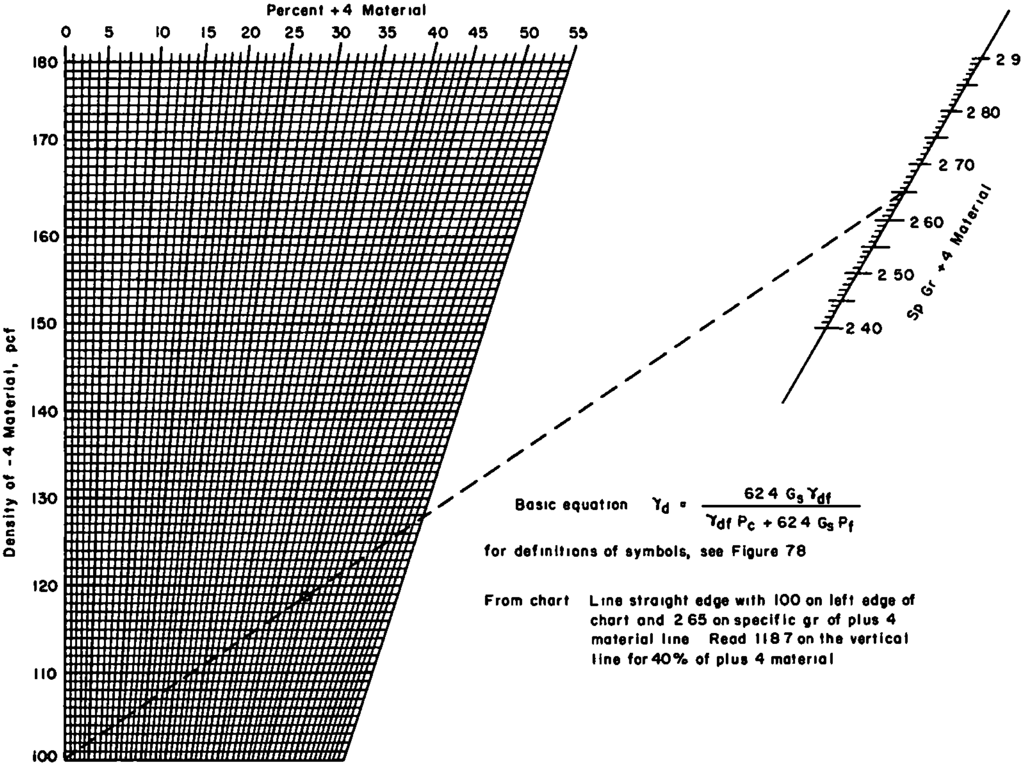


Figure 78. Nomograph for correcting dry unit weight for the content of oversize material (56).



Basic equation $\gamma_d = \frac{62.4\, G_s \gamma_{df}}{\gamma_{df} P_c + 62.4\, G_s P_f}$

for definitions of symbols, see Figure 78

From chart Line straight edge with 100 on left edge of chart and 2.65 on specific gr of plus 4 material line. Read 118.7 on the vertical line for 40% of plus 4 material

Figure 79. Method for determining total unit weights of soils (136).

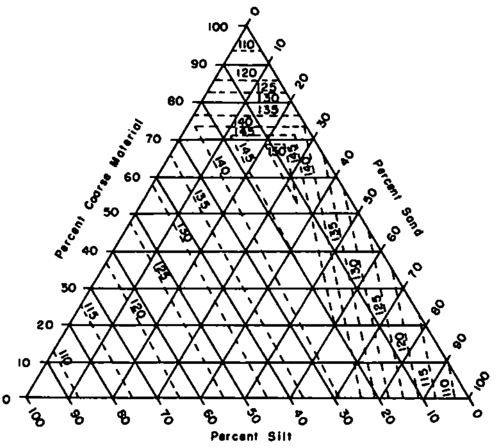


Figure 80. Triangular chart showing maximum dry unit weights for total material for various proportions of coarse aggregate, sand, and silt (58).

Another type of chart is the triangular one in Figure 80. This type of chart is normally used in showing the limits of percent sand, silt, and clay in various soil texture groups. It is adapted here to the three-part combination of coarse material (retained on the No. 4 or ¾-in. sieve), sand (passing No. 4 and retained on No. 200 sieve), and soil fines that may be classified as silt or silt and clay. Here values of dry unit weight have been superimposed. The values of dry unit weight may be obtained by calculation by means of the absolute volume method (58, 76) if the type of aggregates and fines permit. This method could not be used for a soil having a plastic clay fraction because of the swelling nature of the clay when wet.

It is apparent that the previously described methods for calculating dry unit weight, both in formula and chart form are, in the main, valid for materials whose fraction passing the No. 4 sieve (or the ¾-in. sieve) is more than sufficient to fill the voids between the coarse aggregates. Although few soils normally used in fills or subgrades have insufficient material passing the limiting sieve (No. 4 or $^3/_4$-in.) to fill the void spaces between the coarse aggregates, acceptable base course materials may have insufficient material passing the limiting sieve to fill the voids in the coarser materials. For materials having proportions falling within this group, different methods for calculating weights have been devised.

Missouri Methods. —The Missouri State Highway Department has devised such a method for use in construction of crushed rock base (93). Tests on crushed rock from 12 different geological formations showed that the average void content of the coarse aggregate was 42 percent. Thus a cubic foot of material with insufficient material passing the No. 4 sieve to fill all the voids of the plus No. 4 material will have 58 percent of 1 cu ft of coarse aggregate plus some amount of fine materials filling part of the voids. Therefore the coarse portion of a cubic foot of material with an inadequate proportion of fines to fill the voids between the coarse fraction will always weigh 58 percent of the weight of a solid cubic foot of the same kind of rock, which 58 percent is the dry and rodded weight of the fraction retained on the No. 4 sieve. This weight when divided by the percent by weight of the material retained on the No. 4 sieve will give the weight per cubic foot of the total sample, or

$$\gamma_d = \frac{(0.58)\,(G_s)\,(62.4)}{P_c}$$

The foregoing statements may be clarified by the use of an example.

Given:

1. A granular material with 35 percent by weight passing the No. 4 sieve. This is less than 42 percent and is therefore insufficient to fill the voids in the coarse aggretate.
2. The specific gravity (bulk specific gravity, ASTM Definition: E 12-27, determined by test in accordance with ASTM Designation: C 127-42, AASHO T 85-45) is 2.60.
3. Weight of a solid cubic foot of coarse aggregate = 2.60 x 62.4 = 162.24 pcf.
4. Weight of plus No. 4 material is 58 percent of 162.24 or 94.1 lb.
5. The retained portion (65 percent by weight) thus equals 94.1 lb.
6. The weight per cubic foot of the total material is 94.1 ÷ 0.65 = 144.8 pcf.

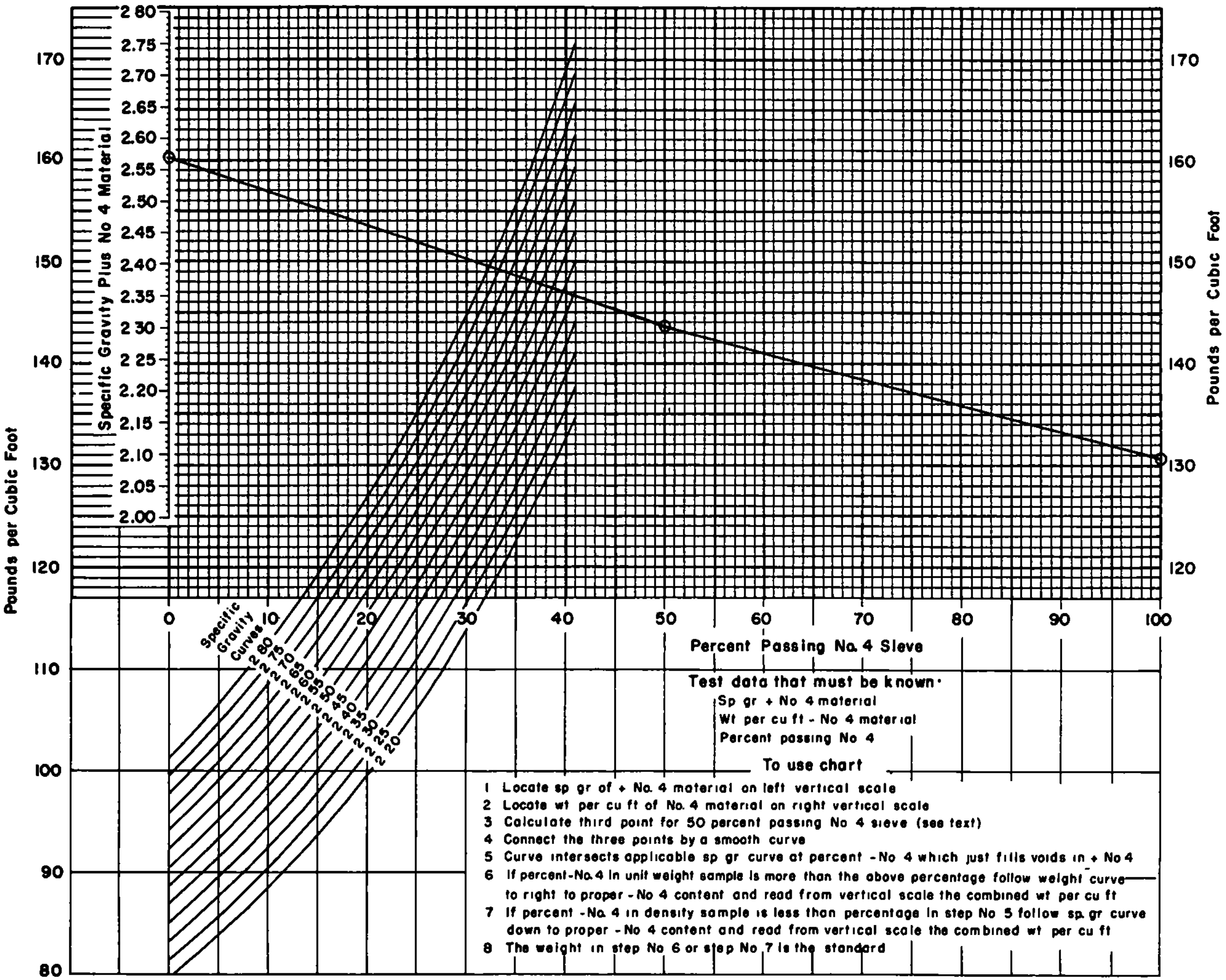
Missouri has developed a chart (Fig. 81) for determining the unit weight of crushed rock mixtures for the two cases where the fines are (a) more than sufficient to fill the voids in the coarse aggregate and (b) insufficient to fill the voids in the coarse aggregate. In using the chart, the specific gravity of the coarse aggregate is plotted on the left vertical scale. This also determines the solid weight per cubic foot of the coarse aggregate and is the point representing 0 percent passing the No. 4 sieve. The compacted dry weight per cubic foot of the material passing the No. 4 sieve, as determined by test is plotted on the right vertical scale, and represents 100 percent passing the No. 4 sieve. A third point is calculated for 50 percent passing the No. 4, using the theoretical unit weight formula (Eq. 1a), and the three points are connected by a smooth curve.

The specific gravity of the coarse portion of the sample is then located in the family of curves. If the specific gravity lies between two of the charted curves an interpolation is made. The intersection of this curve (charted or interpolated) with the curve that connects the weights of 100 percent, 50 percent, and 0 percent plus No. 4 materials represents the percentage point at which the plus No. 4 voids are exactly filled with minus No. 4 sizes.

The following examples illustrate the uses of the chart when the minus No. 4 content of the sample is either more or less than the indicated percentage.

Given:

1. Compacted dry weight per cubic foot of fraction passing No. 4 sieve = 130.4 pcf.



Test data that must be known·

Sp gr + No 4 material

Wt per cu ft - No 4 material

Percent passing No 4

To use chart

1 Locate sp gr of + No. 4 material on left vertical scale
2 Locate wt per cu ft of No. 4 material on right vertical scale
3 Calculate third point for 50 percent passing No 4 sieve (see text)
4 Connect the three points by a smooth curve
5 Curve intersects applicable sp gr curve at percent -No 4 which just fills voids in + No 4
6 If percent-No. 4 in unit weight sample is more than the above percentage follow weight curve to right to proper -No 4 content and read from vertical scale the combined wt per cu ft
7 If percent -No. 4 in density sample is less than percentage in step No 5 follow sp. gr curve down to proper -No 4 content and read from vertical scale the combined wt per cu ft
8 The weight in step No 6 or step No 7 is the standard

Figure 81. Chart of weight per cubic foot for crushed rock (93).

2. Specific gravity of material retained on No. 4 sieve = 2.57.
3. Percent passing No. 4 sieve, for Case I = 47, for Case II = 32.

Procedure:

1. Plot 2.57 specific gravity on left vertical scale. This corresponds to 160.4 pcf.
2. Plot 130.4 lb on right vertical scale.
3. Compute the third point as follows:

$$\gamma_{50} = \frac{\gamma_{df}\ \gamma_{dc}}{\frac{1}{2}\gamma_{df} + \frac{1}{2}\gamma_{dc}} = \frac{2 \times 130.4 \times 160.4}{130.4 + 160.4} = 143.9 \text{ pcf}$$

4. Plot 143.9 on the 50 percent line and draw a smooth curve to connect the three points.
5. Select the point at which a curve representing a specific gravity of 2.57 intersects the curve in Step 4. This is the percentage of material passing the No. 4 sieve that exactly fills the voids in the material retained on the No. 4 sieve (37.2).

Case I: 47 Percent Passing No. 4 Sieve.—Because the percent passing the No. 4 sieve in the sample is greater than the percentage determined in Step 5, follow the horizontal curve to the right to the percentage found in the sample (47 percent) and read the weight of the total material from either vertical scale (144.8 lb).

Case II: 32 Percent Passing No. 4 Sieve.—Because the percent passing the No. 4 sieve in the sample is less than the percentage determined in Step 5, follow the 2.57 specific gravity curve downward to the percentage found in the sample (32 percent) and read the weight of the total material from either vertical scale (136.6 lb).

It is apparent, from this review of current and older methods for correcting the effect of coarse aggregate on unit weight that there remains ample opportunity for correlating existing formulas and charts with laboratory and field compaction results on a wide range of textures, and making adjustments in existing formulas or developing new ones that make it possible to calculate the effect of coarse aggregate content on unit weight with greater accuracy.

CORRECTING MOISTURE CONTENT FOR COARSE AGGREGATE CONTENT BY COMPUTATION

Performing the compaction test on the fraction passing the No. 4 or ¾-in. sieve and correcting the maximum dry unit weight for the content of coarse aggregate must, in most instances be accompanied by similar correction of the moisture content. The Corps of Engineers (26) investigated this relationship between moisture content of soils with and without coarse aggregates and devised the following equation for computing the moisture content of the total material if the moisture content of the material passing the ¼-in. sieve is known and vice versa. The notations in the equation have been changed, but the interrelationship remains as originally reported (26):

$$w = w_f (1-P_c) + AP_c \tag{4}$$

and

$$w_f = \frac{w - AP_c}{1 - P_c} \tag{5}$$

in which

w = moisture content of total material (expressed as a decimal);

w_f = moisture content of portion passing ¼-in. sieve (expressed as a decimal);

P_c = percent by weight (expressed as a decimal) of material retained on the ¼-in. sieve;

A = percent absorption (expressed as a decimal) of material retained on the $\frac{1}{4}$-in. sieve.

The following example serves to illustrate the use of Eq. 4:

Given:

1. Moisture content of the portion passing the $\frac{1}{4}$-in. sieve = 11.33 percent or w_f = 0.1133.
2. Percent retained on the $\frac{1}{4}$-in. sieve = 40 percent, $P_c = 0.4$.
3. Absorption of material retained on $\frac{1}{4}$-in. sieve = 3 percent, A = 0.03.

To determine: The moisture content of the total sample, w.

$$w = w_f (1 - P_c) + AP_c$$

$$w = 0.1133 (1 - 0.4) + 0.03 \times 0.4 = 0.08 \text{ or } 8 \text{ percent}$$

For some projects it may be desirable to compute those relationships for a wide range of values and construct families of curves so that moisture contents may be read from charts similar to that shown in Figure 82. The relationship between moisture content of the total sample and the portion passing the $\frac{1}{4}$-in. sieve is dependent only on the percentage of material retained on the $\frac{1}{4}$-in. sieve and the percent absorption. McLeod (121) reported the use of a similar formula.

A slightly different approach was employed by Zeigler (28). It was assumed that (a) the moisture content of the portion passing the No. 4 sieve at maximum dry unit weight remains constant for various percentages of gravel, and (b) the gravel absorbed 0.4 percent moisture and retains 0.6 percent free moisture for a total of 1.0 percent moisture. This percentage of total moisture was considered the maximum amount that the gravel could hold without "draining off." The equation employed to determine the optimum moisture content of the whole material was

$$w = w_f (1 - P_c) + 0.01 P_c \tag{6}$$

in which the symbols have the same meanings as those given for Eq. 4 except that the fine fraction is defined as material passing the No. 4 sieve. For example, assume that

$$w_f = 0.1133 \text{ and } P_c = 0.6,$$

then

$$w = 0.1133 (1 - 0.6) + (0.01) (0.6) = 0.051 = 5.1 \text{ percent}$$

Figure 83 permits comparison of actual and computed moisture contents and illustrates the effect of increasing the gravel content on the reduction of the optimum moisture content. This may also be seen in the actual moisture content vs dry unit weight curves in Figure 49.

A triangular chart can also be used to show the relationship between optimum moisture content and proportions of various sizes used, as shown in Figure 84.

THE HUMPHRES METHOD FOR GRANULAR SOILS

The Humphres method (102) consists of establishing the maximum obtainable (that is, with current construction equipment) unit weight of a granular material for different percentages of fine aggregate (portion passing the No. 4 sieve). The method is intended for use with ballast, base course, and surfacing materials with specified gradations. The maximum unit weight curve developed, which relates maximum unit weight and percentage of fine aggregate, can be used by the compaction inspector to determine the proper "control" unit weight of material whose gradation fluctuates between fairly wide specification limits. To determine the proper "control" value, the inspector need only determine the percentage of fine aggregate in his sample and refer to the maximum unit weight curve for the material sampled.

To establish the maximum unit weight curve, for one material, the following 12 steps are necessary:

1. Oven-dry a representative sample of the granular material at 110 to 120 F.

2. Divide a sample into two parts: coarse aggregate, retained on No. 4 sieve; fine aggregate, passing No. 4 sieve.

3. Determine the maximum compacted dry unit weight of each part by using a combination of vibratory and static loading. (The vibratory spring load compactor unit is described in detail in HRB Bull. 159 (1957). Other methods of vibratory compaction (120) that yield comparable unit weights can also be used in determining maximum unit weight.) The maximum compacted dry unit weight of the fine aggregate is represented by γ_f^c ($\gamma_{fine}^{compacted}$) and the maximum compacted dry unit weight of the coarse aggregate by γ_c^c ($\gamma_{coarse}^{compacted}$).

4. Determine the loose dry unit weight of each part (γ_f^l; γ_c^l) by gently pouring each through an appropriately-sized funnel into a container of known volume, weighing, and calculating dry unit weight. The size of sample, pouring device, and volume of measure based on maximum particle size given in Table 27 may be used (121).

5. Determine the solid unit weight of each part (γ_f^s; γ_c^s). First determine the specific gravity of each (for fine aggregate, test ASTM D 854-52 or AASHO T 100-54; for coarse aggregate, apparent specific gravity ASTM C 124-42 or AASHO T 85-45), then multiply each specific gravity by 62.4.

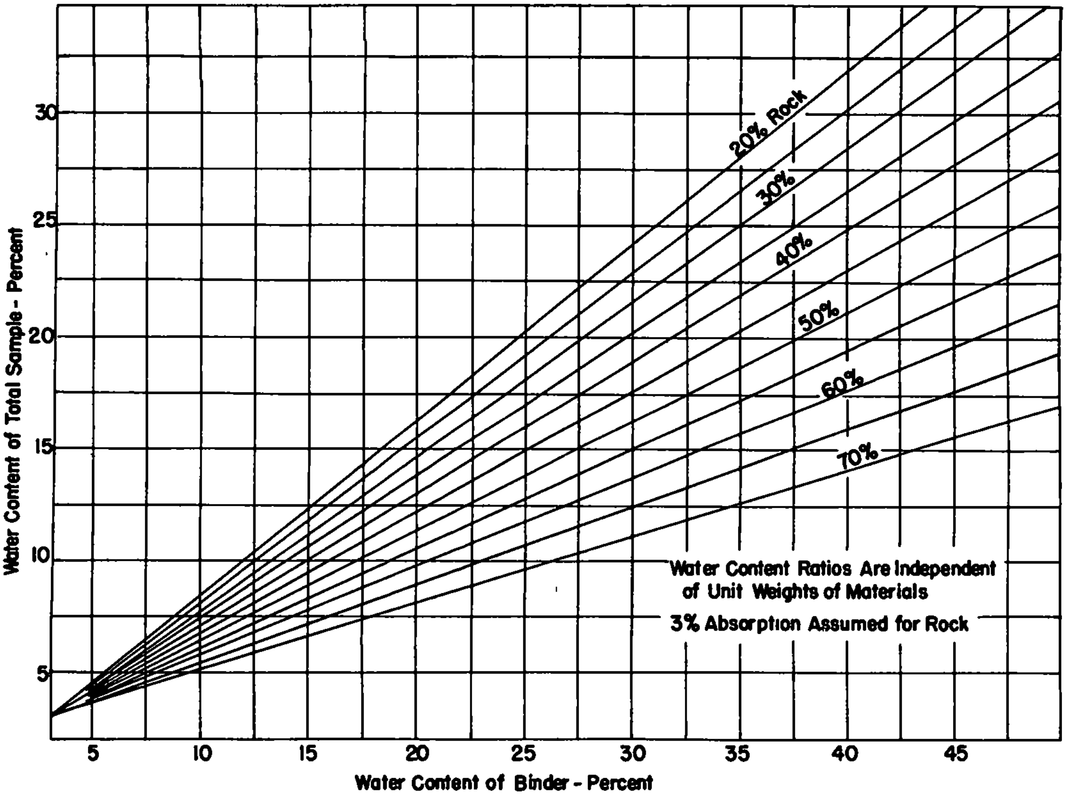


Figure 82. Chart for determining relation between water content of portion passing $\frac{1}{4}$-in. sieve and total sample (26).

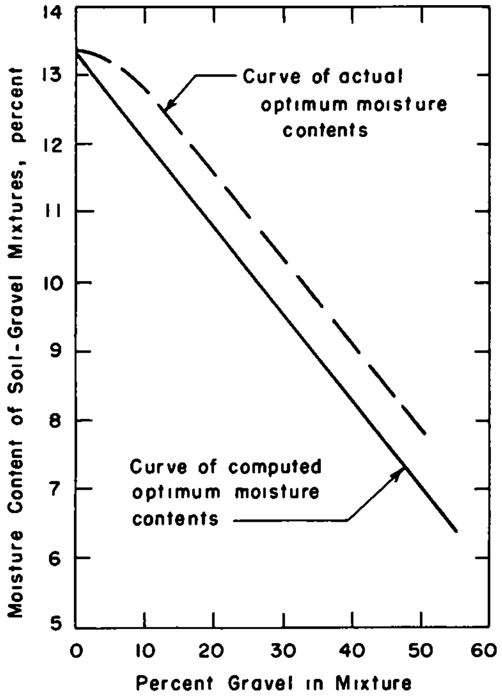


Figure 83. Effect of coarse aggregate (gravel) content on optimum moisture content (28).

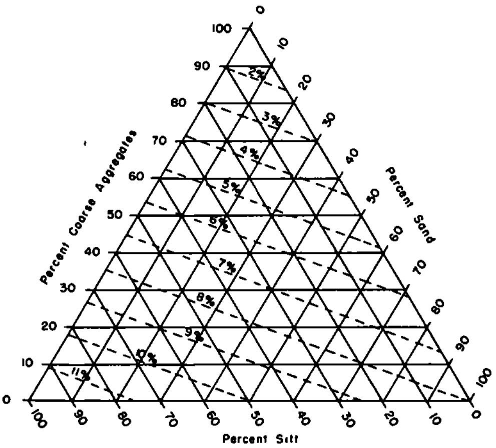


Figure 84. Triangular chart showing optimum moisture content of total material for various proportions of coarse aggregate, sand, and silt (58).

TABLE 27

Max. Size of Soil Particle (in.)	Size of Sample (lb)	Pouring Device	Volume of Measure (cu ft)
3	150	Shovel	1.0
1½	150	Scoop	0.5
¾	100	1½-in. spout	0.5
⅜	25	1-in. spout	0.1
¼	25	½-in. spout	0.1

6. Plot the three unit weights (loose, compacted, and solid) for the coarse aggregate and the fine aggregate on a chart (as in Fig. 85) relating unit weight to percentage of fine aggregate. The three unit weights for coarse aggregate are plotted on the left side of the chart on the zero percent vertical line. The three unit weights for the fine aggregate are plotted on the right side, on the 100 percent vertical line.

The data used in the example in Figure 85 are, as follows:

Coarse aggregate:

$\gamma_c^s = (2.73)(62.4) = 170.3$ pcf

$\gamma_c^c = 107$ pcf

$\gamma_c^l = 89$ pcf

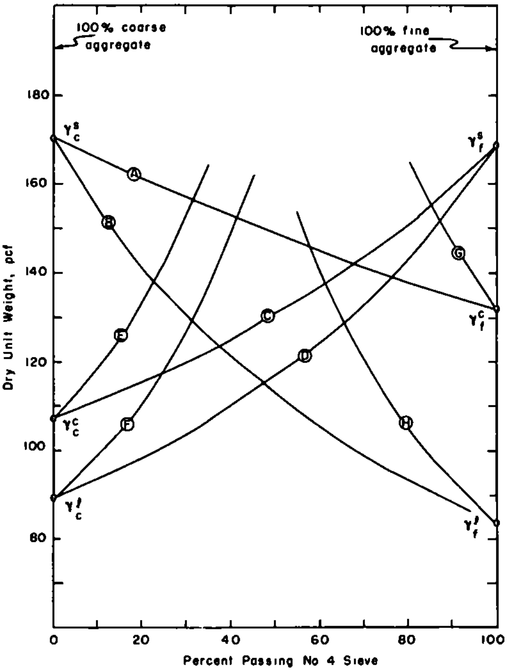


Figure 85. Sample theoretical curves for various combinations of coarse and fine aggregate and for solid, compacted, and loose unit weights (102).

Fine aggregate:

$$\gamma_f^S = (2.71)(62.4) = 169.0 \text{ pcf}$$

$$\gamma_f^C = 132 \text{ pcf}$$

$$\gamma_f^l = 84 \text{ pcf}$$

7. Determine sufficient points to plot each of the curves A, B, C, ...H, as shown in Figure 85, with the aid of the nomographs in Figures 86 and 87 or by using the following equations, and plot the curves. These curves will be used as guides in establishing the maximum unit weight curve. The equations for each curve, A through H, are as follows:

Curve A (theoretical unit weight formula)

$$\gamma_p = \frac{\gamma_c^S \; \gamma_f^S}{\left(\frac{p}{100}\right)\gamma_c^S + \left(\frac{1-p}{100}\right)\gamma_f^C}$$

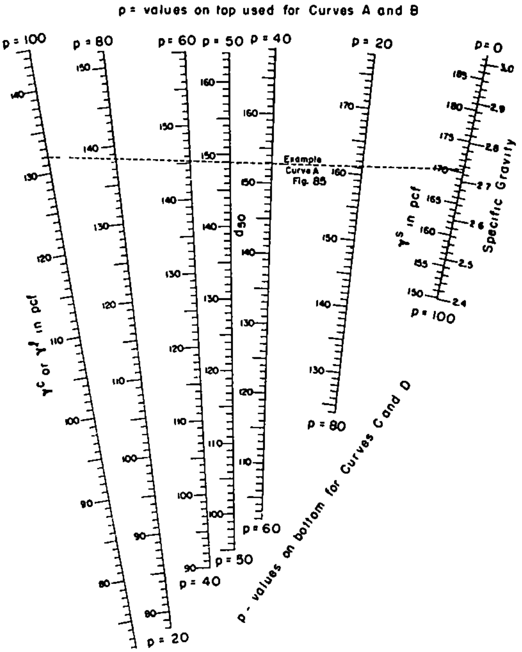


Figure 86. Nomograph for determining unit weight values (γ_p) for curve A, B, C, or D for different values of p, the percentage passing the No. 4 sieve (102).

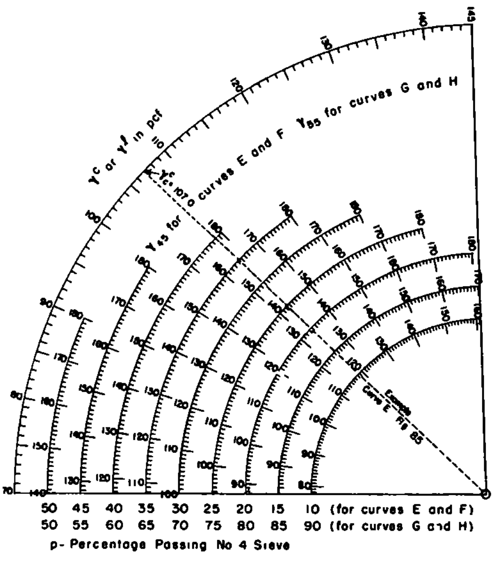


Figure 87. Nomograph for determining unit weight values (γ_p) for curve E, F, G, or H for different values of p, the percentage passing the No. 4 sieve (102).

in which

p = percentage of fine aggregate;

γ_p = unit weight of combination with p percent fine aggregate, pcf;

$\gamma_c{}^s$ = solid unit weight of coarse aggregate, pcf; and

$\gamma_f{}^c$ = compacted unit weight of fine aggregate, pcf.

For example, the ordinate (γ_p) on curve A (Fig. 85) for a given mixture (with 20 percent fine aggregate, $\gamma_c{}^s$ = 170 pcf and $\gamma_f{}^c$ = 132 pcf) is

$$\gamma_{20} = \frac{(170)\ (132)}{\left(\frac{20}{100}\right)(170) + \left(1 - \frac{20}{100}\right)(132)} = \frac{(170)\ (132)}{(0.2)\ (170) + (0.8)\ (132)}$$

$$\gamma_{20} = 160.8 \text{ pcf}$$

Curve B:

$$\gamma_p = \frac{\gamma_c{}^s\ \gamma_f{}^1}{\left(\frac{p}{100}\right)(\gamma_c{}^s) + \left(1 - \frac{p}{100}\right)\gamma_f{}^1}$$

Curve C:

$$\gamma_p = \frac{\gamma_c{}^c\ \gamma_f{}^s}{\left(\frac{p}{100}\right)\left(\gamma_c{}^c\right) + \left(1 - \frac{p}{100}\right)\left(\gamma_f{}^s\right)}$$

Curve D:

$$\gamma_p = \frac{\gamma_c{}^1\ \gamma_f{}^s}{\left(\frac{p}{100}\right)\left(\gamma_c{}^1\right) + \left(1 - \frac{p}{100}\right)\left(\gamma_f{}^s\right)}$$

Curve E:

$$\gamma_p = \frac{\gamma_c{}^c}{1 - \frac{p}{100}}$$

Curve F:

$$\gamma_p = \frac{\gamma_c{}^1}{1 - \frac{p}{100}}$$

Curve G:

$$\gamma_p = \frac{\gamma_f{}^c}{\frac{p}{100}}$$

Curve H:

$$\gamma_p = \frac{\gamma_f{}^1}{\frac{p}{100}}$$

8. Label intersections of the curves (as shown in Figure 88) as follows: Curves B and E intersect at point a, G and D at b, A and D at c, B and D at d, A and F at e, and C and H at f.

9. Calculate the coordinates of point r (Fig. 88) between points $\gamma_c{}^c$ and e as shown in the following equation and plot point r.

$$p_r = 0.5\ p_e$$

$$\gamma_r = \frac{\gamma_c{}^c\ \gamma_e}{0.5\gamma_c{}^c + 0.5\gamma_e}$$

in which

p_r = percentage of fine aggregate in mixture represented by point r;
p_e = percentage of fine aggregate in mixture represented by point e;
γ_r = unit weight of mixture represented by point r, pcf;
γ_e = unit weight of mixture represented by point e, pcf; and
γ_c^c = compacted unit weight of coarse aggregate, pcf.

If, for example, $p_e = 41.5$ percent $\gamma_e = 152.0$ pcf, and $\gamma_c^c = 107.0$ pcf,

$$p_r = -(0.5)(41.5) = 20.75 \text{ percent}$$

$$\gamma_r = \frac{(107)(152)}{(0.5)(107) + (0.5)(152)} = \frac{16270}{53.7 + 76} = 125.6 \text{ pcf}$$

10. Draw a smooth curve from γ_c^c through point r to e; label intersection with curve B, point o.

11. Draw straight lines ab and de and label their intersection point m; draw straight lines ac and df and label their intersection n.

12. Draw the maximum unit weight curve through γ_c^c, r, o, m, n, and γ_f^c as shown in Figure 89.

This maximum unit weight curve shows how the maximum obtainable dry unit weight of a particular material varies with the percentage of fine aggregate in the mixture. In Figure 89 it can be seen that for the sample material, the maximum unit weight increases rapidly as the fine aggregate content increases from 0 to about 35

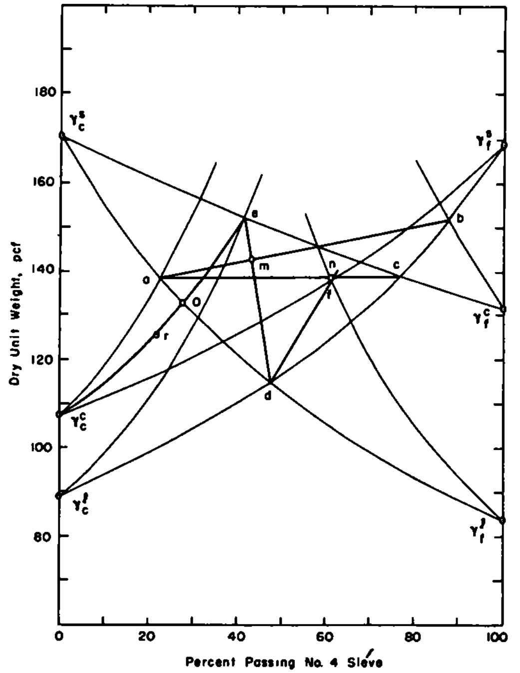


Figure 88. Determination of points (r, o, m, n) for maximum unit weight curve for mixtures of sample materials (102).

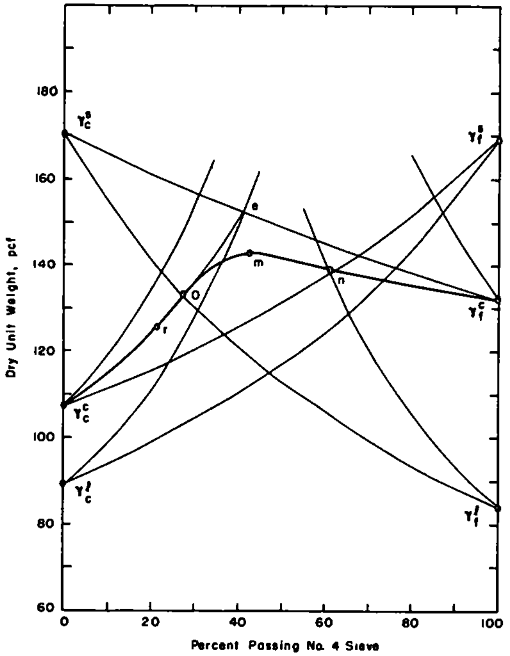


Figure 89. Derived maximum unit weight curve for mixtures of sample materials (102).

percent of the mixture. For the higher percentages of fine aggregate, fluctuations in gradation would have less effect on maximum unit weight.

The Humphres method is complex and lengthy, but has proved very useful in the State of Washington.

If several points on the Humphres maximum dry unit weight curve could be obtained by simply compacting several mixtures of coarse and fine aggregate, much time could be saved. James and Larew (133) investigated this possibility. They performed a series of impact compaction tests on two materials: a crushed limestone and a natural gravel. For each material, they first established the Humphres maximum unit weight curve. Then, they determined the compaction effort required to compact the fine aggregate (100 percent passing the No. 4 sieve) to the same unit weight as obtained in the Humphres method. Finally, they determined the maximum unit weight for each of several mixtures. The resulting maximum unit weight curve for the crushed limestone matched the Humphres curve very closely; the curve for the natural gravel generally fell below the Humphres curve. James and Larew concluded that the Humphres maximum unit weight curve represents a single level of compaction effort for some soil materials. It was also evident that a simple impact compaction test could not be used to duplicate the Humphres method for all soil-aggregate mixtures.

Comparisons of Maximum Unit Weights and Optimum Moisture Contents for Various Compaction Test Methods

The several types of laboratory compactors and test procedures have been described briefly under "Principal Methods for Determining Maximum Unit Weight and Optimum Moisture Content." In fact, all of the preceding information concerns differences in results obtained due to differences in test apparatus and procedure. The subject matter that follows makes direct comparisons between results obtained with AASHO and ASTM impact methods and results obtained by other methods. The comparative results shown are, in the main, limited to the effect of compaction effort on maximum dry unit weight. It is of interest also to examine the differences in optimum moisture content and percent air voids that result from the different test methods.

STANDARD AASHO-ASTM METHOD VS MODIFIED AASHO METHOD

The two most commonly used methods throughout the United States are the Standard AASHO-ASTM Method and the Modified AASHO method as adopted by the Corps of Engineers. Standard AASHO-ASTM method refers to AASHO Designation: T 99-57, Method A, which is the same as ASTM Designation: D 698-58T, Method A. This method is commonly referred to as AASHO T 99 or ASTM D 698. The Modified AASHO method is the basis for AASHO Designation: T 180-57 and is referred to here because most of the test data was collected before the standardization of AASHO T 180-57.

Some of the essential differences in results are indicated for a silty clay in Figure 90. In that figure are shown compaction curves not only for compaction efforts approximately equivalent to those of Standard AASHO (curve 3) and Modified AASHO (curve 1), but also for two other compaction efforts. The two additional curves are included to show that the position of the line of optimum moisture contents approaches the line of saturation as the compaction effort is increased and as the resulting maximum dry unit weight also is increased. In other words, increasing the compaction effort not only increases maximum dry unit weight and decreases optimum moisture content, but insofar as is known, also decreases the percentage of air voids for all soils, unless compaction is seriously affected by the relationship between the size of the mold and the maximum size of the aggregate or some other significant factor in the apparatus or method influencing compaction. The data on number of layers, blows per layer, weight, and drop of the hammer are shown in Table 28.

TABLE 28

DETAILS OF COMPACTION METHODS USED TO OBTAIN COMPACTION CURVES (6-in. Diameter Mold) (41)

No. of Layers	Blows per Layer	Weight of Tamper (lb)	Free Drop (ft)	Applied Energy (ft-lb/cu ft)	Remarks
5	55	10	1.5	56,038	Mod. AASHO[a]
	26	10	1.5	26,490	
	12	10	1.5	12,226	AASHO[a]
3	25	5.5	1.0	5,603	

[a] Compaction efforts indicated are approximately equivalent to those of Standard AASHO and Modified AASHO.

Differences in maximum dry unit weight, optimum moisture content, and air voids for the two principal types of compaction for nine different soils representing a wide range in textural types are given in Table 29. The results from the two compaction tests show that the greatest differences in maximum dry unit weight and optimum moisture content for the two methods are for the more plastic clays, silty clays, loams, and silt loams. The differences become small for the noncohesive sands and even smaller for the uniformly-graded ("one-size") fine sand. Table 28 also provides essential data on the index properties of the nine soils tested. A more simple means for showing the comparative data on maximum dry unit weight and optimum moisture content from the two tests is used in Table 30 which indicates the increase in maximum dry unit weight and decrease in optimum moisture content obtained from the modified test.

The air voids, at optimum moisture content, expressed as percent moisture

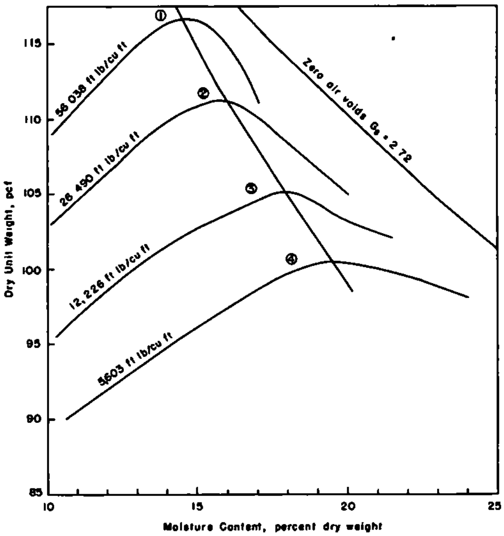
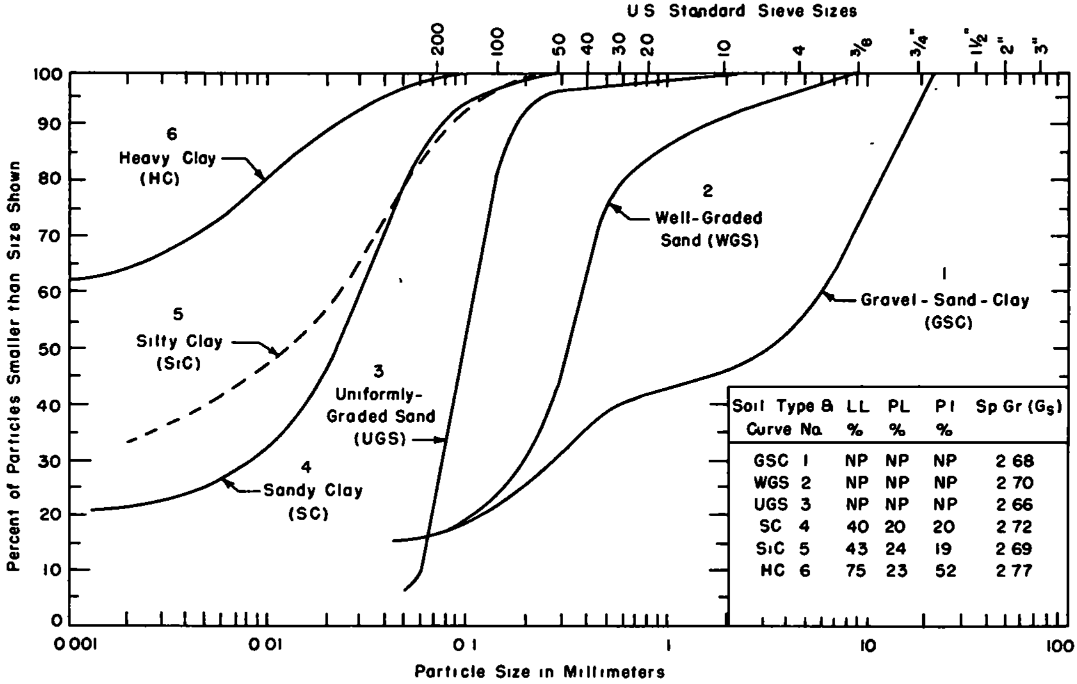


Figure 90. Compaction curves for a silty clay (LL = 37, PI = 14) at four different compaction efforts in a 6-in. diameter mold. Note not only the reduction in optimum moisture content but also the reduction in air voids (41).



Soil Type & Curve No.	LL %	PL %	PI %	Sp Gr (G_s)
GSC 1	NP	NP	NP	2 68
WGS 2	NP	NP	NP	2 70
UGS 3	NP	NP	NP	2 66
SC 4	40	20	20	2 72
SiC 5	43	24	19	2 69
HC 6	75	23	52	2 77

Figure 91. Index properties and grain-size distributions of soils used in full-scale compaction studies in Great Britain (49, 77).

TABLE 29

COMPARISON OF RESULTS OF STANDARD AASHO AND MODIFIED AASHO COMPACTION TESTS

Soil	Classification		LL	PI	G_s	Standard AASHO Test			Modified AASHO Test			Reference Source
	AASHO	Unified				Max Dry Unit Wt (pcf)	OMC (%)	% Water by Wt to Fill Voids at OMC	Max Dry Unit Wt (pcf)	OMC (%)	% Water by Wt to Fill Voids at OMC	
Keith (Neb) B-horizon silt loam	A-6(10)	CL	37	16	2 66	105 0	18 4	3 4	117 4	14 3	1 4	126
Vicksburg (Miss) silty clay	A-4(10)	CL	37	14	2 72	105 0	18 0	4 9	116 7	14 7	2 3	41
Houston (Texas) A-horizon clay	A-7-5(20)	CH	76	45	2 67	96 4	23 6	3 7	107 1	20 3	0 6	126
North Dakota B-horizon Barnes loam	A-7-6(10)	ML-CL	41	17	2 56	104 0	20 5	2 6	114 0	14 3	1 2	126
Gogebic (Wis) A-horizon sandy loam	A-4(4)	ML	24	2	2 71	109 1	14 0	6 4	117 0	12 5	4 0	126
Vicksburg ¾-in clay gravel	A-2-6(0)	GC	27	12	2 68	127 4	7 0	4 7	135 0	5 2	3 7	51
Clinton (Miss) clayey sand	A-1(0)	SF	16	2	2 68	116 0	11 5	4 8	122 0	10 0	3 7	40
Lakeland (Fla) fine sand	A-3(0)	SP	NP	NP	2 71	113 7	10 1	7 9	115 9	10 2	6 8	126
Florida A-2 horizon uniform fine sand	A-3(0)	SP	NP	NP	2 68	102 2	15 0	8 9	104 4	16 0	7 7	126

by weight required to fill the voids, are given in Table 31 for the nine soils tested according to both Standard and Modified AASHO methods.

Table 31 shows that for the lighter textured silty soils both the Standard AASHO T 99 and the Modified methods reduced the air voids to relatively low values (and thus produced high percentages of saturation). For silty soils, increasing the percentage saturation beyond that obtained by the compaction effort of T 99 at optimum moisture content generally causes a sharp reduction in strength. For clayey soils, the degree of saturation is not so critical.

STANDARD AASHO-ASTM METHOD VS CALIFORNIA IMPACT METHOD

It has been shown under the "Size and Shape of the Mold" that the dry unit weights attained by the use of the California Impact Method (95) differ from those attained by other methods under an equivalent compaction effort. Figure 15 shows that the California Method resulted in dry unit weights that are greater than the values obtained by the Standard AASHO-ASTM method for all six soils, whose characteristics are indicated in Table 7. For the three graded sandy soils, the dry unit weights obtained by the California Method are greater than the values by the Modified AASHO Method. Detailed data are given in Table 32.

It may be seen in this table that the optimum moisture contents, determined by the California Method, for the six soils are generally lower than the values determined by the other tests. The comparison of test results determined by the Standard AASHO-ASTM Method and by the California method is shown in Table 33. In comparing the Modified AASHO test results with those obtained by the California method, it may be seen in Table 32 that optimum moisture contents are greater for the California method for the silty clay and silty clay loam (for which dry unit weights are equal or less than for Modified AASHO), are equal for the sandy silty clay and the silty sand (for which the California method produced dry unit weights slightly higher than did the Modified AASHO method), and are less for the sandstone and sand and for the clean sand. It is recognized in this summation that in most instances the values of dry unit weight differ only from 1 to 3 pcf and the optimum moisture contents only from 0 to 3 percentage units between the two methods, and that those differences are almost within the limits of error of reproducibility of the test results.

An approximate measure of the air voids at optimum moisture content was determined by scaling from the graphs (95) the percentage of water by weight required to fill the voids. These approximate values are given in Table 34, which shows that, except for the clean sand, the California impact method results in markedly lower values of air voids than the other two impact-type compaction test methods. Comparison of laboratory test results with values obtained in field construction lifts may be found in Bulletin 272.

STANDARD AASHO-ASTM METHOD VS BUREAU OF RECLAMATION METHOD

The Bureau of Reclamation method (70, 106) employs a 1/20-cu ft mold and a unit compaction effort (12,375 ft-lb per cu ft) equivalent to that of Standard AASHO Method T 99. Results of tests comparing the Bureau method and the Standard method have been

TABLE 30

COMPARISON OF RESULTS OF STANDARD AASHO AND MODIFIED AASHO COMPACTION TESTS

	Results of the Standard AASHO Compaction Test		Effect of Modified AASHO Test on:-	
Type of Soil	Maximum Dry Unit Weight (pcf)	Optimum Moisture (%)	Maximum Dry Unit Weight (pcf)	Optimum Moisture (%)
			Increased by	Decreased by
Nebraska silt loam	105.0	18.4	12.4	4.1
Miss. Vicksburg silty clay	105.0	18.0	11.7	3.3
Texas Houston clay	96.4	23.6	10.7	3.3
North Dakota loam	104.0	20.5	10.4	6.2
Wisconsin sandy loam	109.1	14.0	7.9	1.5
Vicksburg clay gravel	127.4	7.0	7.6	1.8
Miss. clayey sand	116.0	11.5	6.0	1.5
Fla. (Lakeland) fine sand	113.7	10.1	2.2	0.1
Florida fine sand	102.2	15.0	2.2	0.0

TABLE 31

COMPARISON OF PERCENT MOISTURE BY WEIGHT REQUIRED TO FILL VOIDS AT OPTIMUM MOISTURE CONTENT WHEN COMPACTED ACCORDING TO STANDARD AASHO AND MODIFIED AASHO METHODS

Soil Type	Percent Moisture by Weight	
	Standard AASHO	Modified AASHO
Nebraska silt loam	3.4	1.4
Miss. Vicksburg clay	4.9	2.3
Texas Houston clay	3.7	0.6
North Dakota loam	2.6	1.2
Wisc. sandy loam	6.4	4.0
Vicksburg clay gravel	4.7	3.7
Miss. clayey sand	4.8	3.7
Fla. (Lakeland) fine sand	7.9	6.8
Fla. fine sand	8.9	7.7

discussed under "The Size and Shape of the Mold." Comparative results obtained by use of the Bureau of Reclamation large-scale mechanical compactor designed for gravelly soils have also been presented under "The Size and Shape of the Mold."

STANDARD AASHO-ASTM METHOD VS PROCTOR METHOD

Hveem (95) compared the results of the early (2) Proctor manual impact compaction test method using the 1/30-cu ft mold, the 5½-lb rammer, and the 12-in. firm blow, with the results of Standard AASHO, Modified AASHO, and California impact methods. Hveem's tests showed that the early Proctor method yielded average maximum dry unit weights of the order of about 95 percent of those yielded by the Modified AASHO method, and about 105 percent of the values yielded by the Standard AASHO methods. Table 31 permits comparison of individual values for the various methods. Values of air voids at maximum dry unit weight, expressed as percent moisture by weight required to fill the voids, were greater than those for a modified AASHO in four of five cases (see Table 32) and less than the values for Standard AASHO method in three cases out of five, indicating no significant difference in air voids due to the use of the manual method.

It has been mentioned previously that the Proctor test method has been changed to employ the use of a 5¾-lb tamper (35) and a 1/20-cu ft mold. Data have not been found that permit comparison of the more recent Proctor method with the results from Standard methods.

STANDARD AASHO-ASTM METHOD VS DIETERT AND MODIFIED DIETERT METHODS

The Dietert test (ASTM Designation: C 181-47), a standard method of test for workability index of fire clay plastic refractories, has been used to determine maximum dry unit weight and optimum moisture content for soil compaction purposes. The essential elements of the test have been described under principal compaction test methods (impact type) and are given in Table 2. The Dietert test consists of a 14-lb cylindrical weight sliding on a central shaft through a free drop of 2 in. striking a tamper in contact with the soil. Because of its use as a means for determining maximum dry unit weight and optimum moisture content of soils for construction purposes it is of interest to compare results with standard methods.

Little (25) found that one of the useful features of the test is that it requires a soil sample only one-tenth the size required by the Standard AASHO test, but also finds it usefulness limited to soil passing a ⅛-in. sieve (3 mm). Little made comparative tests with the Standard AASHO method on several soils having a wide range of liquid limits. In these tests Little applied 20 blows of an 18-lb hammer, 10 on each end of the specimen. The results obtained by Little are given in Table 35. The data in this table show that the Dietert test as used resulted in maximum dry unit weights averaging about 3.3 pcf higher than those attained in the AASHO T 99 test and that optimum moisture contents were, on the average, 1.3 percentage units lower in the AASHO T 99 test.

Due to the differences in results, Little experimented using a wide range of number of blows in an effort to seek correlation between the AASHO T 99

TABLE 32

COMPARISON OF COMPACTION TEST DATA FOR CALIFORNIA IMPACT METHOD WITH RESULTS FROM STANDARD AASHO AND MODIFIED AASHO METHODS (95)

Soil Type	California Impact Method (5 layers)			Modified AASHO Method			Standard AASHO Method			California Mechanical Compactor			Early Proctor Method				
	Maximum Dry Unit Wt (pcf)	OMC (%)	% Water by Weight to Fill Voids[a]	Maximum Dry Unit Wt (pcf)	OMC (%)	% Water by Weight to Fill Voids[a]	Maximum Dry Unit Wt (pcf)	OMC (%)	% Water by Weight to Fill Voids[a]	Maximum Dry Unit Wt (pcf)	OMC (%)	% Water by Weight to Fill Voids[a]	Maximum Dry Unit Wt (pcf)	OMC (%)	% Water by Weight to fill Voids[a]	% of Mod AASHO Max Dry Unit Wt	% of Mod AASHO Max Dry Unit Wt
Sandstone and sand (-¾-in.)	111	17	-	110	18	-	103	21	-	109	19	-	108	18	-	98.1	104.8
Sandy silty clay	118	14	0.5	116	14	1.5	107	18	1.8	-	-	-	111	16	2.2	95.7	103.7
Clean sand	103	15	9.2	105	17	4.2	95	19.5	9.0	-	-	-	98	19	8.0	93.3	103.2
Silty sand	129	10	0.7	128	10	1.0	121	12	1.8	125	9	2.7	124	11	1.9	96.9	102.5
Silty clay	115	15	2.2	118	12	3.0	98	23	3.7	117	15	1.1	112	17	1.4	94.9	114.3
Silty clay loam	105	21	1.5	105	19	3.5	95	23	6.0	98	21	5.6	98	22	4.8	93.3	103.2

[a] At optimum moisture content

TABLE 33

COMPARISON OF RESULTS OF THE STANDARD AASHO AND CALIFORNIA IMPACT METHOD (95)

Soil Type	Standard AASHO Test Results		Effect of California Impact Method on	
	Maximum Dry Unit Weight (pcf)	Optimum Moisture Content (%)	Maximum Dry Unit Weight (pcf)	Optimum Moisture Content (%)
			Increased by	Decreased by
Silty clay	98	23	17	8
Sandy silty clay	107	18	11	4
Silty clay loam	95	23	10	2
Silty sand	121	12	8	2
Clean sand	95	19.5	8	4.5
Sandstone and sand	103	21	8	4

TABLE 34

PERCENT MOISTURE CONTENT BY WEIGHT REQUIRED TO FILL VOIDS AT OPTIMUM MOISTURE CONTENT FOR THREE IMPACT TYPE COMPACTION TEST METHODS (95)

Soil Type	California Impact Method	Modified AASHO Method	Standard AASHO Method	California Mechanical Compactor
Silty clay	2.2	3.0	3.7	1.1
Sandy silty clay	0.5	1.5	1.8	-
Silty clay loam	1.5	3.5	6.0	5.6
Silty sand	0.7	1.0	1.8	2.7
Clean sand	9.2	4.2	9.0	-

TABLE 35

RESULTS OF TESTS COMPARING THE AASHO AND DIETERT TEST METHODS (25)

Soil	LL	PL	AASHO Method		Dietert Method	
			OMC (%)	Max. Dry Unit Wt. (pcf)	OMC (%)	Max. Dry Unit Wt. (pcf)
Brown very sandy clay	18	12	12.0	122.5	10.0	125.0
Brown sandy clay	25	13	10.7	125.8	9.3	129.9
Brown silty clay (top soil)	33	20	17.0	104.2	16.5	104.9
	33	15	17.0	105.7	16.2	108.0
	34	19	15.3	104.3	15.5	106.0
	40	25	20.5	97.5	17.0	103.0
Gray blue silty clay (alluvium)	46	21	19.5	105.0	20.0	105.2
Slightly silty gray London clay	67	20	23.4	100.6	20.5	107.2

method and the Dietert method. On the London clay, a total of six blows yielded a maximum dry unit weight nearly equivalent to that attained in the AASHO test but resulted in a slightly higher optimum moisture content.

Maclean and Williams (31) also report the results of an investigation comparing the two methods of compaction. They employed three soil types: a nonplastic well-graded sand, passing the No. 10 sieve; a sandy clay (LL = 27, PI = 8); and a clay (LL = 53, PI = 30). They subjected the soils to 10 blows. Their results are given in Table 36.

Their study indicated that the Dietert test yielded higher values than the AASHO method for some soils and lower values for others. They concluded that the Dietert compactor could not be simply modified (for example, by altering either the weight, height of drop of the weight, or number of blows) to give results that agreed with the standard AASHO test.

Williams and Maclean, in their report of full-scale field compaction tests (49) listed comparative values of maximum dry unit weight and optimum moisture content from the Dietert test; the British standard test 1377:1948 test No. 9 (which is generally similar to the AASHO T 99, Method C); and the Modified AASHO test. In describing the Dietert test their record shows the use of an 18-lb weight dropping two inches. Their tests were made on five soils: a heavy clay, type CH (LL = 75, PI = 47); a silty clay, type CL, (LL = 43, PI = 19); a sandy clay, type CL, (LL = 27, PI = 8); a well-graded nonplastic sand; and a well-graded nonplastic gravel-sand clay. The grain-size distribution curves of these soils are shown in Figure 91. The comparative values obtained in the British studies are given in Table 37.

The British Road Research Laboratory reported additional tests performed with the Dietert test, comparing it with the British standard 1377:1948 Test No. 9 that showed the effect of the weight of dry soil used per specimen (as well as the effect of layer thickness in the British Standard test). In these tests the Dietert test employed a

TABLE 36

COMPARISON OF MAXIMUM DRY UNIT WEIGHTS AND OPTIMUM MOISTURE CONTENTS GIVEN BY THE AASHO T99 AND DIETERT COMPACTION TESTS (31)

Soil	Maximum Dry Unit Weight (pcf)		Optimum Moisture Content (%)	
	AASHO Test	Dietert Test	AASHO Test	Dietert Test
Sand	122	117	13	13
Sandy clay	116	116	15	14
Heavy clay	103	108	22	20

TABLE 37

COMPARISON OF MAXIMUM DRY UNIT WEIGHTS AND OPTIMUM MOISTURE CONTENTS OBTAINED BY THE BRITISH ROAD RESEARCH LABORATORY ON FIVE SOILS, BY USING THREE METHODS OF COMPACTION

Soil	Class.	British Standard Test		Modified AASHO Test		Dietert Test	
		Max. Dry Unit Wt. (pcf)	OMC (%)	Max. Dry Unit Wt. (pcf)	OMC (%)	Max. Dry Unit Wt. (pcf)	OMC (%)
Heavy clay	CH	97	26	113	17	102	23
Silty clay	CL	104	21	120	14	109	17
Sandy clay	ML	115	14	128	11	116	14
Sand	SW	121	11	130	9	119	11
Gravel-sand clay	GW	129	9	138	7	--	--

sliding weight of 18 lb dropping 2 in. The results of the investigation showing the effect of dry soil weight on maximum dry unit weight and optimum moisture content are shown in Figures 92 and 93. Both the British Standard test and the Dietert test agree fairly well with regard to optimum moisture content, but the maximum dry unit weight differed markedly for soils of high clay content or high sand content.

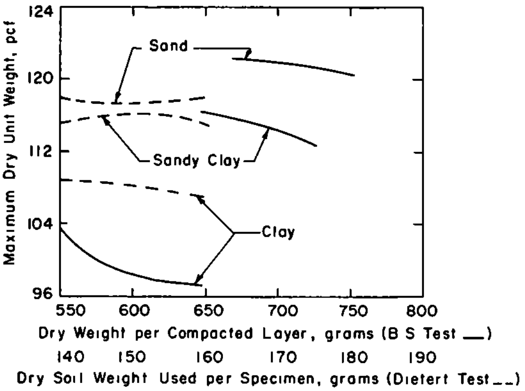


Figure 92. Variation of maximum dry unit weight with dry weight of compacted soil in British Standard and Dietert compaction tests (60).

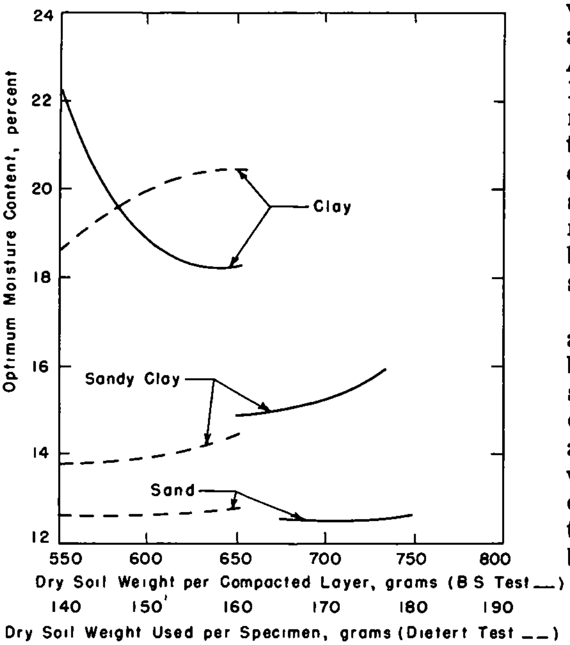


Figure 93. Variation of optimum moisture content with dry weight of compacted soil in British Standard and Dietert compaction tests (60).

Bruce (83), in a report, to the Soil Science Society of America, used a modified Dietert test, a cylinder 2 in. in diameter and 4 in. in length fitting over a solid steel plug. The tamper foot, only slightly smaller than the cylinder diameter, was fastened to the central ½-in. diameter steel rod on which the hammer slid. A 4,712-g (10.4-lb) sliding weight fell through a drop of 6 in.

Several sets of compaction curves were made at different numbers of blows and compared to results with the Standard AASHO test at similar numbers of blows. Bruce's apparatus produced unit weights markedly higher than those produced by the AASHO apparatus for similar numbers of blows. The adopted procedure uses six to eight 100-g air-dry samples passing a No. 4 sieve and an application of 10 blows of the hammer at each end of the sample.

The results of the Dietert compactor and small mold have been included here because, on first examination, with the small samples required and the simplicity of the apparatus, it appears to be able to produce results comparable with those from standard tests. The data included demonstrate quite clearly that no simple correlation can be made between the two tests.

STANDARD AASHO-ASTM METHOD VS ABBOTT AND DORNII METHODS

Comparative tests with the Abbott cylinder (65) and the Standard and Modified AASHO have been made on four different textural types of soil. The Abbott cylinder is widely known in India. The method consists of compacting 200 g of soil passing a U.S. Standard No. 10 sieve with a 5.5-lb rammer in a 2.5-in. diameter mold at 10, 20, 30, and 40 blows and observing the unit weight for each group of blows. Tests showed that on a clayey soil (LL = 35, PI = 16) the AASHO maximum dry unit weight fell between the 30- and 40-blow Abbott values; for a silty soil (LL = 30, PI = 11), between 20 and 30 blows; for a sandy soil

(LL = 26, PI = 6) and for a nonplastic sand, well above the value for 40 blows. The optimum moisture content for the Abbott cylinder was 2 percentage units higher than the AASHO value for the clayey soil; 1 percent for the sandy soil; and equal for the silty soil.

The Dornii test, said by Myslivec (101) to be a U.S.S.R. standard test is not described in complete detail. The soil is tamped 25 blows with a ram weighing 4.5 kg (9.9 lb) and falling from a height of 30.5 cm (12 in.). The contact area of the ram (not given) is the same as the area of the compaction cylinder. A single value of maximum dry unit weight is given for a loam soil 1.756 g per cu cm (109.6 pcf) with an optimum moisture content of 18.0 percent. Comparable Standard AASHO Method T 99 values are 1.715 g per cu cm (107.4 pcf) and 20 percent, respectively.

STANDARD AASHO-ASTM METHOD VS IMPACT-TYPE MECHANICAL COMPACTORS

The published literature contains few if any accounts comparing the results of impact-type mechanical compactors with the results of impact-type manual compaction carefully performed in accordance with standard AASHO-ASTM methods. Near approaches to comparisons of this nature are the investigations of the Corps of Engineers (51) and the Bureau of Reclamation (106).

The mechanical compactor constructed by the Corps of Engineers was designed for compacting in molds from 4 to 12 in. in diameter with hammer weights up to 60 lb and a free drop of 6 in. The tamping foot formed a sector of a circle with an angle of 41 deg for the 6-in. diameter mold.

Comparative tests were made on three soils: (a) a typical Vicksburg loess (LL = 28, PI = 4); (b) a clayey silt material (LL = 40, PI = 12); and (c) a clayey sand (LL = 18, PI = 2). It is significant that all three were very uniformly graded ("one-size" material) within a major portion of the units of their grain sizes.

Compaction tests were performed with the 6-in. diameter mold. The 10-lb rammer was used in the manual tests. Three compaction efforts were used for each soil with the manual method and three for each soil with the mechanical method. These efforts ranged from that of the Standard AASHO to above that of the Modified AASHO effort. Due to the size of the tamper foot of the mechanical compactor and spacing of blows, it required 22 blows for one complete coverage of the specimen. Therefore, the number of blows were held at multiples of 22 to obtain uniform compaction, resulting in slightly different efforts for manual and mechanical compaction. However, the results can be compared by reducing them to equal efforts by the use of Figure 94 which shows the maximum dry unit weights attained at optimum moisture contents for both manual and mechanical compaction.

For the Vicksburg loess, the compaction data are in good agreement with those obtained by manual methods with the 10-lb rammer. For soil 2, a clayey silt, the compaction curves for the compactor were closer to the zero air voids curve (1 to 2 percentage units) and maximum

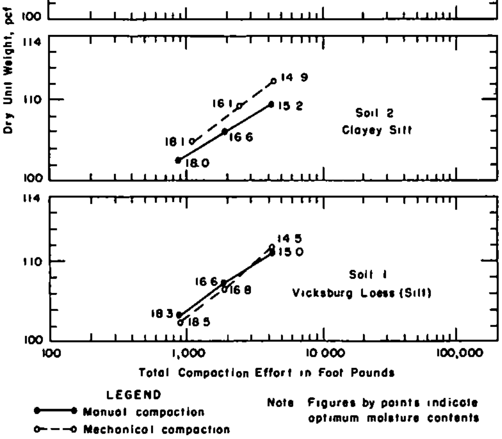


Figure 94. Comparison of maximum dry unit weights for manual impact and mechanical impact-type compaction (51).

dry unit weights were of the order of 2 pcf greater than for manual compaction. For soil 3, the clayey sand, the curves for manual operation with the 10-lb rammer were closer to the zero air voids curve than those for the compactor by up to 2 percentage units of moisture content (by weight). Maximum dry unit weights were of the order of 2 pcf higher for manual compaction.

Figure 94 shows that the two methods are in good agreement for the loess (soil 1), that the compactor yielded higher dry unit weights for the clayey silt (soil 2), and that manual compaction yielded higher maximum dry unit weights for the clayey sand (soil 3).

The Bureau of Reclamation (106) constructed a large mechanical compactor and large diameter mold for compacting gravel of 3-in. maximum size aggregate. This compactor has been described under "The Size and Shape of the Mold." A comparison of results obtained from tests using the Bureau of Reclamation $\frac{1}{20}$-cu ft mold and the 1.5-cu ft mold (each with a compaction effort of 12,375 ft-lb per cu ft) is given in Table 6. These tests showed slightly higher dry unit weight for the sandy and clayey soils in the large mold (19.2-in. diameter)—a trend that is counter to that found by some other investigators using molds with smaller differences in sizes. However, Table 6 shows that differences may not markedly exceed differences within the range of error of reproducibility.

There are numerous "home-made" and commercially manufactured mechanical compactors of the impact type in operation in testing laboratories performing "routine" compaction tests that serve as bases for specification values for construction. No doubt a large proportion of these mechanical compactors have been calibrated on one or more soils so the maximum dry unit weights and optimum moisture contents obtained are in close agreement with those resulting from standard methods. However, it would be of value to each user for a "soil reference laboratory" of the type used to test cements to use a "standard" group of soils for comparing results obtained with mechanical compactors with those obtained by a skilled operator using standard methods.

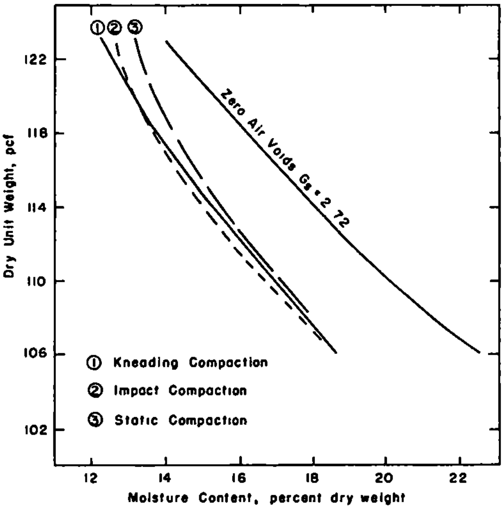


Figure 95. Comparison of lines of optimum moisture content for kneading, impact, and static compaction on a Vicksburg silty clay (LL = 37, PI = 14, G_s = 2.72). Kneading compaction was performed with a Triaxial Institute compactor (72, 73).

STANDARD AASHO-ASTM METHOD VS KNEADING-TYPE COMPACTION

The principal types of manually operated kneading-type compactors—California Manual (91) and Harvard Miniature (53, 63, 98)—and of mechanically operated kneading-type compactors—California and Triaxial Institute (52, 53, 55, 72, 73, 95) and the Northwestern University Compactor (62)—have been described briefly under "Principal Methods for Determining Maximum Unit Weight and Optimum Moisture Content."

By adjustment of the tamping foot unit pressure (or in combination with number of layers and tamps per layer), kneading-type compactors may be made to yield a maximum dry unit weight equivalent to any value of maximum dry unit weight attained by AASHO Method : T 99-57 or T 180-57 (122) or by the Corps of Engineers modification of AASHO Method: T 180-57 (123). However, for the kneading-type compactor, the optimum moisture content and the percent of air voids may differ from those obtained by the impact method. When more than one compaction effort is under consideration, this difference is expressed in terms of a line drawn through the optimum moisture contents. This "line of optimums" has been discussed in part with regard to the "dwelling" time of the pressure of the tamping foot (the time period in each tamp that it exerts pressure on the soil) of a kneading-type compactor (62) on a soil specimen during compaction. The "dwelling" time may be determined from a time-pressure curve of the type shown in Figure 4. The "line of optimums" for a given "dwelling" time for a given soil and compactor is shown in Figure 36.

The fact that the compaction effort of a kneading-type compactor can be adjusted to yield a maximum dry unit weight equivalent to that for the Standard AASHO method, or for any other method for a given soil does not mean that it will yield similar equivalent values for all types of soils. In fact, the maximum dry unit weight (and optimum moisture content) may differ markedly from standard values for different soil types.

Thus, the results from impact and kneading types of compaction may be compared broadly by the relative positions of their respective "lines of optimums" or by differences in maximum dry unit weight and optimum moisture content for a given compaction effort (usually number of layers, tamps per layer, and tamping foot pressures), just as compaction effort for the impact type is compared in terms of number of layers, tamps per layer, and the height of hammer drop of a stated weight.

Although the purpose of an investigation by Seed, Lundgren, and Chan (72) was to show the extent in which different methods of laboratory compaction affect the stability of soils, they performed compaction tests according to accepted procedures for impact, static, and kneading types of compaction. Their studies included a silty clay from Vicksburg, Miss., whose index properties have been widely published. Lines connecting optimum moisture contents for different compaction efforts were prepared for each type of compaction and are shown in Figure 95. Although the values from which the plots were made are admittedly approximate in as much as they were taken from compaction curves, it is believed they represent the trend of the results obtained. The figure shows that, although the positions of the lines of optimums do not differ markedly, impact compaction results in the lowest degree of saturation for a major portion of the range bracketed, the kneading compactor provides slightly higher degrees of saturation, and static compaction provides the highest degree of saturation for the full range of the tests for the soil tested.

Figure 96 shows the lines of optimum moisture contents for a California sandy clay. Although there is some conflict, it may be seen that the positions of the lines are in about the same order as those in Figure 95.

It has been shown (62) that the dwelling time of the tamper foot has significant influence on the position of the line of optimums. The dwelling time used in the tests for which the lines of optimums are shown in Figures 95 and 96 is not stated. However, a comparison article by Seed and Monismith (73) shows a typical time-pressure trace for a 300-psi tamping foot pressure as consisting of a 0.20-sec loading period, a 0.40-sec dwelling period for full load, and a 0.20-sec unloading period.

Results showing lines of optimums for the three methods of compaction on a California (Antioch) sandy clay show very small differences in degree of saturation at optimum moisture content (72).

The compaction efforts used in these tests for which the results are shown in Figure 95 for the silty clay are given in Table 38.

Comparative data were not found for the California manually operated kneading compactor (91). However, it was stated that comparative tests were made in which soil specimens were prepared in the hand-operated kneading compactor and in the mechanically operated kneading compactor. Similar numbers of layers, tamps per layer, and tamping foot pressures were used. The results were so close that they resulted in identical compaction curves (91).

Comparative tests were made between impact compaction and kneading compaction with the Northwestern University compactor (62). Examples of impact compaction curves at various compaction efforts and kneading type compaction curves at various foot pressures are shown in Figure 97. Also shown are the lines of optimums for impact compaction and for kneading compaction when the period of loading is 0.04 min.

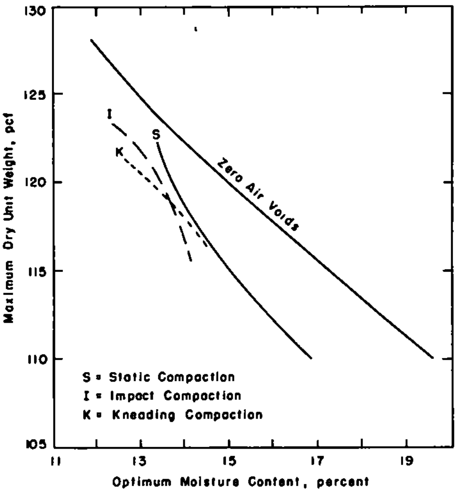


Figure 96. Comparison of lines of optimum moisture content for kneading, impact, and static compaction on a California sandy clay (72).

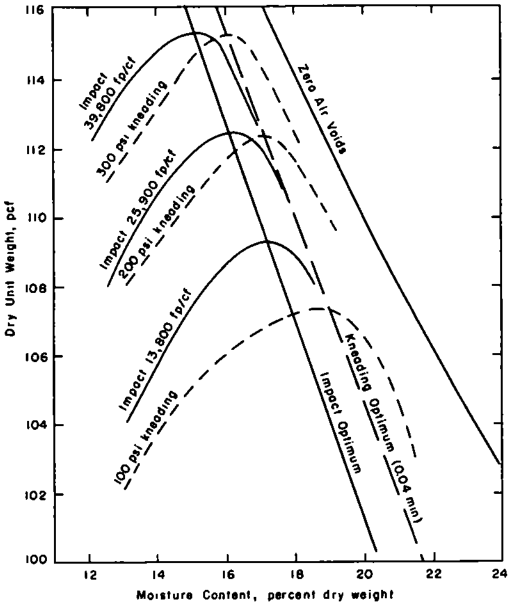


Figure 97. Comparison of impact and kneading compaction on a Vicksburg silty clay (LL ≅ 37, PI ≅ 14, G_s = 2.72); all tests were made with Northwestern pneumatic compactor (62).

Tests showed that the period of time that the tamping foot pressure (dwelling time) was being applied to the soil had a marked effect on the position of the line of optimums. The greater the period of applying tamping foot pressure, the closer the line of optimums approached the zero air voids curve (line of saturation). This has been shown in Figure 36 and has been discussed under "The Kneading-Type Compaction Test." Data on the compaction efforts used in the studies on a silty clay with the Northwestern apparatus are given in Table 39.

The Harvard miniature kneading compactor (53, 63) was employed to perform compaction tests on a Clinton, Miss., clayey sand and a Vicksburg silty clay to obtain

TABLE 38

DATA PERTAINING TO COMPACTION EFFORTS USED IN IMPACT, STATIC, AND KNEADING COMPACTION TESTS (72)

Type of Compaction	No. of Layers	Tamps per Layer	Kneading Foot Pressure (psi)	Static Pressure (psi)	Weight of Impact Hammer (lb)	Free Drop (in.)
Kneading	5	25	400	-	-	-
		25	150	-	-	-
		25	40	-	-	-
Impact	5	25	-	-	10	18
	3	25	-	-	10	12
		25	-	-	5.5	12
		25	-	-	5.5	8
Static				900		
				200		
				90		

TABLE 39

DATA ON COMPACTION EFFORTS USED IN IMPACT AND KNEADING COMPACTION TESTS (62)

Type of Compaction	No. of Layers	Tamps per Layer	Kneading Foot Pressure (psi)	Weight of Impact Hammer(lb)	Free Drop (in.)	Compaction Effort (ft-lb/cu ft)
Impact	3	25	-	20	9	13,800
	5	28	-	20	9	25,900
		43	-	20	9	39,800
Kneading	5	40	100	-	-	-
			200	-	-	-
			300	-	-	-

results to compare with those from impact and static methods. The results for the clayey sand are shown in Figure 98. These tests show that impact compaction produced a degree of saturation substantially lower than did either the static or kneading types of compaction for all maximum dry unit weights bracketed in the tests. The static compression method yielded the highest degree of saturation at the higher pressures. This may or may not have been accounted for by the squeezing out of water at the high pressure of 4,000 psi.

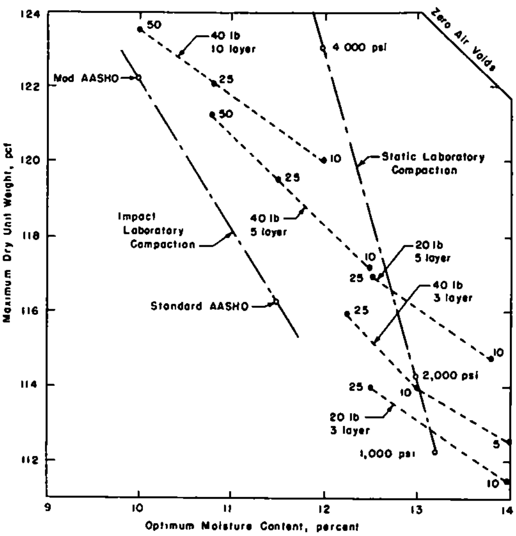


Figure 98. Comparison of lines of optimum moisture content for various compaction efforts for impact on a Clinton, Miss., clayey sand with LL = 18, PI = 2. Figures beside lines are spring compression values, number of layers, and blows per layer (53).

The results for the silty clay are quite different than those for the clayey sand as may be seen by comparing the results shown in Figure 98 with those in Figure 99. In Figure 99 it may be seen that for the silty clay, the static compression produced the lowest degree of saturation, the impact method an intermediate value, and the kneading compaction the highest degree of saturation.

Thus, in these tests, the positions of the lines of optimums with respect to the line of saturation differed markedly for the two soils. In tests by Kassiff (98), no significant difference in positions of lines of optimums was found for kneading- and impact-type tests. Kassiff performed both types of tests at several compaction efforts on Negev loess soil (sand, silt, and clay were 10, 65, and 25 percent, respectively, LL= 20, PI = 5, G_s = 2.74, class ML-CL). Standard impact tests were according to AASHO T 99 methods using the 1/30-cu ft mold. Additional tests were made so that data were available for compaction efforts of 7,425, 12,375, 35,750, and 56,250 ft-lb per cu ft. Tests were also made with the Harvard miniature kneading compactor using four combinations of number of layers, tamps per layer and pressures (in kilograms) respectively as follows: (a) 3-25-10, (b) 3-25-20, (c) 5-25-20, and (d) 5-50-20. The lines of optimums for the two methods and the relationship of that line to the zero air voids curve remained identical for the two methods insofar as it was possible to distinguish, and did not show the differences found by McRae and Rutledge (62) and Wilson (53, 63).

There remains the direct comparison of the standard impact and kneading compactors with the kneading type adjusted to yield identical results for a given type of soil and then testing a number of different soils. Hveem (95) performed a series of tests using Standard AASHO, Modified AASHO, and the "mechanical compactor" (it is assumed it was used as a kneading-type compactor) on several different types of soils. The number of layers, tamps per layer, and tamping foot pressures are not stated but it is assumed they were held constant. Index properties of the several types of soils are given in Table 7. The results of compaction tests using the Standard AASHO and Modified AASHO methods are summarized in Table 28. Comparison shows that the dry unit weights for the mechanical compactor are markedly higher than those for the Standard AASHO test (Designation: T 99) and lower than those for the Modified AASHO method. Optimum moisture contents were lower than those obtained in the Standard AASHO test and, with one exception, higher than those for the Modified AASHO method. The degree of saturation at optimum moisture content and maximum dry unit weight was higher than that for the Modified AASHO impact method in two out of three instances.

It is known that the method of compaction has strong influence on the strength volume change and probably on other properties of soils. Data reviewed in this section indicate that much remains to be learned concerning the type of compaction that yields the most desirable properties in compacted soils. Researches could well establish more finite limits regarding the influence of various types and amounts of compaction on the values of maximum dry unit weight and optimum moisture content with respect to the degree of saturation. This could be part of far more important research pertaining to the properties of compacted soils.

STANDARD AASHO-ASTM METHOD VS VIBRATORY COMPACTION

The only known data available comparing the results of standard laboratory impact compaction tests and laboratory vibratory compaction tests are those of the ASTM cooperative group that has been conducting a study of the laboratory vibration test (120). These studies have been mentioned previously under "The Vibration Compaction Test." The tests have been described in summary form in Table 3. A comparison of the six vibratory methods in terms of average maximum unit weight attained for six different types of soils on which they were tested is given in Table 10. Also given in Table 10 are the available data on frequency, surcharge, period of vibration, and amplitude. The maximum dry unit weights obtained by six different methods of vibration are shown in Figure 39. The grain-size distribution curves of the six soils tested in the vibration studies are shown in Figure 38. The soil types represented are in accordance with the numbers adjacent to the grain-size curves in the figure as follows: (a) a fine sand, (b) a medium sand, (c) a coarse sand, (d) a dense-graded sand and gravel, (e) a dense-graded crushed rock, and (f) an "open-graded" crushed

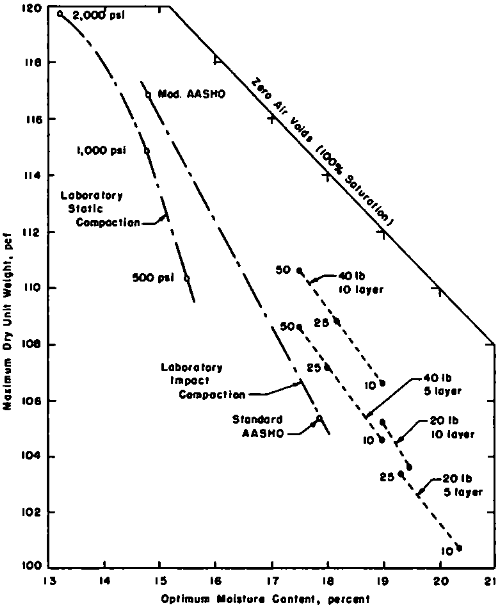


Figure 99. Comparison of lines of optimum moisture content for various compaction efforts for impact, Harvard miniature kneading, and static compaction on a Vicksburg silty clay with LL = 37, PI = 14. Figures beside dotted lines are spring compression values, number of layers, and blows per layer (53).

rock. The objective here is to compare the results obtained by vibration with those obtained by standard methods.

The nonplastic granular soils whose grain-size distribution curves are shown in Figure 38 are of two types; those with hard rounded surfaces (the sands) and those with coarse and interlocking aggregates (the crushed materials). During impact compaction, the sharp, angular pieces of crushed materials rupture, particularly where sharp points contact other aggregates resulting in degradation. This has been mentioned in discussing "The Size and Shape of the Mold" and its effect indicated in Figure 14. It is discussed under "Effect of Coarse Aggregates." The angular particles

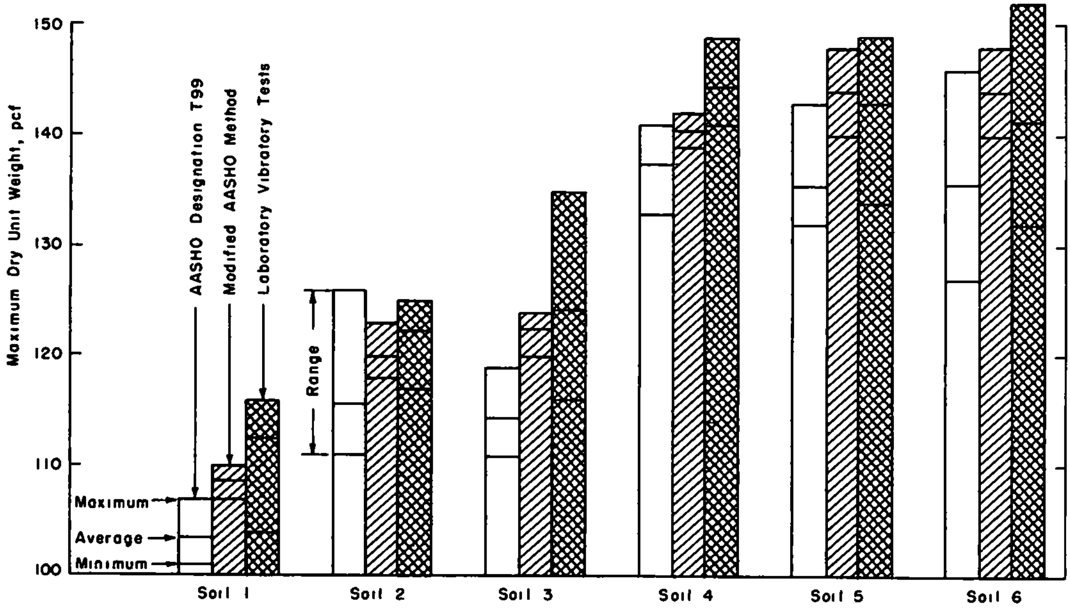


Figure 100. Comparison of maximum dry unit weight values obtained by different investigators using Standard AASHO, Modified AASHO, and vibratory compaction methods (120).

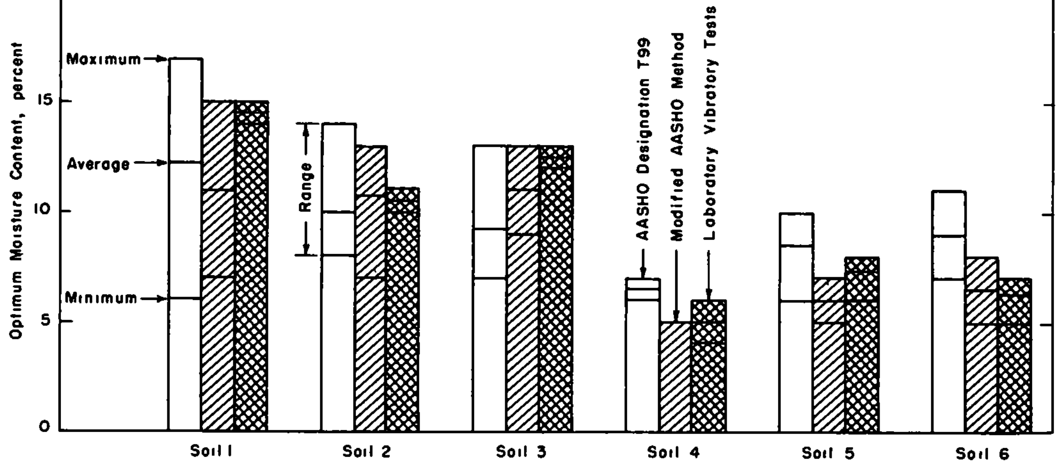


Figure 101. Comparison of optimum moisture content values obtained by different investigators using Standard AASHO, Modified AASHO, and vibratory compaction methods (120).

become rammed into closer contact, and by virtue of their ruptured surfaces and high friction at points of contact, retain their position and thus their unit weight in the mold. As a result, crushed aggregates can be compacted by impact methods to moderately high and high unit weights depending on the compaction effort and the amount of degradation. On the contrary, the hard, rounded surfaces of water-transported and sorted sands are displaced in the mold under impact and there is no force to hold them together in a denser, more compact state. This makes them particularly susceptible to densification by vibration.

The greatest, average, and lowest values of maximum dry unit weight obtained under the Standard AASHO, the Modified AASHO, and the five methods of vibration, that yielded the highest unit weights, are compared in Figure 100. Similar relationships for optimum moisture contents are shown in Figure 96. The number of different investigators performing the tests were (a) for the Standard AASHO test, five each for soils 1 and 3, 6 for soil 2, and 4 each for soils 4, 5, and 6; and (b) for the modified test, 3 each for soil 2, and 2 each for the remaining soils. Each vibratory test was performed by a different cooperator.

Figure 100 shows that with one exception (soil 2) the Modified AASHO method yielded unit weights higher than the Standard AASHO method did, and with one exception, vibrated unit weights exceeded those attained in the Modified AASHO test. Figure 101 shows a variation in optimum water contents for the vibratory method. Only two cooperators reported maximum vibrated unit weight for soils 1 and 2 when vibrated "wet" and three cooperators reported maximum unit weights for the remaining soils when vibrated "wet." The maximum, minimum and average values shown in Figure 101 represent only the values reported; i.e., the average values do not include zero values of moisture content for soils vibrated dry.

The different variables mentioned under "The Vibration Test" (frequency, amplitude, surcharge, period of vibration, as well as the normal factors of moisture content and soil type) have not been thoroughly explored for either the laboratory test or field vibratory compaction. Each of these factors has some influence on the unit weight attained. An example of the effect of vibration time, moisture content and surcharge load is shown in Figure 102. For this soil and vibration method, the

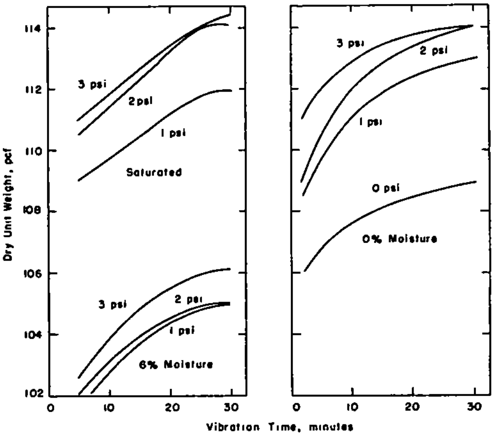


Figure 102. The effect of vibration time, percent moisture, and surcharge weight on vibrated unit weight of a fine sand (soil 1). Test conducted in accordance with Felt method 8 (see Table 3) (120).

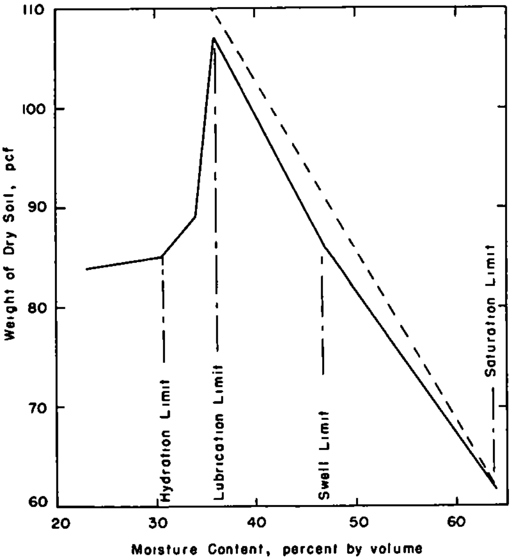


Figure 103. Dry unit weight-moisture content relation. Moisture content is expressed in terms of the combined volumes of soil solids and soil moisture (5).

vibrated unit weight is about equal when vibrated dry as when vibrated in a saturated state, yet an intermediate water content (6 percent) yielded low unit weights. Surcharge weight and vibration time each appear to have sufficient influence on vibrated unit weight that they cannot be neglected in testing.

STANDARD AASHO-ASTM METHOD VS STATIC COMPACTION

The maximum unit weight obtained by static compaction can, like that obtained by kneading compaction, be changed by adjusting the unit pressure to yield a maximum unit weight equivalent to that obtained from a standard impact procedure. Therefore, any direct comparison between results of methods must be based on the shapes of the moisture content-dry unit weight relationship curves, the optimum moisture contents, and the degree of saturation (percent air voids).

There exists no standard method for the static load compaction test. This has been mentioned under "Principal Methods for Determining Maximum Unit Weight and Optimum Moisture Content" and also under "Principal Factors Influencing Maximum Unit Weight and Optimum Moisture Content in the Compaction Test." One of the better known methods was that formerly used by the California Division of Highways (1, 8, 16). The Corps of Engineers has reported the results of static load compaction tests (40, 41), stating that it used the original "Porter" or "California" Method of compaction.

Inasmuch as the compression of soil is a function of time, it is of interest to observe the shapes of compaction curves obtained under static load compression. Hogentogler (5) obtained curves with very sharp peaks when the resulting values of unit weight were plotted against moisture content expressed as percent of the total volume of soil solids and soil water, an example of which is shown in Figure 103. Some engineers (74) hold that compaction of cohesive soils is essentially consolidation with limited lateral support. The soil contained 44 percent sand, 12 percent silt, 11 percent clay, and 33 percent colloids. Other index properties were not given. Hogentogler did not state the details of compression loading but it is evident that ample time was given for compression. Examination of static load compaction curves obtained by others (4, 40, 41) fails to show any other than a well-rounded curve and normal proportion of air voids. Figure 104 shows compaction curves for a silty clay compacted by static as well as by impact methods. For the compaction curves in this figure unit weight is plotted (a) vs moisture content in percent of weight of dry soil as shown by curve 1A (static load compression) and curve 1B (impact compaction), and (b) vs moisture content in percent of total volume of soil solids and soil water—curve 2A (static load compaction) and curve 2B (impact compaction). It may be seen here (40, 41) and in other sources (83) that, where comparison is possible, the static load compression curve assumes a shape not unlike that from the standard impact test.

Although comparative data are limited, the static load compaction test, when performed at a number of unit pressures and compared with impact tests made at several compaction efforts, does yield optimum moisture contents at a slightly higher degree of saturation than does the impact test. That is evident from the lines of optimums in Figures 95, 96 and 98 although it is not true for the data in Figure 99.

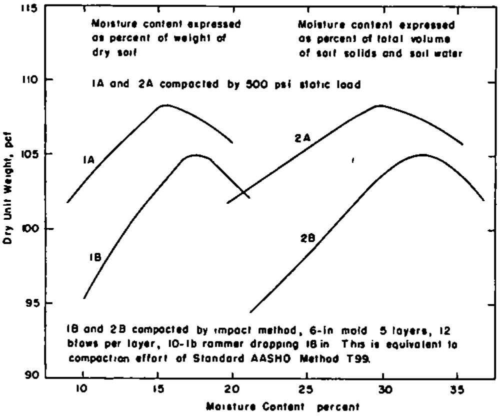


Figure 104. Comparison of shapes and optimum moisture contents of moisture-unit weight curves when soil is compacted by impact and static load methods. Soil is a Vicksburg silty clay with LL = 37, PL = 23, G_s = 2.72 (41).

There is need to determine the cause for discrepancy between the different methods for the different types of soils so that the most realistic laboratory compaction test method can be devised. It may be that static load compression will yield more realistic results when compared to field construction values for compaction under large tires and high inflation pressures. Also, because static load compaction is so often used in fabricating specimens for test, there is need for a static load compaction test designed to yield as nearly as is practicable, unit weights and optimum moisture contents that are consistent with those occurring in field construction compaction.

Index of Figures That Illustrate Effects of Main Factors in Laboratory Compaction Tests

Discussion and data presented heretofore under "Principal Factors Influencing Maximum Unit Weight and Optimum Moisture Content in the Compaction Test" show that it is difficult to separate the effects of the individual factors. Research data have not been available in which certain factors have been held constant to determine the limits of influence of other factors as variables. Also, sufficient data are not available to make it feasible to use statistical methods to determine more precisely the influence of individual factors on optimum moisture content and maximum dry unit weight. Thus, the reader must in his efforts learn from these assembled data the influence of a single factor and constantly alert himself for possible influences of other factors. An examination of the text figures alone will aid in obtaining a perspective of the problem. The following is a list of subjects and the numbers of figures that show the relationship of that subject to one or more other factors that influence compaction results:

1. Nature of the soil: 15, 29, 47-52, 57-62, 67.
2. Type of compactor: 100, 101.
3. Nature of the compaction effort: 15, 26-37, 39, 52, 67, 68, 90, 92-99, 102, 104.
4. Individual items in processing the soil: 16-23.
5. Size of the mold: 11, 13-14, 63.
6. Type of rammer:
7. Other items in the compaction procedure: 16, 25, 43, 45, 46, 102.
8. Calculation of the effect of coarse aggregate: 50-51, 73-84.
9. Admixtures: 71.

Reproducibility of Results from Laboratory Compaction Tests

A large proportion of items discussed under "Principal Factors Influencing Maximum Unit Weight and Optimum Moisture Content in the Compaction Test" have some influence on the reproducibility of results in the test. It is not intended here to restate, or summarize the statements that have been made. Rather, it is the purpose to present the experiences of organizations and individuals that concern reproducibility and to present findings that indicate the variance in results (a) for an individual repeating tests on the same soil, under the same test procedure, using the same equipment in the same laboratory under similar conditions; and (b) for different individuals in different laboratories performing the test according to the same test procedure (for example, AASHO Designation: T 99-57, Method A) on carefully prepared and carefully split samples of soil from the same source.

Investigations have shown that the values of optimum moisture content and maximum dry unit weight obtained by the British standard test (that is approximately equivalent to AASHO Designation: T 99-57, Method C, and ASTM D 698-58 T, Method C) when reported to the nearest whole number do not differ on repetition of the test by more than ± 1 percent and ± 1 pcf respectively when the test is carefully done (60). The writers have found similar results from personal experience and have also found agreement among a number of testing engineers that this high degree of reproducibility is possible on most soils when the test is performed with care by those experienced in performing the test. Soils containing a high proportion of large aggregates, soils containing aggregates that degrade under compaction, soils that exhibit pronounced thixotropic properties and highly expansive clays are examples of materials that present difficulty in obtaining a high degree of reproducibility even on repetition of the test by the same operator. It is not unusual to obtain variance of ± 2 pcf or more from the median result for soils of these types.

The variance in results between different individuals in different laboratories is somewhat greater. A recent report by Shook and Fang (134) showed the results of cooperative tests made on AASHO Road Test materials. Forty-four agencies performed the Standard AASHO compaction test T 99-57, Method A on the embankment soil, a yellow-brown clay. The average optimum moisture content was 13.5 percent and the maximum dry unit weight was 119.2 pcf. The reported optimum moisture contents varied from 9.5 to 15.5 percent; however, the standard deviation was only 1.0 percent moisture. The reported maximum dry unit weights varied from 114.0 to 125.1 pcf; the standard deviation was 2.2 pcf.

Additional examples of the variance in test results were brought out in a report on the results of cooperative tests by a subcommittee of ASTM Committee D-18, Soils for Engineering Purposes (120). In this study, the soils were all nonplastic and granular in nature, ranging from fine sands to graded crushed rock. Curves indicating the average grain-size distribution of each of the six soils (from tests made by 5 to 6 cooperators) are shown in Figure 38. Maximum, minimum, and average values of maximum dry unit weight obtained in the Standard (AASHO T 99) and Modified (now AASHO Designation: T 180-57) tests are shown in Figure 100. Corresponding values for optimum moisture content are shown in Figure 101.

The purpose of further examination of these results is to determine the variance from a median value. The lowest, highest, average, and median values and variance from the median values of optimum moisture content and maximum dry unit weights for the Standard (AASHO T 99) and Modified AASHO methods are listed in Tables 40 and 41. Table 40 shows that the variance from a median (mid-point between highest and lowest value) value ranges from ± 0.5 to ± 5.5 percentage units for the value of optimum moisture content and from ± 3.0 to ± 9.5 pcf for the value of maximum dry unit weight, both sets of values being for the Standard test (AASHO T 99). The smallest variance in optimum moisture content was for the dense graded sand gravel, the highest for the fine sand. The smallest variance in unit weight was for the fine sand (± 3.0 pcf and the highest (± 9.5 pcf) was for open graded rock. It would have been of interest to have had a much larger sample of cooperators and studied the results obtained by statistical methods.

Except on one soil, only two cooperators performed the Modified AASHO test on each of the samples of soil. On one soil, three cooperators performed the test. Thus, with one exception, the average and median values are identical. These results are given in Table 41. The variance for this test with its greater compaction effort was smaller than for the standard test. If four to six cooperators had performed the Modified AASHO test, as they did the standard test, the possibilities for a greater variance for each soil would have been increased.

The reported studies show that the reproducibility of test results between different laboratories on a plastic soil and on nonplastic granular soils is not close. These data are significant because they illustrate the spread of values that can obtain within a given organization operating a central laboratory, district laboratories, as well as "on the site" field laboratories for the control of construction.

TABLE 40

RESULTS OF COOPERATIVE STUDY OF THE STANDARD COMPACTION TEST (120) (Method ASTM D 698-57T, AASHO T 99-57)

Soil	No. of Cooperators	Optimum Moisture Content (% of Dry Weight)					Maximum Dry Unit Weight (pcf)				
		Low	High	Average	Median	Variance	Low	High	Average	Median	Variance
Fine sand	5	6	17	12.2	11.5	±5.5	101	107	103.4	104.0	±3.0
Medium sand	6	8	14	10.0	11.0	±3.0	111	126	115.8	118.5	±7.5
Coarse sand	5	7	13	9.2	10.0	±3.0	111	119	114.4	115.0	±4.0
Dense-graded sand-gravel	4	6	7	6.5	6.5	±0.5	133	141	137.5	137.0	±4.0
Dense-graded crushed rock	4	6	10	8.5	8.0	±2.0	132	143	135.5	137.5	±5.5
Open-graded crushed rock	4	7	11	9.0	9.0	±2.0	127	146	135.8	136.5	±9.5

TABLE 41

RESULTS OF COOPERATIVE STUDY OF THE MODIFIED AASHO COMPACTION TEST (120)

Soil	No. of Cooperators	Optimum Moisture Content (% of Dry Weight)					Maximum Dry Unit Weight (pcf)				
		Low	High	Average	Median	Variance	Low	High	Average	Median	Variance
Fine sand	2	7	15	11.0	11.0	±4.0	107	110	108.5	108.5	±1.5
Medium sand	3	7	13	10.7	10.0	±3.0	118	123	120.0	120.5	±2.5
Coarse sand	2	9	13	11.0	11.0	±2.0	121	124	122.5	122.5	±1.5
Dense-graded sand-gravel	2	5	5	5.0	5.0	±0.0	139	142	140.5	140.5	±1.5
Dense-graded crushed rock	2	5	7	6.0	6.0	±1.0	140	148	144.0	144.0	±4.0
Open-graded crushed rock	2	5	8	6.5	6.5	±1.5	140	148	144.0	144.0	±4.0

Methods for Estimating Moisture Content-Unit Weight Relationships

Because the proper moisture content and dry unit weight of a soil are very important in earthwork construction, studies have been made to determine what relationships existed between optimum moisture content and maximum dry unit weight and the other index properties (liquid limit, plastic limit, shrinkage limit, gradation, etc.) that are normally determined in routine identification test. The studies showed some close interrelationships. Among the several investigators who developed these were Woods and Litehiser (9), Rowan and Graham (27), J.M. Turnbull (32, 33), Davidson and Gardiner (45), Jumikis (112), and Ring et al (135).

Woods and Litehiser (9) experimented early with the original Proctor test (2) and found that although "scatter" diagrams resulted, definite trends existed between maximum dry unit weight, optimum moisture content, and plasticity. The relationships are shown in Figure 105. Increases in the plastic properties of the soils were accompanied by increases in optimum moisture content and by decreases in maximum dry unit weight. Jumikis (112) studied the relationships between liquid limit (LL) and optimum moisture content (OMC) for many New Jersey glacial soils and found that the OMC vs LL relationships were dependent on the plasticity index of the soils. The relationships are shown in Figure 106.

Rowan and Graham (27) developed formulas for estimating the Proctor maximum dry unit weight and optimum moisture content from the mechanical analysis and shrinkage test results. Because the report does not state the details of the test it is assumed that the test method employed the Proctor method (2), consisting of 25 firm 12-in. strokes of a 5.5-lb tamper on each of three layers in a mold about 4 in. in diameter and 5 in. high (approximately $\frac{1}{27}$ cu ft) or the revised Proctor procedure (35) employing a 5.75-lb tamper and a $\frac{1}{20}$-cu ft mold, rather than the then current AASHO Designation: T 99 test procedure. The estimate for maximum dry unit weight was based on the premise that it (unit weight) was equal to the dry unit weight of the shrinkage specimen after the shrinkage limit test. The estimating equations are

$$\text{Calculated Density (pcf)} = \frac{D}{1 + \frac{D - C}{62.5\, G_s}} \tag{7}$$

$$\text{Calculated Optimum Moisture (percent)} = SL\left(\frac{B}{A}\right) \tag{8}$$

in which

$D = \frac{CA}{B}$;

C = 62.5 × shrinkage ratio, pcf;

A = percentage passing No. 4 sieve;

B = percentage passing No. 40 sieve;

G_s = specific gravity;

SL = shrinkage limit, percent.

Rowan and Graham tested the formulas using data from 10 soils (see Tables 42 and 43) and found the calculated optimum moisture contents to be from 1 to 5 percentage units higher than actual values; the calculated maximum unit weights closely approxi-

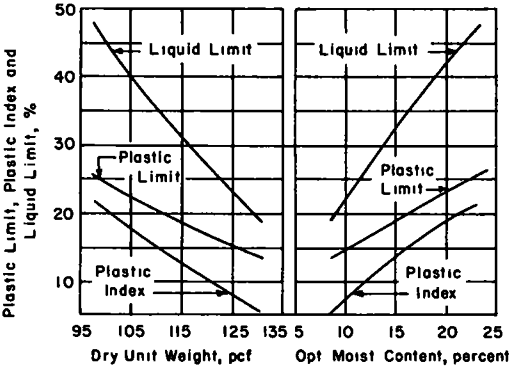


Figure 105. Average relationships between plastic properties and maximum dry unit weight and optimum moisture content for 1367 Ohio soils (9).

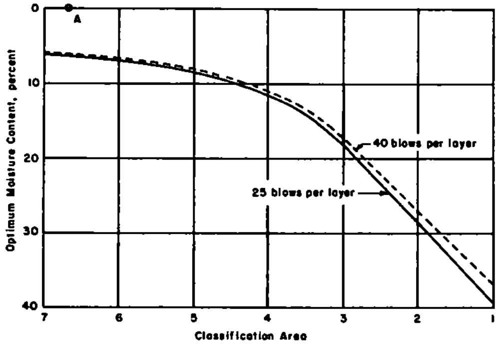


Figure 107. Relationship between Turnbull classification area and optimum moisture content for 25 and 40 blows per layer (32). Additional work (131A) indicates the lines should be extended straight from their intersections with the "classification area 4" line to point A (C.A. = 6.77).

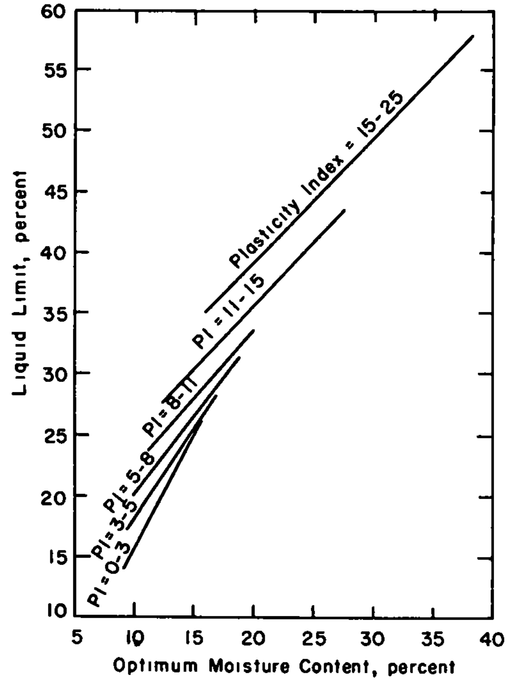


Figure 106. Optimum moisture content vs liquid limit relationships for various New Jersey glacial soils for various plasticity indexes (112).

mated the actual values, the greatest difference was about 5 percent.

Davidson and Gardiner (45) extended the work of Rowan and Graham by comparing the calculated and laboratory test values of 210 soils from widespread geographical locations. Tests were performed in the Iowa State University laboratory on 7 Iowa soils and 1 Virginia soil. Additional data from laboratory tests (including compaction tests made in accordance with AASHO Designation: T 99) included those on 92 Iowa soils from 28 counties and from tests performed by the U.S. Bureau of Public Roads on 110 soils from widely distributed sources.

Application of the Rowan and Graham formulas to the data assembled did not result in the same degree of correlation between calculated and laboratory test values as was found by Rowan and Graham in their tests. The greatest variance was found when the formula was applied to highly plastic soils. Davidson and Gardiner developed correction factors that could be used to adjust the basic formulas. The corrected equations are

$$\text{Maximum dry unit weight (pcf)} = \frac{6{,}250\,K_1}{SL\,(\frac{B}{A} - 1) + \frac{100}{R}} \qquad (9)$$

$$\text{Calculated optimum moisture (percent)} = SL\,(\frac{B}{A}) + K_2 \qquad (10)$$

TABLE 42

MECHANICAL ANALYSIS OF SOILS USED IN COMPUTATION OF PROCTOR MAXIMUM DRY UNIT WEIGHT AND OPTIMUM MOISTURE CONTENT (27)

Soil Sample	Percent Passing Sieve No.					Silt and Clay (%)	Clay (%)
	4	10	35	80	200		
1	100	91	81	76	70	67	18
2	100	88	69	56	43	37	14
3	100	96	88	84	78	77	26
4	100	93	85	78	73	68	19
5	100	91	82	77	72	70	16
6	100	97	91	87	83	81	26
7	---	100	98	94	90	88	59
8	---	---	100	98	85	64	24
9	---	---	100	87	80	79	50
10	100	98	95	90	79	77	32

TABLE 43

INDEX PROPERTIES OF SOILS USED IN COMPUTATION OF PROCTOR MAXIMUM DRY UNIT WEIGHT AND OPTIMUM MOISTURE CONTENT (27)

Soil Sample	Liquid Limit	Plastic Limit	Plasticity Index	Shrink. Limit	Shrink. Ratio	Approx. Spec. Gravity[a]	Proctor OMC (%)	Proctor Max. γ_d (pcf)	Calc. Proctor OMC (%)	Calc. Proctor Max. γ_d (pcf)
1	39	22	17	22.6	1.67	2.66	16	111	15	112
2	21	16	5	17.8	1.81	2.66	9.5	119.5	9.5	125
3	44	27	17	21.5	1.68	2.63	18	105	16	110
4	32	24	8	21.2	1.65	2.54	14.5	110	15	108.5
5	27	23	4	22.7	1.62	2.56	14.7	111	15.5	108.5
6	41	24	17	20.9	1.71	2.65	17.7	108	17	110
7	74	34	40	26.2	1.50	2.55	22	96	22.5	95
8	26	23	3	18.5	1.79	2.68	12	112	15.5	112
9	49	28	21	25.4	1.69	2.42	23	104	22	106
10	40	28	12	31.0	1.62	2.65	21.6	104	26	104

[a] As calculated from shrinkage limit and shrinkage ratio.

in which

$$K_1 = \frac{312 - 2\,(PI)}{300};$$

PI = plasticity index;

R = shrinkage ratio;

SL, A, and B as defined under Eq. 7;

$$K_2 = \frac{PI}{3} - 4$$

Eq. 9 does not include the specific gravity term G_s that appears in Eq. 7. The G_s values used by Rowan and Graham were calculated from shrinkage test data; Davidson and Gardiner substituted the shrinkage data directly into the formula.

Turnbull (32) of Australia used a different approach to the subject. He devised a method for predicting the optimum moisture content from the gradation of the sample. For a single measure of gradation, he used the area above the grain-size distribution curve and named it the "classification area" (33). Figure 107 shows the relationship of classification area to optimum moisture content for 101 soils. The two curves in Figure 104 refer to the two compaction efforts used. Compaction tests have been made under 25 blows and 40 blows per 2-in. layer of a 5.5-lb tamper falling freely from a height of 18 in. The two curves fit the test values of optimum moisture content very closely; 72 percent of the predicted values are within 1.0 percentage point of the test values.

To simplify the determination of the "classification area," Turnbull subdivided the grain-size distribution chart by equally spaced ordinates. Figure 108 shows the grain-size distribution of a sample of Cecil coarse sandy loam. To determine the classification area, ½ of the length (in percent) of ordinate 13, above the grain-size curve, is added to the sum of the lengths of the other ordinates above the curve, and that sum is multiplied by 0.00301. For example, for the Cecil coarse sandy loam, the lengths of the ordinates (to be added) above the curve are 94, 88, 83, 77, 72, 66, 61, 55, 50, 45, 41, 38, 35, 31, 27, 23, 17, 9, 2, and 0.

The sum of these, 867, when multiplied by 0.00301 yields a classification area of 2.61.

The predicted optimum moisture contents, based on the classification area, for the two compaction efforts (25 and 40 blows per layer), may be determined from the curves in Figure 107. For a classification area of 2.61, the predicted optimum for the lower compaction effort is 22 percent.

In Figure 108, it may be noted that the particle sizes shown beside the sieve numbers are equal to 1.24 times the actual width of the sieve opening in millimeters. This has been done to bring the sieve analysis into line with the sedimentation analysis. The diameter of a sphere, having the same volume as a cubical particle just passing through the sieve, is 1.24 times the sieve opening.

Turnbull employed this prediction method mainly to determine the effect on optimum moisture content of adding coarse material to a soil for which optimum was known.

Ring, Sallberg, and Collins (135) reported the results of two studies conducted by the U.S. Bureau of Public Roads. In the first study, test data were evaluated from 972 soil samples from 31 states. Optimum moisture content and maximum dry unit weight were correlated with plastic limit and liquid limit (see Figure 109). An evaluation of the chart using more than 500 additional soils, showed that 81 percent of the predicted optimum moisture contents were within 2.5 percentage points of the test values and that 63 percent of the predicted maximum unit weights were within 4.5 pcf of the test values.

In the second study, optimum moisture content and maximum dry unit weight were correlated with several measures of plasticity and gradation. Test data were analyzed for 527 plastic soil samples, representing a broad coverage of soils within the continental United States. Methods developed for predicting optimum moisture content and maximum dry unit weight based on plastic limit and fineness average, are given in Figures 110 and 111, respectively. (The fineness average is equal to ⅕ of the sum of the percentages finer than the following sizes in millimeters: 2.0, 0.42, 0.020, 0.005, and 0.001.) Comparisons of the predictions with the basic test data resulted in standard errors of estimate of ± 2.17 percent moisture and ± 4.32 pcf. In other words, approximately 67 percent of the predicted optimums were within 2.17 percentage points of the test values; 67 percent of the predicted unit weights were within 4.32 pcf of the test values.

Ring, Sallberg, and Collins compared several prediction methods by tabulating actual and predicted test data for 10 soils. These data are given in Tables 44 and 45.

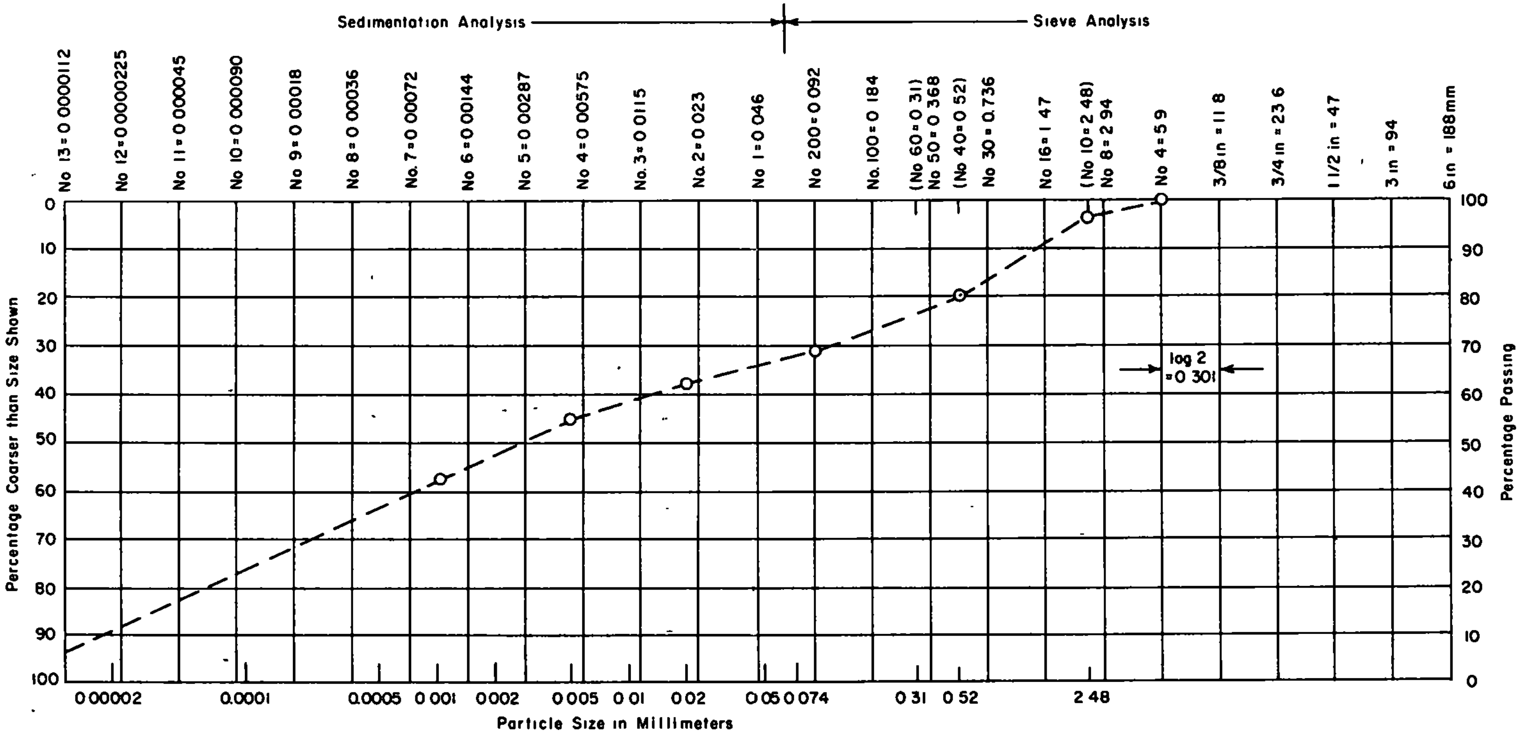


Figure 108. Grain-size distribution of Cecil coarse sandy loam on a chart for determining Turnbull classification area (33).

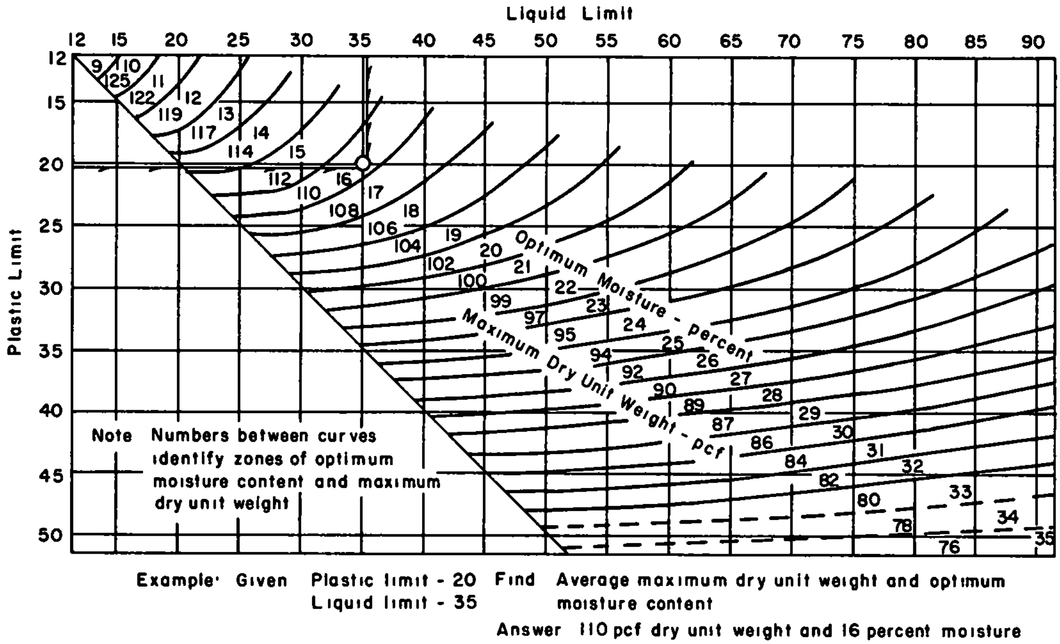


Figure 109. Relation of average maximum dry unit weight and optimum moisture content (AASHO T99-49) to plastic limit and liquid limit (135).

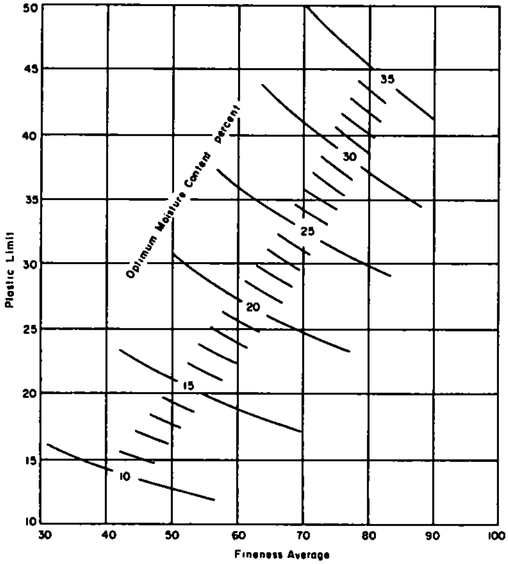


Figure 110. Relation of optimum moisture content (AASHO T99-57, Method A) to plastic limit and fineness average (135).

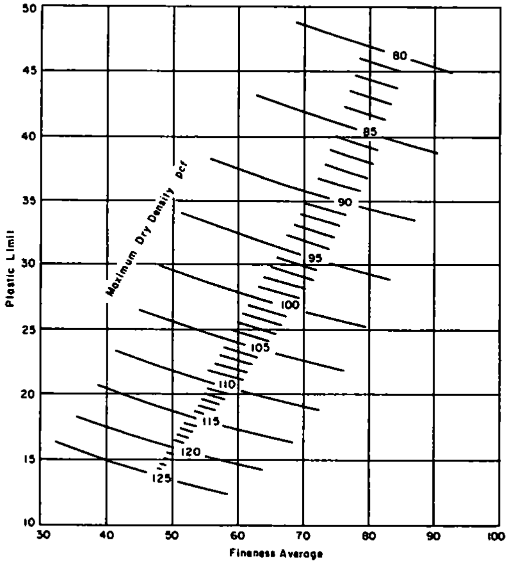


Figure 111. Relation of maximum dry density (AASHO T99-57, Method A) to plastic limit and fineness average (135).

TABLE 44

COMPARISON OF PREDICTED OPTIMUM MOISTURE CONTENTS WITH TEST VALUES

Soil Classification		Test Value[a]	Optimum Moisture Content (%)					
AASHO	Unified		PL and FA[b]	PL and LL	Jumikis	Turnbull[c]	Davidson and Gardiner	Rowan and Graham
A-6(9)	CL	14	13	14	13	19	12	9
A-4(4)	ML	14	15	15	14	13	18	18
A-4(8)	ML-CL	16	17	15	16	18	14	14
A-4(3)	SM-SC	17	18	18	22	14	14	15
A-7-6(12)	CL	18	18	18	22	20	21	16
A-6(11)	CL	20	19	18	21	24	23	18
A-7-6(13)	CL	20	16	18	23	19	14	7
A-7-6(20)	MH-CH	22	25	26	--[d]	22	28	18
A-7-5(20)	CH	25	25	24	--[d]	28	18	6
A-7-5(20)	MH	31	32	27	--[d]	38	32	21

[a] Determined by AASHO Designation: T 99-57, Method A.

[b] Fineness average, equal to 1/6 of the sum of percentages finer than the following sizes in millimeter: 2.0, 0.42, 0.074, 0.020, 0.005, and 0.001.

[c] Optimum for test using 25 blows per 2-in. layer.

[d] Beyond limits of chart.

TABLE 45

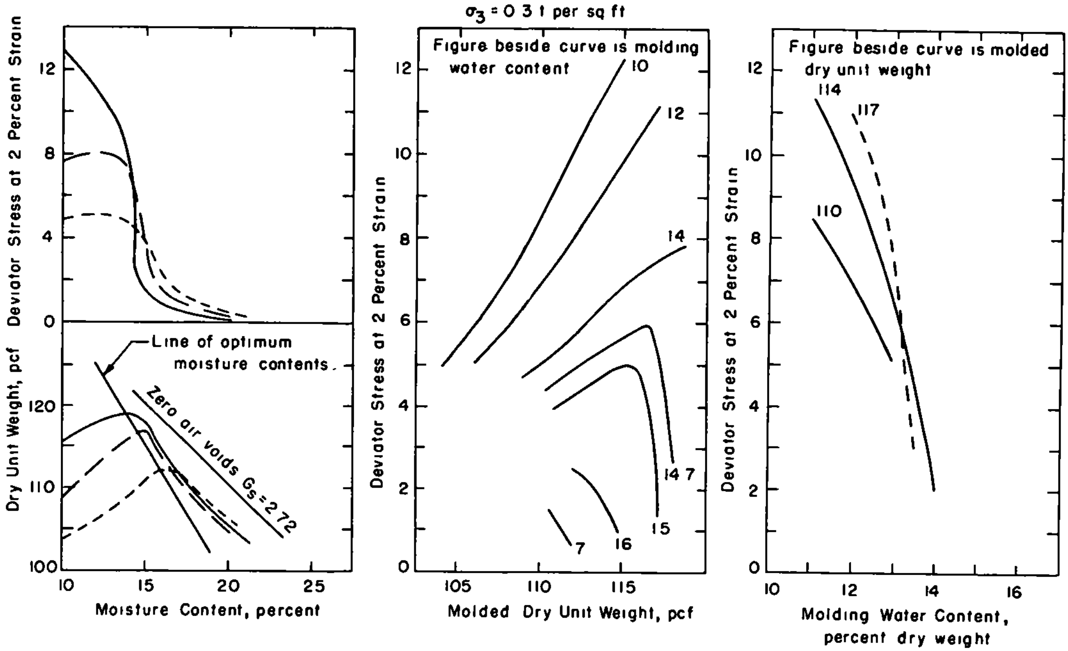
COMPARISON OF PREDICTED MAXIMUM DRY UNIT WEIGHTS WITH TEST VALUES

Soil Classification		Test Value[a]	Maximum Dry Unit Weight (pcf)			
AASHO	Unified		PL and FA	PL and LL	Davidson and Gardiner	Rowan and Graham
A-6(9)	CL	119	118	114	118	125
A-4(4)	ML	109	110	112	112	109
A-4(8)	ML-CL	107	107	112	110	109
A-4(3)	SM-SC	109	105	106	108	111
A-7-6(12)	CL	106	106	106	99	105
A-6(11)	CL	107	105	106	99	108
A-7-6(13)	CL	109	110	106	111	125
A-7-6(20)	MH-CH	100	92	92	85	105
A-7-5(20)	CH	94	94	95	98	126
A-7-5(20)	MH	89	87	90	81	100

[a] Determined by AASHO Designation: T 99-57, Method A.

Methods for Reporting Moisture Content-Unit Weight Data

Compaction is now regarded by many engineers as a design tool. The dry unit weight and moisture content can be controlled economically within limits during construction to produce soils that most nearly exhibit the properties (unconfined compression, triaxial shear strength, California Bearing Ratio, consolidation, swell, swell pressure, shrinkage, permeability, etc.) desired by the engineer. This is especially true for the construction of subgrades, stabilized bases, earth dams, diversion dikes, embankments subjected to extended periods of inundation, and backfill around conduits. To determine the range in values of bearing capacity, swell, swell pressure, etc., of a soil for a range in values of dry unit weight, it may be necessary to conduct compaction tests at more than one compaction effort. It may be desirable to perform tests to develop a family of curves whose limits will encompass the range of values for the properties desired. Because the individual soils may exhibit a wide range in values of individual properties for the permissible range in moisture content and unit weight, it is desirable to present such data on an interrelated basis so that the engineer may view as many of the test data as are practicable at the same time and assess the effect of moisture content and dry unit weight on the soil properties.



LEGEND

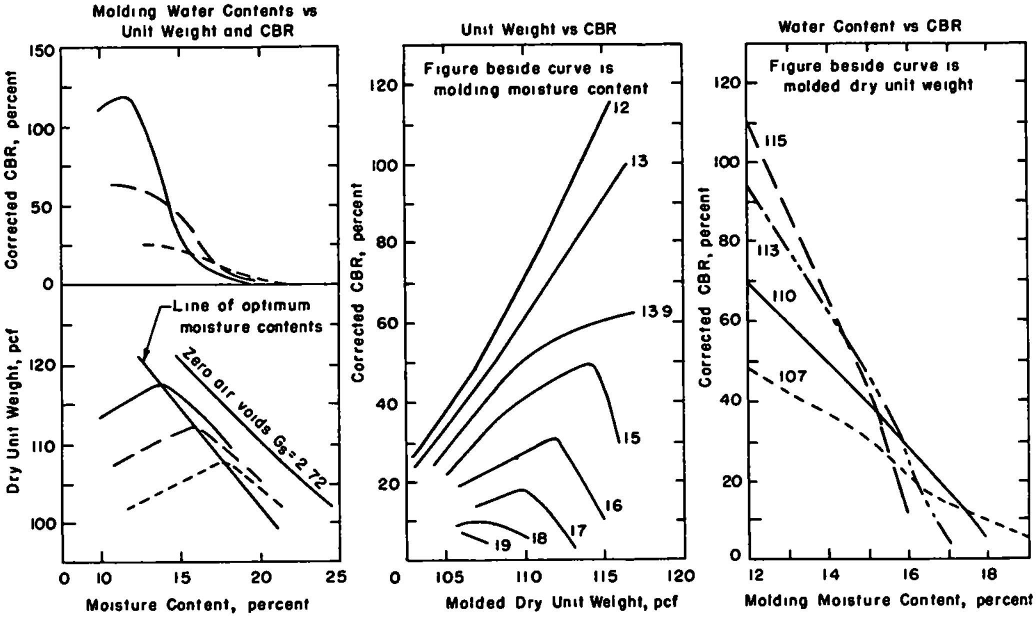
	Layers	Blows per Layer	Weight Hammer	Drop, in
———	5	55	10 lb	18
— —	5	26	10 lb	18
- - - -	5	12	10 lb	18

Note Tests performed on as-molded specimens 1.4 in in diameter and approximately 3 in high. Tests were of unconsolidated-undrained type. Soil is a lean clay having LL = 36, PI = 15, specific gravity = 2.72.

Figure 112. Unit weight, water content, and triaxial shear test data. Laboratory compaction data vs deviator stress at 2 percent strain (89).

No special effort has been made to devise such means for presenting moisture content-dry unit weight data with other data for any of the currently used methods for design that are used in relation to highways. However, examination of some reports that have been arranged for rapid appraisal of test data (including moisture content-unit weight relationships) has shown that such methods as suggested do facilitate the assessment of test data and aids in its interpretation and analysis in relation to strength properties or other soil properties. Figures 112 and 113 are examples of reporting compaction test data in a manner to facilitate its interpretation and use in comparison with soil properties influenced by compaction. It is believed that they aid in appreciation of triaxial shear and CBR test data. They are included here merely to show that the method of presenting data may influence their use in design and construction.

The wide variety of methods and arrangements used in reporting soil test data for use by engineers whose duties include the structural design of pavements (including subgrades, subbases, and bases) and other elements of the road structure, suggest that studies on methods of reporting data may be beneficial. It would be of interest to study currently used design methods and determine whether it is feasible to develop better methods of reporting the results of laboratory compaction tests in conjunction with the results of other tests whose results are influenced by moisture content and dry unit weight.



LEGEND

	Layers	Blows per Layer	Weight Hammer	Drop, in	
———	5	55	10 lb	18	Modified AASHO
— —	5	26	10 lb	18	
- - - -	5	12	10 lb	18	Effort equal to AASHO

Note Specimens tested as molded Penetration surcharge = 0 35 psi

Figure 113. Unit weight, water content, and CBR data. Dynamic compaction as molded. Soil a lean clay, LL = 36, PI = 15, specific gravity = 2.72 (89).

REFERENCES

1. Purcell, C.H., "Grading Methods and Grading Equipment—Construction and Compaction of Embankments." Amer. Road Builders Assoc., Bull. 17, p. 6 (Nov. 1930).
2. Proctor, R.R., "Fundamental Principles of Soil Compaction." Engineering News-Record, 111: Nos. 9, 10, 12, and 13 (Aug. 31, Sept. 7, 21, and 28, 1933).
3. Kelso, A.E., "The Construction of the Silvan Dam, Melbourne, (Australia) Water Supply." Proc. Inst. Civil Engineers (London), 239: pt. I, pp. 403-406 (1936).
4. Allen, H. and Johnson, A.W., "The Results of Tests to Determine the Expansive Properties of Soils." HRB Proc., 16: 220-233 (1936).
5. Hogentogler, C.A., Jr., "Essentials of Soil Compaction." HRB Proc., 16: 309-316 (1936).
6. Hogentogler, C.A., and Willis, E.A., "Stabilized Soil Roads." Public Roads, 17: No. 3, pp. 45-65 (May 1936).
7. Hamilton, L.W., Preece, E.F., Stanton, T.E., Johnson, A.W., Woods, K. B., and Casagrande, L., "Compaction of Earth Embankments." HRB Proc., 18: pt. 2, pp. 142-181 (1938).
8. Stanton, T.E., "Highway Fill Studies and Soil Stabilization." California Highways and Public Works, Vol. 16 (June-July 1938).
9. Woods, K.B., and Litehiser, R.R., "Soil Mechanics Applied to Highway Engineering in Ohio." Ohio State Univ. Eng. Exp. Sta., Bull. 99 (July 1938).
10. Kansas State Highway Department, "Report of Research on the Sand Method of Density Determination." Departmental Report (June 1, 1939).
11. Kansas State Highway Department, "Report of Research on the Sand Method of Density Determination in Deep Holes." Departmental Report (Aug. 4, 1939).
12. Shelburne, T.E., "Degradation of Aggregates Under Road Rollers." Proc., ASTM 39: 950-970 (1939).
13. Shelburne, T.E., "Crushing Resistance of Surface Treatment of Aggregates." Purdue Univ. Eng. Exp. Sta. Bull., Research Series 76 (Sept. 1940).
14. Belcher, D.J., "A Field Investigation of Low-Cost Stabilized Roads." Purdue Univ., Eng. Exp. Sta., Res. Series 81, 25: No. 2A (April 1941).
15. Buchanan, S.J., "Soil Compaction." Proc., 5th Texas Conf. on Soil Mechanics and Foundation Engineering, Austin, pt. 2 (1942).
16. Porter, O.J., "Foundations for Flexible Pavements." HRB Proc., 22: 100-136 (1942).
17. Maddison, L., "Laboratory Tests on the Effect of Stone Content on the Compaction of Soil Mortar." Roads and Road Construction (London) 22: 37-40 (Feb. 1, 1944).

17A. Aaron, H., Spencer, W.T., and Marshall, H.E., "Research on the Construction of Embankments." Public Roads, 24: No. 1 (1944).

18. U.S. Corps of Engineers, "The California Bearing Ratio as Applied to the Design of Flexible Pavements for Airports." U.S. Waterways Exp. Sta. Tech. Memo. 213-1 (July 1945).
19. McDowell, C., "Progress Report on Development and Use of Strength Tests for Subgrade Soils and Flexible Bases." HRB Proc., 26: 484-511 (1946).
20. Johnson, A.M., "The Role of Calcium Chloride in Compaction of Some Granular Soils." HRB Proc., 26: 594-601 (1946).
21. Yoder, E.J., and Woods, K.B., "Compaction and Strength Characteristics of Soil-Aggregate Mixtures." HRB Proc., 26: 511-520 (1946).
22. Willis, E.A., "Discussion on 'A Study of Lateritic Soils'." HRB Proc., 26: 589-591 (1946).
23. Yoder, E.J., and Woods, K.B., "Compaction and Strength Characteristics of Soil-Aggregate Mixtures." HRB Proc., 26: 511-520 (1946).
24. Yoder, E.J., "Effect of Calcium Chloride on the Compactive Effort and Water Retention Characteristics of Soils." HRB Proc., 27: 490-504 (1947).
25. Little, A.L., "Laboratory Compaction Technique." Proc., 2nd Internat. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam 1: 224-230 (1948).

26. Shockley, W.G., "Correction of Unit Weight and Moisture Content for Soils Containing Gravel Sizes." U.S. Corps of Engineers, Waterways Exp. Sta., Soils Div., Embankment and Foundation Branch, Tech. Data Sheet 2. (June 16, 1948).
27. Rowan, W.H., and Graham, W.W., "Proper Compaction Eliminates Curing Period in Constructing Fills." Civil Engineering 18: 450-451 (July 1948).
28. Zeigler, E.J., "Effect of Material Retained on the No. 4 Sieve on the Compaction Test of Soils." HRB Proc., 28: 409-414 (1948).
29. Gawith, A.H., "An Improved Soil Compaction Rammer." Proc., 2nd Internat. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 2: 292 (1948).
30. Lane, K.S., "Providence Vibrated Density Tests." Proc., 2nd Internat. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 4: 243-247 (1948).
31. Maclean, D.J., and Williams, F.H.P., "Research on Soil Compaction at the Road Research Laboratory." Proc., 2nd Internat. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 4: 247-256 (1948).
32. Turnbull, J.M., "Computation of the Optimum Moisture Content in the Moisture-Density Relationship of Soils." Proc., 2nd Internat. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 4: 256-262 (1948).
33. Turnbull, J.M., "A New Classification of Soils Based on the Particle Size Distribution Curve." Proc., 2nd Internat. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 5: 315-319 (1948).
34. Proctor, R.R., "Laboratory Soil Compaction Methods, Penetration Resistance Measurements, and Indicated Saturated Penetration Resistance." Proc., 2nd Internat. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 5: 242-247 (1948).
35. Proctor, R.R., "The Relationship Between the Foot Pounds per Cubic Foot of Compactive Effort and the Shear Strength of the Compacted Soils." Proc., 2nd Internat. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 5: 219-223, (1948).
36. Proctor, R. R., "The Relationship Between the Foot Pounds per Cubic Foot of Compactive Effort Expended in the Laboratory Compaction of Soils and the Required Compactive Efforts to Secure Similar Results with Sheepsfoot Rollers." Proc., 2nd Internat. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 5: 231-234 (1948).
37. Hirashima, K.B., "Highway Experience with Thixotropic Volcanic Clay." HRB Proc., 28: 481-496 (1948).
38. Proctor, R.R., "Relationship Between the Foot Pounds per Cubic Foot of Compactive Effort to Soil Density and Subsequent Consolidation Under Various Loadings." Proc., 2nd Internat. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 5: 223-227 (1948).
39. Burmister, D.M., "The Importance and Practical Use of Relative Density in Soil Mechanics." Proc., ASTM, 48: 1249-1268 (1948).
40. U.S. Corps of Engineers, "Soil Compaction Investigation, Report No. 1, Compaction Studies on Clayey Sands." U.S. Waterways Exp. Sta., Tech. Memo. 3-271 (April 1949).
41. U.S. Corps of Engineers, "Soil Compaction Investigation, Report No. 2, Compaction Studies on Silty Clay." U.S. Waterways Exp. Sta., Tech. Memo. 3-271 (July 1949).
42. U.S. Corps of Engineers, "Soil Compaction Investigation, Report No. 3, Compaction Studies on Sand Subgrade." Waterways Exp. Sta., Tech. Memo. 3-271 (Oct. 1949).
43. Turnbull, W.J., Johnson, S.J., and Maxwell, A.A., "Factors Influencing Compaction of Soils." HRB Bull, 23, (1949).
44. Lambe, T.W., "How Dry Is a Dry Soil?" HRB Proc., 29: 491-496 (1949).
45. Davidson, D.T., and Gardiner, W.P., "Calculation of the Standard Proctor Density and Optimum Moisture Content from Mechanical Analysis, Shrinkage Factors, and Plasticity Index." HRB Proc., 29: 477-481 (1949).

46. Nelson, G.H., and Sowers, G.W., "Effect of Re-Using Soil on Moisture-Density Curves." HRB Proc., 29: 482-487 (1949).

47. Grady, J.D., "Discussion on Effect of Re-Using Soil on Moisture-Density Curves." HRB Proc., 29: 488-490 (1949).

47A. Wyoming Highway Department, "Soils Manual." Cheyenne (1949).

48. U.S. Corps of Engineers, "Soil Compaction Investigation, Report No. 4, Sub-grade Compaction Studies." U.S. Waterways Exp. Sta. Tech. Memo. 3-271 (Feb. 1950).

49. Williams, F.H.P., and Maclean, D.J., "The Compaction of Soil: A Study of the Performance of Plant." Road Res. Lab., Road Res. Tech. Paper 17, H.M. Stationery Office, London (1950).

50. Reagel, F.V., "Standard Density of Bases." Missouri Highway Dept., Dept. of Materials, Div. of Geology and Soils, Instruction Circular 1950-2 (June 12, 1950).

51. U.S. Corps of Engineers, "Soil Compaction Investigation: Report No. 5, Miscellaneous Laboratory Tests." U.S. Waterways Exp. Sta. Tech. Memo. 3-271 (June 1950).

52. Vallerga, B.A., "Triaxial Institute Kneading Compactor." Univ. of California, Berkeley, Inst. of Transportation and Traffic Engineering, Information Circular 10, pp. 9-10 (June 10, 1950).

53. Wilson, S.D., "Small Soil Compaction Apparatus Duplicates Field Results Closely." Engineering News-Record, 145: No. 18, pp. 34-36 (Nov. 2, 1950).

54. Krynine, D.P., "Some Comments on Earth Compaction." HRB Bull. 42, 14-20 (1951).

55. Vallerga, B.A., "Recent Laboratory Compaction Studies of Bituminous Paving Mixtures." Proc., Assoc. of Asphalt Paving Technologists, 20: 117-153 (1951).

56. Washington Department of Highways, "Nomograph for Density Correction." (1951).

57. Walker, F.C., and Holtz, W.S., "Control of Embankment Material by Laboratory Testing." Proc., ASCE, 77: Separate 108 (Dec. 1951).

58. Smith, H., "Gravel Compaction and Testing, and Concrete Mix Design at London Airport." Proc., 1: Inst. of Civil Engineers (Great Britian), No. 1, pt. 2, pp. 1-54 (Feb. 1952).

59. Dubose, L.A., "Evaluating Taylor Marl Clay for Improved Use in Subgrades." Texas A & M College, Texas Eng. Exp. Sta. Res. Report 35 (March 1952).

60. Soil Mechanics for Engineers, "Compaction of Soil." Great Britian Road Res. Lab., H.M. Stationary Office, London, pp. 154-207 (1952).

61. "Compaction of Embankments, Subgrades, and Bases." HRB Bull. 58 (1952).

62. McRae, J.L., and Rutledge, P.C., "Laboratory Kneading of Soil to Simulate Field Compaction." HRB Proc., 31: 593-600 (1952).

63. Wilson, S.D., "Effect of Compaction on Soil Properties." Proc., Conf. on Soil Stabilization, Mass. Inst. of Tech., Boston, pp. 147-161 (1952).

64. Mainfort, R.C., and Lawton, W.L., "Laboratory Compaction Tests for Coarse Graded Paving and Embankment Materials." U.S. Civil Aeronautics Administration Tech. Develop. Report 177, Indianapolis (1952).

65. "Compaction of Alluvial Soils." Jour. Indian Roads Congress (India), 17: 291-343 (Jan. 1953).

66. Turnbull, W.J., and Shockley, W.G., "Field Compaction Tests on Lean Clay Soil." Proc., 3rd Internat. Conf. on Soil Mechanics and Foundation Engineering, Switzerland, 1: 313-316 (1953).

67. Mainfort, R.C., and Lawton, W.L., "Laboratory Compaction Tests of Coarse Graded Paving and Embankment Materials." HRB Proc., 32: 555-566 (1953).

68. Whitman, W.L., and Land, J.L., "Machine Compactor for Proctor Density and Pneumatic Specimen Remover." HRB Proc., 32: 567-575 (1953).

69. Krynine, D.P., "Discussion on Control of Embankment Material by Laboratory Testing." Trans. ASCE, 118: 29-33 (1953).

70. Walker, F.C., and Holtz, W.G., "Closing Discussion on Control of Embankment Material by Laboratory Testing." Trans., ASCE 118: 35-38 (1953).
71. McDowell, Chester, "Selection of Densities for Subgrades and Flexible Base Materials." HRB Bull. 93, 1-15 (1954).
72. Seed, H.B., Lundgren, R., and Chan, C.K., "Effect of Compaction Method on Stability and Swell Pressure of Soils." HRB Bull. 93: 33-48 (1954).
73. Seed, H.B., and Monismith, C.L., "Relationship Between Density and Stability of Subgrade Soils." HRB Bull. 93, 16-32 (1954).
74. Sowers, G.G., and Kennedy, C.M., "Effect of Repeated Load Applications on Soil Compaction Efficiency." HRB Bull.93, 61-64 (1954).
75. U.S. Corps of Engineers, "Soil Compaction Investigation, Report No.6: Effect of Size of Feet on Sheepsfoot Rollers." U.S. Waterways Exp. Sta. Tech. Memo. 3-271 (June 1954).
76. Bruzelius, N.G., "A Study of the Compaction of Soil." Statens Väginstitut, Meddelande 87, Stockholm (1954).
77. Lewis, W.A., "Further Studies in the Compaction of Soil and Performance of the Compaction Plant." (Great Britian) Dept. of Scientific and Industrial Res., Road Res. Lab. Tech. Paper 33 (1954).
78. Ray, P.N., and Chapman, T.G., "The British Standard Compaction Test for Soils: A Study of Some Factors Affecting the Test Results." Geotechnique, 4: No. 4, pp. 169-177, (Dec. 1954).
79. Moore, W.H., "Relation Between Compaction and Stability of Soils." Texas Highways, 2: 28-35 (Nov. 1954).
80. Slate, F.O., and Yalcin, A.S., "Stabilization of Bank Run Gravel by Calcium Chloride." HRB Bull. 98, 21-32 (1954).
81. California Institute of Technology, "Vibration Compaction of Cohesive Soils." Pasadena (Dec. 1954).
82. U.S. Corps of Engineers, "Field Moisture Content Investigation, Report No. 2, October 1945—November 1952 Phase." U.S. Waterways Exp. Sta. Tech. Memo. 3-401 (April 1955).
83. Bruce, R.R., "An Instrument for the Determination of Soil Compactibility." Proc., Soil Science Soc. of America, 19: No. 3, pp. 253-257 (July 1955).
84. Remillon, A., "Stabilization of Laterite Soils." HRB Bull. 108, 96-101 (1955).
85. Beavis, H.M., and Purdam, R.K., "Compactibility and Stability of Soils for Flexible Pavements and the Modifying Effect of Small Amounts of Cement." New Zealand Engineering, 10: 348-353 (Nov. 15, 1955).
86. Foster, C.R., "Reduction in Soil Strength with Increase in Density." Trans., ASCE, 120, Paper 2763, pp. 803-822 (1955).
87. Spencer, W.T., Allen, H., and Smith, P.C., "Report on Pavement Research Project in Indiana." HRB Bull. 116, 18-25 (1956).
88. "Detergent Shows Promise as an Aid in Soil Compaction." Roads and Streets, 99: No. 3, p. 112 (March 1956).
89. U.S. Corps of Engineers, "Soil Compaction Investigation, Report No. 7: Effect on Soil Compaction of Tire Pressure and Number of Coverages of Rubber Tired Rollers and Foot Contact Pressure of Sheepsfoot Rollers." U.S. Waterways Exp. Sta. Tech. Memo. 3-271 (June 1956).
90. "Detergent Shows Promise as Soil Compaction Aid." Street Engineering 1: No. 3, p. 29 (March 1956).
91. Seed, H.B., "A Low-Cost Kneading Compactor." Univ. of California, Berkeley, Inst. of Traffic and Transportation Engineering, Information Circular 27 (Nov. 1956).
92. U.S. Department of the Interior, "Earth Manual." Tent. ed., Bureau of Reclamation, Denver (Feb. 1957).
92A. "Standard Definitions of Terms Relating to Specific Gravity." In "Standards on Bituminous Materials for Highway Construction, Waterproofing and Roofing." ASTM, Philadelphia pp. 337-338 (April 1957).
93. Reagel, F.V., Communication of F.V. Reagel, Missouri State Highway Department, to L.D. Hicks, Chairman of Committee on Compaction of Embankments, Subgrades and Bases. (July 18, 1957).

94. McDowell, C., "Principles of Controlled Compaction." WASHO Proc., pp. 128-149 (1957).
95. Hveem, F.N., "Maximum Density and Optimum Moisture of Soils." HRB Bull. 159, 1-19 (1957).
96. Seed, H.B., and Chan, C.K., "Thixotropic Characteristics of Compacted Clays." Proc., ASCE, Vol. 83: Jour. Soil Mechanics and Foundations Division, SM-4, Paper 1427, pp. 1427-1 to 25, pt. 1 (Nov. 1957).
97. Burchett, E., "The Determination of the Theoretical Maximum Density of Gravel and Crushed Aggregate Materials." Tennessee Dept. of Highways and Public Works, Nashville (Oct. 1957).
98. Kassif, G., "Compaction and Shear Characteristics of Remoulded Negev Loess." Proc., 4th Internat. Conf. on Soil Mechanics and Foundation Engineering, London 1: 56-61 (1957).
99. Dhawan, C.L., and Bahri, J.C., "Stable Density." Proc., 4th Internat. Conf. on Soil Mechanics and Foundation Engineering, London 1: 149-152 (1957).
100. Turnbull, W.J., and Foster, C.R., "Compaction of a Graded Crushed Stone Base Course." Proc., 4th Internat. Conf. on Soil Mechanics and Foundation Engineering, London 2: 181-185 (1957).
101. Myslivec, A., "The Degree of Compaction of Soil According to the Proctor and Dornii Tests." Proc., 4th Internat. Conf. on Soil Mechanics and Foundation Engineering, London 2: 338-340 (1957).
102. Humphres, H.W., "A Method for Controlling Compaction of Granular Materials." HRB Bull. 159, 41-57 (1957).
103. U.S. Corps of Engineers, "Effect of Lift Thickness and Tire Pressure." U.S. Waterways Exp. Sta. Report 8, Soil Compaction Investigation, Tech. Memo. 3-271 (Oct. 1957).
104. Gokhale, Y.C., and Rao, N.M., "Relative Compacting Efficiencies of Vibration and Smooth Wheel Rollers." Indian Roads Congress, Road Res. Bull. 3, New Delhi (1957).
105. Tamez, E., "Some Factors Affecting the Dynamic Compaction Test." ASTM, Special Tech. Publ. 232, pp. 54-66 (1957).
106. Holtz, W.G., and Lowitz, C.W., "Compaction Characteristics of Gravelly Soils." ASTM, Special Tech. Publ. 232, pp. 67-101 (1957).
107. Humphres, H.W., "Discussion on Compaction Characteristics of Gravelly Soils." ASTM, Special Tech. Publ. 232, pp. 422-427 (1957).
108. Kersten, M.S., and Krieger, F.L., "Effect of Mechanical Manipulation on the Plasticity of Soils." HRB Proc., 36: 703-712 (1957).
109. Barber, E.S., "Discussion on Thixotropic Characteristics of Compacted Clays." Proc., ASCE, Vol 84 (1958).
110. Barber, E.S., "Discussion on Laterite Soils and Their Engineering Characteristics." Proc., ASCE, Vol. 84 (1958).
111. Miller, E.A., and Sowers, G.F., "The Strength Characteristics of Soil-Aggregate Mixtures." HRB Bull. 183, 16-23 (1957).
112. Jumikis, A.R., "Geology and Soils of the Newark (N.J.) Metropolitan Area." Proc., ASCE, Vol. 84 (1958).
113. Turnbull, W.J., and Foster, C.R., "Stabilization of Materials by Compaction." Trans., ASCE, 123: Paper 2907, pp. 1-15, 25-26, (1958) (Also Discussions by G. A. Leonards, pp. 16-17; J.A. Focht, pp. 19-20; E.J. Zegarra, pp. 20-23; and K.B. Hirashima, pp. 23-24).
114. "Suds on Sheepsfoot as Compaction Deterrent Cut by Detergent." Southwest Builder and Contractor, 131: No. 2, pp. 28-30, 32, (Jan. 10, 1958).
115. Norling, L.T., and Packard, R.G., "Expanded Short-Cut Test Method for Determining Cement Factors for Sandy Soils." HRB Bull. 198, 20-31 (1958).
116. "Glossary of Terms and Definitions in Soil Mechanics." Proc., ASCE, Vol. 84 (1958).
117. U.S. Corps of Engineers, "Flexible Airfield Pavements." Engineering Manual 1110-45-302 (Aug. 15, 1958).

118. Lewis, W.A., "Investigation of the Performance of Pneumatic Tyred Rollers in the Compaction of Soil." Department of Scientific and Industrial Res., Road Res. Lab., (Great Britain) Res. Note RN/3206/WAL (March 1958).

119. Lewis, W.A., and Parsons, A.W., "An Investigation of the Performance of a 3¾-Ton Vibrating Roller for Compacting Soil." Department of Scientific and Industrial Res., Road Res. Lab. (Great Britian) Note RN/3219/WAL/AWP (1958) (unpublished).

120. Felt, E.J., "Laboratory Methods of Compacting Granular Materials." ASTM Special Tech. Publ. 239 89-108 (June 22-27, 1958).

121. "Procedures for Testing Soils." ASTM, (April 1958).

122. AASHO "Standard Specifications for Highway Materials and Methods of Sampling and Testing Part.III." (Additional Specifications, Tests and Revisions to Parts I and II; includes references to (a) Standard Definitions of Terms Relating to Subgrade, Soil Aggregate, and Fill Materials, Designation: M 146-56; (b) The Moisture-Density Relations of Soils using a 5½-lb Rammer and a 12-in. Drop, Methods A, B, C, and D, Designation: T 99-57; and (c) The Moisture-Density Relations of Soils Using a 10-lb Rammer and an 18-In. Drop, Methods A, B, C, and D, Designation: T 180-57). Washington, D.C. (1958).

123. U.S. Corps of Engineers, Office of Chief of Engineers, "Guide Specifications for Military Construction." CE 807.03 (Jan. 15, 1959).

124. ASTM, "Tentative Definitions of Terms and Symbols Relating to Soil Mechanics." ASTM Designation: D 653-58T, ASTM Standards pt. 4, pp. 1211-1288 (1958).

125. Robbins, E.G., Communication. (June 22, 1959).

126. Bureau of Public Roads, Personal communication from P.C. Smith, Bureau of Public Roads, in which he furnished compaction data on several soils. (July 6, 1959).

127. Bliss, I.C., "Field Report of Special Test Section." Investigation of Various Size Rollers on Embankment Compaction FA Route 113 Section 102 White-Gallatin Counties, Ill. Personal communication. (Oct. 5, 1959).

128. U.S. Corps of Engineers, "Proof Test Section, Columbus Air Force Base, Structural Investigation of Pavements." U.S. Waterways Exp. Sta. Tech. Report 3-533 (Dec. 1959).

128A. California Division of Highways, "Method of Test for Relative Compaction of Untreated and Treated Soils and Aggregates." California Method Test 216-E, pt. II, Method B; Materials Manual, Testing and Control Procedures, Vol. 1 (March 1960).

129. U.S. Department of Interior, "Earth Manual." Bureau of Reclamation (July 1960).

130. Johnson, A.W., and Sallberg, J.R., "Factors That Influence Field Compaction of Soils." HRB Bull. 272 (1960).

131. Hofmann, W.P., Personal communication to A.W. Johnson on effects of freezing temperatures on compaction. (March 1, 1961).

131A. Turnbull, J.M., Personal communication to P.C. Smith. (Oct. 1961).

131B. Hosking, J.R., "An Investigation into Some Factors Affecting the Results of Bulk Density Tests for Aggregate." Cement, Lime and Gravel (London) pp. 319-326 (Nov. 1961).

132. Jackson, J.G., Jr., "Influence of Foot Size on Soil Compaction." HRB Proc., 40: 611-616 (1961).

133. James, H.D., and Larew, H.G., "Compaction of Coarse-Grained Granular Materials." HRB Proc., 40: 676-680 (1961).

134. Shook, J.F., and Fang, H.Y., "Cooperative Materials Testing Program." at the AASHO Road Test, HRB Special Report 66 (1961).

135. Ring, G.W., III, Sallberg, J.R., and Collins, W.H., "Correlation of Compaction and Classification Test Data of Soils." Presented at HRB Annual Meeting (1962).

136. Virginia Dept. of Highways, Personal communication to U.S. Bureau of Public Roads. (1961).

137. U.S. Bureau of Reclamation, "Tentative Procedure for Relative Density of Cohesionless Free-Draining Soils Using a Vibratory Table." Commissioner's Office, Denver, Colo. (1961).

Appendix A

SOIL, WATER, AND AIR VOLUME-WEIGHT RELATIONSHIPS

Some mathematical relationships among volumes and/or weights of the solid, the air, and the water components of soil are useful both in analyzing data from laboratory compaction and in analyzing the results of compaction in construction. Several basic formulas are presented together with arithmetical examples.

Unit weight is the common means for expressing degree of compaction and it is sometimes the true measure of degree of compaction. For practical purposes this is true for fine grain soils, but not necessarily so for coarse grain materials that may degrade under compaction. Unit weight does not account for the specific gravity of the soil solids. Thus, in comparing the degree of compaction of soils that differ markedly in specific gravity, by comparing their dry unit weights, a false comparison results. The objective of compaction is to reduce the total intergranular pore space. Thus the only true measure of degree of compaction is the degree in which the porosity has been reduced.

The effective moisture content (as it influences compaction) is measured in terms of the moisture that occupies intergranular space and is not influenced by the moisture absorbed into the permeable voids of the coarser particles in the total soil. Thus effective moisture content must, in some instances, be determined in evaluating compaction.

The stability of a soil is related not only to its moisture content expressed as percent of dry weight of soil but also in moisture content expressed as percent saturation. Thus in addition to determining porosity as a true measure of the degree of compaction it becomes of interest to determine the degree of saturation either in terms of percent saturation (percent of total porosity filled with water) or in terms of air voids.

A diagrammatic representation of the composition of soil is shown in Figure 114. The moisture content, dry unit weight, and the proportions of solids, and water-filled and air-filled voids may be determined by means of simple formulas that express the interrelationships involved.

Specific Gravity (of Solids), G_s

Given a specific gravity of 2.7, the dry unit weight of solids is determined by multiplying the specific gravity and the unit weight of water. For example, 2.7 x 62.43 = 168.56 pcf.

Moisture Content, w

If W_w = wet weight of a soil mass = 12.4 lb or 5,625 g, and W_d = dry weight of a soil mass = 10.6 lb or 4,808 g, the moisture content

$$w = \frac{W_w - W_d}{W_d} \times 100 = \frac{12.4 - 10.6}{10.6} \times 100 \text{ or } \frac{5,625 - 4,808}{4,808} \times 100 = 17 \text{ percent}$$

Dry Unit Weight, γ_d

The dry unit weight of a soil mass is the weight of the soil per unit of total volume of soil mass (116). For example, if V = total volume of the soil mass = 0.1 cu ft or 2,832 cu cm, W_d = dry weight of the soil mass = 10.6 lb or 4,808 g,

$$\gamma_d = \frac{W}{V} = \frac{10.6}{0.1} = 106 \text{ pcf or, } \frac{4,808}{2,832} = 1.698 \text{ g/cc}$$

Proportions of Solid and Air and Water Volumes

If n_s = the percent of soils solids;
γ_d = dry unit weight (106 pcf or 1.698 g/cc);

G_s = specific gravity (2.7);
V_s = volume of soil solids

Then

$$n_s = \frac{\gamma_d}{G_s} \times 100 = \frac{\frac{106}{62.43}}{2.70} \times 100 = 62.885 \text{ percent}$$

and

$$V_s = \frac{62.885}{100} = 0.6289 \text{ cu ft soil solids.}$$

If

V = total volume of the soil mass;
V_v = volume of voids (air and water);
V_s = volume of soil solids;
V_w = volume of water filled voids;
V_a = volume of air filled voids;

$$V_v = V - V_s = 1 - 0.6289 = 0.3712 \text{ cu ft total voids.}$$

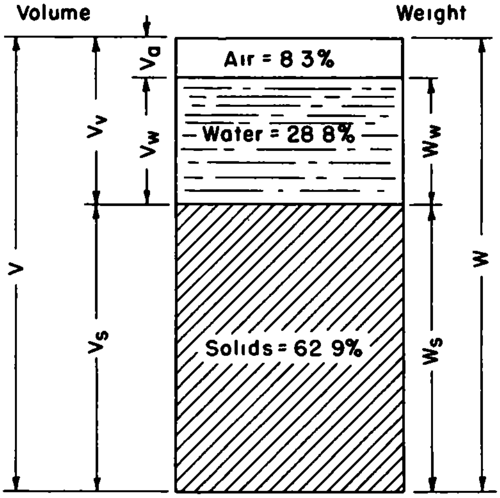


Figure 114. Diagrammatic representation of the composition of soil.

Also, if

W_d = dry weight of soil mass

$$V_w = \frac{W_d \text{ x } w}{100 \text{ x } 62.43} = \frac{10.6 \text{ x } 17}{100 \text{ x } 62.43} = 0.2886 \text{ cu ft of water}$$

and

$$V_a = V - V_w = 0.3712 - 0.2886 = 0.0826 \text{ cu ft of air.}$$

In some areas where the soil exists at a uniformly higher moisture content than optimum (77) it may be convenient to compact the soil in the field at the existing moisture content and specify compaction to a given percentage of air voids, V_a. The following expression gives the relationship between the dry unit weight and the other variables:

$$\gamma_d = \frac{\gamma_w \left(1 - \frac{V_a}{100}\right)}{\left(\frac{1}{G_s} + \frac{w}{100}\right)}$$

Where γ_d = dry unit weight of soil;
γ_w = unit weight of water (62.43 pcf in lb-ft units);
V_a = air voids (percent);
G_s = specific gravity of soil solids;
w = moisture content of the soil (percent).

Example:

$$106 = \frac{62.43 \left(1 - \frac{V_a}{100}\right)}{\frac{1}{2.7} + \frac{17}{100}} = \frac{62.43 - \frac{62.43 \; V_a}{100}}{0.37 + 0.17}$$

V_a = 8.31 percent

The corresponding values of porosity, percent soil solids, percent water-filled voids, percent air-filled voids and void ratio may be computed as follows:

If

n = porosity (percent total voids);
n_s = percent soil solids;
n_w = percent water filled voids;
n_a = percent air filled voids; and
e = void ratio,

$$n = \frac{V_v}{V} \times 100 = \frac{0.3712}{1} \times 100 = 37.12 \text{ percent porosity (percent total voids)}$$

$$n_s = \frac{V_s}{V} \times 100 = \frac{0.6289}{1} \times 100 = 62.89 \text{ percent soil solids}$$

$$n_w = \frac{V_w}{V} \times 100 = \frac{0.2886}{1} \times 100 = 28.86 \text{ percent water-filled voids}$$

$$n_a = \frac{V_a}{V} \times 100 = \frac{0.0825}{1} \times 100 = 8.25 \text{ percent air-filled voids}$$

$$e = \frac{V_v}{V_s} = \frac{0.3712}{0.6289} = 0.5902 \text{ void ratio}$$

Zero Air Voids Curve (Line of Saturation)

In Figure 115, the curved line showing the unit weight at zero air voids is a function of moisture content (116); that is, the moisture content, w, (expressed as percent of dry weight of soil) necessary to fill completely the voids of a soil mass to saturation at a given dry unit weight. It is computed as follows from data given in preceding calculations:

If

V_s = volume of solids = 0.6289 cu ft;
V_v = volume of voids = 0.3712 cu ft;
γ_d = 106 pcf,

then the weight of water, W_w, required to fill the voids becomes

$$0.3712 \times 62.43 = 23.17 \text{ lb, and}$$

the moisture content at saturation $w_{sat} = \dfrac{W_w}{\gamma_d} \times 100$

$$w_{sat} = \frac{23.17}{106} \times 100 = 21.86 \text{ percent}$$

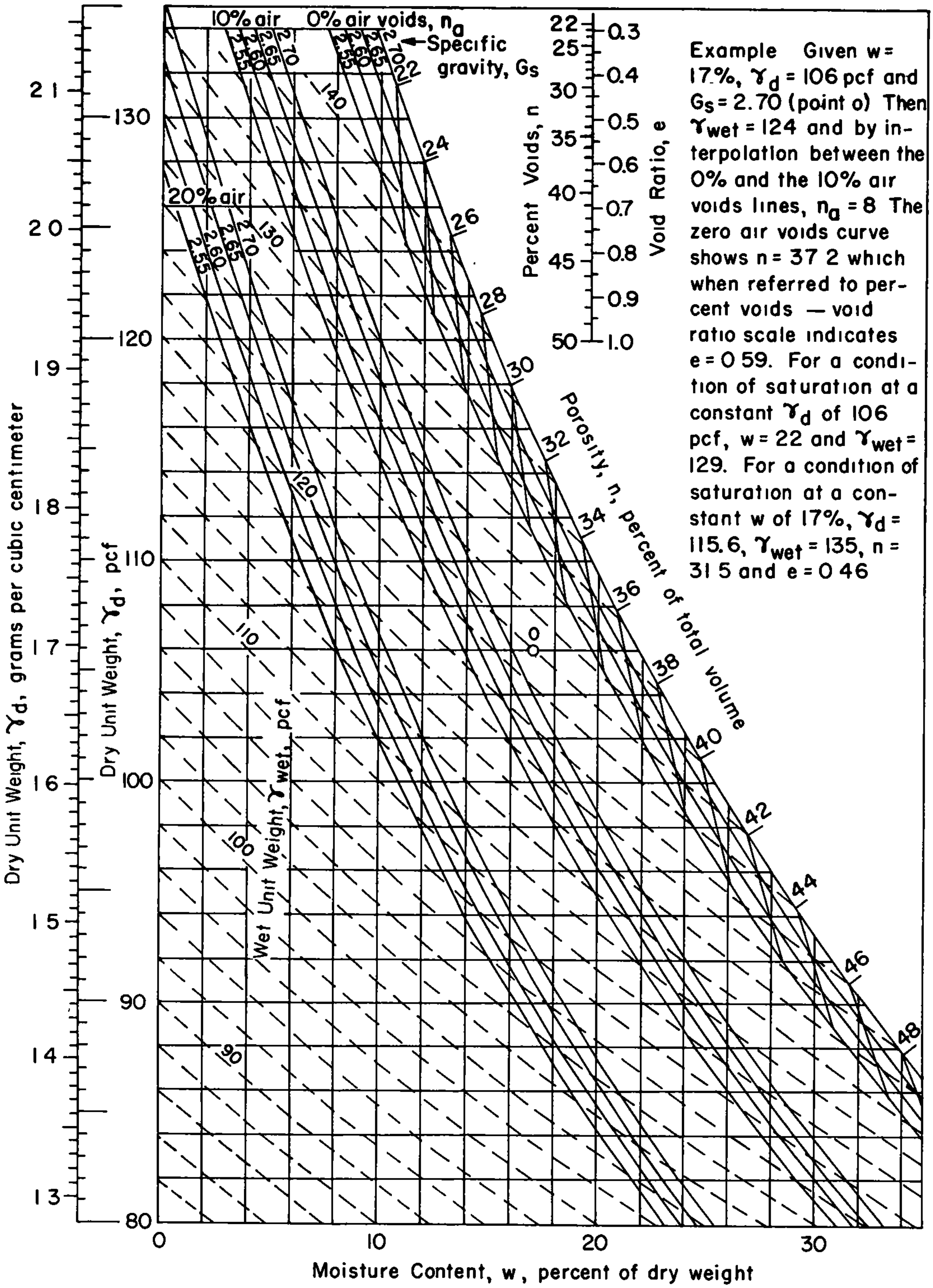
This computation can be made by inserting the appropriate values in an equation as follows:

If

w = moisture content in percent
γ_d = dry unit weight in pcf, and
G_s = specific gravity, then

$$w_{sat} = \left(\frac{62.43}{d} - \frac{1}{G_s}\right) \times 100$$

$$w_{sat} = \left(\frac{62.43}{106} - \frac{1}{2.7}\right) \times 100 = 21.86 \text{ percent}$$



Example Given w = 17%, γ_d = 106 pcf and Gs = 2.70 (point o) Then γ_{wet} = 124 and by interpolation between the 0% and the 10% air voids lines, n_a = 8 The zero air voids curve shows n = 37 2 which when referred to percent voids — void ratio scale indicates e = 0 59. For a condition of saturation at a constant γ_d of 106 pcf, w = 22 and γ_{wet} = 129. For a condition of saturation at a constant w of 17%, γ_d = 115.6, γ_{wet} = 135, n = 31 5 and e = 0 46

Figure 115. Chart of solids-water-voids relations of soil masses (source, Bureau of Public Roads).

and the saturated unit weight, γ_{sat}, is

$$\frac{\gamma_d (100 + w_{sat})}{100} = \frac{106 \times 121.86}{100} = 129.17 \text{ pcf}$$

Line of Constant Air Voids

The values for a line of constant air voids (see lines representing 10 and 20 percent air voids in Figure 115) may be determined by substituting the appropriate values of specific gravity, G_s, dry unit weight, γ_d, and percent air voids n_a, in the following equation and calculating the moisture content corresponding to the value of dry unit weight used:

If

n_a = percent air voids for which computation is made (use 10 percent),

γ_d = dry unit weight (use 106 pcf or $\frac{106}{62.43}$ = 1.698 g/cc),

G_s = specific gravity of solids = 2.7,

γ_w = unit weight of water = 62.43 pcf or 1 g/cc

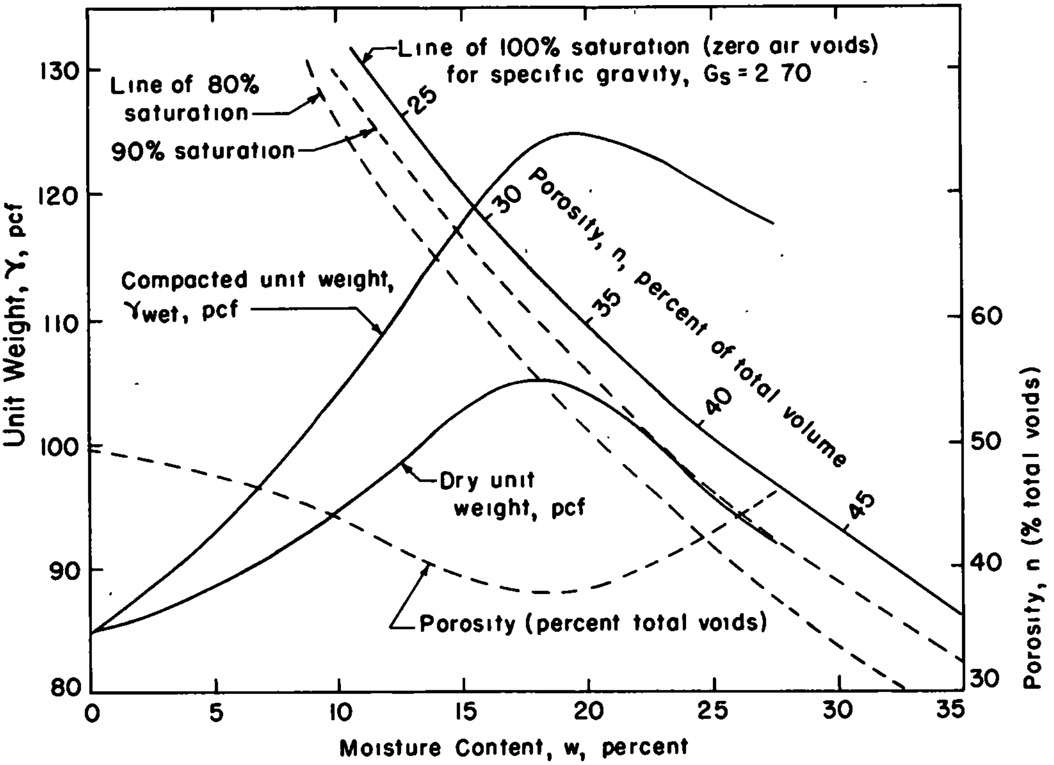


Figure 116. The moisture content-unit weight relationship showing the curves of (1) compacted unit weight, γ_{wet}, vs moisture content, and (2) dry unit weight, γ_d, vs moisture content and porosity corresponding to dry unit weights shown. Soil is a silty clay, LL= 37, PI = 14, compaction effort = AASHO Method T99 (12,375 fp/cf).

$$\frac{w}{100\,\gamma_w} = \frac{1 - \frac{n_a}{100}}{\gamma_d} - \frac{1}{G_s}$$

$$\frac{w}{100 \times 1} = \frac{1 - \frac{10}{100}}{1.698} - \frac{1}{2.7}$$

w = 15.97 percent, the moisture content corresponding to a dry unit weight of 106 pcf for 10 percent air voids.

By computing values of moisture content, w, for the necessary range of values of dry unit weight, γ_d, and plotting the values on a graph and connecting the points by a line, the result will be the 10 percent air voids line (for a specific gravity of 2.7), as shown in Figure 115. For convenience, Table 46 gives values for determining the zero air voids curve.

Percent Saturation, S

In earthwork construction above the ground water table, the soil voids usually contain both air and water and it may be desirable to analyze the behavior of soil in terms of the degree in which the voids are filled with water, that is, the degree of or per-

TABLE 46

DETERMINATION OF ZERO AIR VOIDS CURVE

γ_d(pcf)	Grams per cc	2.44	2.46	2.48	2.50	2.52	2.54	2.56	2.58	2.60	2.62	2.64	2.66	2.68	2.70	2.72
138	2.210	4.3	4.6	4.9	5.2	5.6	5.9	6.2	6.5	6.8	7.1	7.4	7.6	7.9	8.2	8.5
136	2.178	4.9	5.3	5.6	5.9	6.2	6.5	6.8	7.1	7.4	7.7	8.0	8.3	8.6	8.9	9.2
134	2.146	5.6	5.9	6.3	6.6	6.9	7.2	7.5	7.8	8.1	8.4	8.7	9.0	9.3	9.6	9.9
132	2.114	6.3	6.6	7.0	7.3	7.6	7.9	8.2	8.5	8.8	9.1	9.4	9.7	10.0	10.3	10.6
130	2.082	7.0	7.4	7.7	8.0	8.3	8.7	9.0	9.3	9.6	9.9	10.1	10.5	10.7	11.0	11.3
128	2.050	7.8	8.1	8.5	8.8	9.1	9.4	9.7	10.0	10.3	10.6	10.9	11.2	11.5	11.7	12.0
126	2.018	8.6	8.9	9.2	9.6	9.9	10.2	10.5	10.8	11.1	11.4	11.7	11.9	12.2	12.5	12.8
124	1.986	9.4	9.7	10.0	10.4	10.7	11.0	11.3	11.6	11.9	12.2	12.5	12.8	13.0	13.3	13.6
122	1.954	10.2	10.5	10.9	11.2	11.5	11.8	12.1	12.4	12.7	13.0	13.3	13.6	13.9	14.1	14.4
120	1.922	11.1	11.4	11.7	12.0	12.4	12.7	13.0	13.3	13.6	13.9	14.1	14.4	14.7	15.0	15.3
118	1.890	11.9	12.3	12.6	12.9	13.2	13.5	13.9	14.2	14.5	14.7	15.0	15.3	15.6	15.9	16.2
116	1.858	12.8	13.2	13.5	13.8	14.1	14.4	14.8	15.1	15.4	15.7	15.9	16.2	16.5	16.8	17.1
114	1.826	13.8	14.1	14.4	14.8	15.1	15.4	15.7	16.0	16.3	16.6	16.9	17.2	17.5	17.7	18.0
112	1.794	14.8	15.1	15.4	15.7	16.1	16.4	16.7	17.0	17.3	17.6	17.9	18.2	18.4	18.7	19.0
110	1.762	15.8	16.1	16.4	16.8	17.1	17.4	17.7	18.0	18.3	18.6	18.9	19.2	19.4	19.7	20.0
108	1.730	16.8	17.2	17.5	17.8	18.1	18.4	18.8	19.0	19.3	19.6	19.9	20.2	20.5	20.8	21.1
106	1.698	17.9	18.3	18.6	18.9	19.2	19.5	19.8	20.1	20.4	20.7	21.0	21.3	21.6	21.9	22.1
104	1.666	19.1	19.4	19.7	20.0	20.4	20.7	21.0	21.3	21.6	21.9	22.2	22.4	22.7	23.0	23.3
102	1.634	20.3	20.6	20.9	21.2	21.5	21.8	22.2	22.4	22.7	23.0	23.3	23.6	23.9	24.2	24.5
100	1.602	21.5	21.8	22.1	22.4	22.8	23.1	23.4	23.7	24.0	24.3	24.6	24.8	25.1	25.4	25.7
98	1.570	22.7	23.1	23.4	23.7	24.0	24.3	24.6	24.9	25.2	25.5	25.8	26.1	26.4	26.7	26.9
96	1.538	24.1	24.4	24.7	25.0	25.4	25.7	26.0	26.3	26.6	26.9	27.2	27.4	27.7	28.0	28.3
94	1.506	25.4	25.8	26.1	26.4	26.7	27.0	27.4	27.7	28.0	28.2	28.5	28.8	29.1	29.4	29.7
92	1.474	26.9	27.2	27.5	27.9	28.2	28.5	28.8	29.1	29.4	29.7	30.0	30.3	30.6	30.8	31.1
90	1.442	28.4	28.7	29.1	29.4	29.7	30.0	30.3	30.6	30.9	31.2	31.5	31.8	32.1	32.3	32.6
88	1.410	30.0	30.3	30.6	30.9	31.3	31.6	31.9	32.2	32.5	32.8	33.1	33.4	33.6	33.9	34.2
86	1.378	31.6	31.9	32.3	32.6	32.9	33.2	33.5	33.8	34.1	34.4	34.7	35.0	35.3	35.6	35.8
84	1.346	33.3	33.7	34.0	34.3	34.6	35.0	35.3	35.6	35.9	36.2	36.4	36.7	37.0	37.3	37.6
82	1.314	35.2	35.5	35.8	36.1	36.5	36.8	37.1	37.4	37.7	38.0	38.3	38.5	38.8	39.1	39.4
80	1.281	37.1	37.4	37.7	38.0	38.4	38.7	39.0	39.3	39.6	39.9	40.2	40.5	40.7	41.0	41.3

The equation for determining any point on the zero air voids curve is: $w = \left(\frac{62.43}{\gamma_d} - \frac{1}{G_s}\right) \times 100.$

cent of saturation. The percent saturation, S, is the ratio, expressed as a percentage, of (a) the volume of water in a given soil mass to (b) the total volume of intergranular space (voids) (116). The percent saturation, S, may be determined on a volumetric basis, as follows:

If

V_w = volume of water-filled voids = 0.2886 cu ft and

V_v = total volume of voids = 0.3712 cu ft

$$S = \frac{V_w}{V_v} \times 100 = \frac{0.2886}{0.3712} \times 100 = 77.77 \text{ percent}$$

or, from values of porosity, if

n = total porosity in percent = 37.115

n_w = percent of water-filled voids = 28.864

$$S = \frac{n_w}{n} \times 100 = \frac{28.864}{37.115} \times 100 = 77.77 \text{ percent}$$

The percent saturation, S, may also be computed from appropriate values of percent moisture content, w, void ratio, e, and specific gravity G_s, as follows:

$$w = S \frac{e}{G_s}$$

$$17 = S \frac{0.5902}{2.7}$$

$$S = 77.77 \text{ percent}$$

Lines indicating 80 and 90 percent saturation for a soil having a specific gravity, G_s, of 2.70 are shown in Figure 116.

The percent of saturation, S, may also be expressed in terms of percent air voids, n_a, as has been shown previously and as is indicated in the moisture content-unit weight chart in Figure 115. For example, for a specific gravity $G_s = 2.7$, a moisture content, w = 17 percent, and a dry unit weight, γ_d = 106 pcf (point 0 in Figure 115), the air void content in terms of percent (n_a) may be interpolated between the line of zero air voids and the line of 10 percent air voids by scaling the distance between the two lines and determining the relative proportion of that distance from the zero air void line to point 0.

Use of Chart for Determining Soil Solids-Water-Voids Relationships

Point 0 in Figure 113 represents a moisture content, w = 17 percent; a dry unit weight, γ_d = 106 pcf; and a specific gravity, $G_s = 2.7$. Using the chart for interpolation, the wet unit weight, γ_{wet} (at a w = 17 percent) = 124 pcf. By interpolating between the 0 and 10 percent air void curves, the percent air voids, $n_a = 8$. The zero air-voids curve (for a specific gravity $G_s = 2.7$) indicates that the total porosity, n = 37.2 Conversion of the porosity, n, to void ratio, e, on the scale in the upper right of Figure 115 gives e = 0.59.

For a condition of saturation at a constant dry unit weight, γ_d = 106 pcf, the values obtained in Figure 115 are w_{sat} = 22 percent and γ_{sat} = 129 pcf. For a condition of saturation at a constant moisture, w = 17 percent, the appropriate values are γ_{sat} = 135 pcf, n = 31.4 percent and e = 0.46.

Appendix B

DEFINITIONS OF TERMS

The terms and symbols used in this bulletin comply as closely as possible with the "Standard Definitions of Terms Relating to Subgrade, Soil Aggregate, and Fill Materials" AASHO Designation: M146-56 (122) and "Glossary of Terms and Definitions in Soil Mechanics" (116, 124), recommended by a joint committee of the American Society of Civil Engineers and the American Society for Testing Materials. Most of the definitions and symbols, given in this section, have been taken directly from the previous references; terms not included therein and terms believed in need of further explanation are defined according to usage and the source reference is given where appropriate.

Absolute Maximum Density (Dry Unit Weight)—The greatest unit weight that can be attained at a high compaction effort with acceptable laboratory compaction equipment and methods. The absolute maximum unit weight is used in determining the relative density (see definition) and is not to be confused with the value of maximum unit weight obtained at a given compaction effort in the Standard AASHO and ASTM test procedures for obtaining maximum unit weight and optimum moisture content. A study (120) is in progress aimed toward the development of a standard test procedure for absolute maximum unit weight.

Apparent Specific Gravity—See "Specific Gravity, Apparent."

Bulk Specific Gravity—See "Specific Gravity, Bulk."

Clay Soil—Fine-grained "soil" or the fine-grained portion of "soil" that can be made to exhibit plasticity (putty-like properties) within a range of "water contents" and that exhibits considerable strength when air-dry. The term has been used to designate the percentage finer than 0.002 mm (0.005 mm in some cases), but it is strongly recommended that this use be discontinued because there is ample evidence that from an engineering standpoint the properties described in this definition are many times more important.

Clay Size—That portion of the "soil" finer than 0.002 mm (0.005 mm in some cases). (see "Clay.")

Compaction—The densification of a "soil" by means of mechanical manipulation.

Compactibility— A soil property that indicates the degree to which a soil may be densified. Clay soils and well-graded granular materials are highly compactible; that is, a highly compressible clay soil may be highly densified by a compression (rolling) type of compaction, while well-graded granular soils, may be densified in high degree by vibratory compaction.

Compaction Curve (Moisture Content-Unit Weight Curve) (Moisture Content-Density Curve)—The curve showing the relationship between the "dry unit weight" (density) and the "moisture content" (water content) of a soil for a given compaction effort.

Compaction Test—A laboratory compacting procedure whereby a soil at a known "water content" is placed in a specified manner into a mold of given dimensions, subjected to a compaction effort of controlled magnitude, and the resulting "unit weight" determined. The procedure is repeated for various "water contents" sufficient to establish a relation between "water content" and "unit weight."

Compaction Effort—A term applicable to either field or laboratory compaction. In the case of laboratory compaction, a compaction effort consists of the application of a given amount of energy per unit volume of compacted soil. The compaction effort can be varied in the laboratory by changing the weight of the compacting hammer, number of blows per layer, or number of layers of soil in the compaction cylinder (or, in vibration by changing the frequency, and amplitude and time of vibration). In the case of field compaction, a compaction effort consists of compaction by a given piece of equipment passing a given number of times on a given thickness of lift (48).

Compressibility—Property of a soil pertaining to its susceptibility to decrease in volume when subjected to load.

Consolidation—The gradual reduction in volume in a soil mass resulting from an increase in compressive "stress." (Through usage, the term consolidation has become associated with a reduction in soil volume resulting from a static load; for example, from a building, a bridge, an embankment, or a surcharge load on an embankment. It should not be confused with the reduction in volume caused by the densifying effect of traffic.)

Degradation—The wearing or breaking down of materials (authors' definition).

Degree of Saturation—See "Percent Saturation."

Density—See "Unit Weight." Although it is recognized that density is defined as mass per unit volume, in the field of soil mechanics the term is frequently used in place of unit weight.

Dry Unit Weight (Dry Density)—See "Unit Weight."

Dynamic Compaction—Compaction of soil by the impact of a free-falling weight or hammer (48). Also compaction by blows of a pneumatic-type or explosion-type tamper.

Fines—Portion of a soil finer than a No. 200 U.S. standard sieve.

Fine Aggregate—Aggregate passing a No. 4 sieve (authors' definition).

Gradation (Grain-Size Distribution) (Soil Texture)—Proportion of material of each grain size present in a given soil.

Grain-Size Analysis (Mechanical Analysis)—The process of determining "gradation."

Grain-Size Distribution—See "Gradation."

Gravel—Rounded or semirounded particles of rock that will pass a 3-in. and be retained on a No. 4 U.S. standard sieve.

Index Property—A soil property that can be used to indicate the general characteristics of the soil, not a direct measure of its engineering characteristics. Examples are liquid limit, plastic limit, gradation, optimum moisture content, and maximum dry unit weight.

Liquid Limit, LL—The "water content" corresponding to the arbitrary limit between the liquid and plastic states of consistency of a "soil." Specifically, the water content at which a pat of soil, cut by a groove of standard dimensions, will flow together for a distance of ½ in. under the impact of 25 blows in a standard liquid limit apparatus.

Maximum Density (Maximum Unit Weight)—See "Unit Weight."

Mechanical Analysis—See "Grain-Size Analysis."

Minimum Density (Minimum Unit Weight)—The loosest state (lowest dry unit weight) of a cohesionless granular soil that can be reproduced consistently by laboratory test method. The value of minimum density is used in determining the percent relative density (120).

Modified AASHO Compaction—A modification by the Corps of Engineers of the Standard AASHO compaction method, consisting of dynamic compaction in a 4-in. diameter mold using 25 blows of a 10-lb hammer dropped 18 in. on each of five equal layers. Dynamic compaction in a 6-in. diameter CBR mold using 55 blows of a 10-lb hammer dropped 18 in. on each of five equal layers is considered equivalent to Modified AASHO, as the energy expended per unit volume is the same (121, 48). See text for further explanation regarding use of this term.

Moisture Content (Water Content), w—The ratio, expressed as a percentage, of (a) the weight of water in a given soil mass to (b) the weight of solid particles. The weight of water is determined by drying a given sample to constant weight at a temperature of 110 C (230 F).

Moisture-Density Curve—See "Compaction Curve."

Moisture-Density Test—See "Compaction Test."

Moisture-Unit Weight Curve—See "Compaction Curve."

Optimum Moisture Content, OMC, w_O—The water content at which a soil can be compacted to the maximum dry unit weight by a given compaction effort.

Penetration Resistance (Proctor)—Unit load required to produce a specified penetration into soil at a specified rate of a probe or instrument. For a Proctor needle, the specified penetration is 2½ in. and the rate is ½ in. per sec.

Penetration Resistance Curve (Proctor Penetration Curve)—The curve showing the relationship between (a) the penetration resistance and (b) the water content.

Percent Compaction (Relative Compaction)—The ratio, expressed as a percentage, of (a) dry unit weight of a soil to (b) maximum unit weight obtained in a laboratory compaction test. (In this publication relative compaction is used to express field unit weight values in terms of laboratory maximum).

Percent Saturation, S, (Degree of Saturation)—The ratio, expressed as a percentage, of (a) the volume of water in a given soil mass to (b) the total volume of intergranular space (voids).

Porosity, n—The ratio, usually expressed as a percentage, of (a) the volume of voids of a given soil mass to (b) the total volume of the soil mass.

Proctor Compaction Test—See "Compaction Test." Details of the Proctor compaction are given in Table 1. (authors).

Proctor Penetration Curve—See "Penetration Resistance Curve."

Proctor Test—See "Proctor Compaction Test."

Relative Compaction—See "Percent Compaction."

Relative Density, Dd—The ratio of (a) the difference between the void ratio of a "cohesionless soil" in the loosest state and any given void ratio to (b) the difference between its void ratios in the loosest and densest states.

Sand—Particles of rock that will pass the No. 4 sieve and be retained on the No. 200 U.S. standard sieve.

Saturation Curve—See "Zero Air Voids Curve."

Shrinkage Limit, SL—The maximum "water content" at which a reduction in "water content" will not cause a decrease in volume of the "soil" mass.

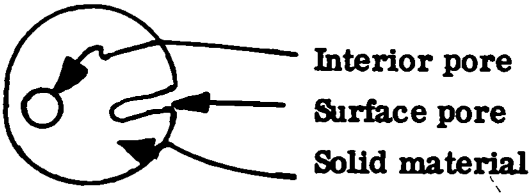
Soil (Earth)—Sediments or other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter.

Specific Gravity—General definition (other definitions in part from (92A, 124) and in part by authors.) Ratio of (a) the weight of any volume of a substance to (b) the weight of an equal volume of water (at the same temperature). Because the volume of displaced water in milliliters (cc) equals its weight in grams, this ratio, for all practical purposes, can be written as follows:

$$\text{Specific Gravity} = \frac{\text{Weight}}{\text{Volume}}$$

This equation as well as the other, subsequent specific gravity equations are correct if weights and volumes are expressed in grams and milliliters, respectively.

Specific Gravity (Coarse or Fine Aggregate)—The three types of specific gravity (bulk, oven-dry basis; bulk, saturated surface-dry basis; and apparent) are described next in terms of the weight: volume ratio under "Specific Gravity" and the following sketch which illustrates the types of pore space within the aggregates.



Bulk Specific Gravity (Oven-Dry Basis):

$$G = \frac{\text{Weight}}{\text{Volume}}$$

in which

Weight = oven-dry weight of aggregate, in grams and
Volume = volume of solid material plus volume of interior and surface pores, cc.

Bulk Specific Gravity (Saturated Surface-Dry Basis):

$$G = \frac{\text{Weight}}{\text{Volume}}$$

in which

Weight = saturated surface-dry weight of aggregate, in grams, and
Volume = volume of solid material plus volume of interior and surface pores, cc.

Apparent Specific Gravity:

$$G = \frac{\text{Weight}}{\text{Volume}}$$

in which

Weight = oven-dry weight of aggregate, in grams and
Volume = volume of solid material plus volume of interior pores, cc.

Specific Gravity (Soil), G_s—The ratio of (a) the oven-dry weight (in grams) of the sample to (b) its volume (in cc), which includes interior pores within the soil particles, but does not include the volume of surface pores.

Standard Compaction—A descriptive term referring to the laboratory compaction test method and results obtained under designations AASHO T 99 and ASTM D 698 before the adoption of the 1957 (AASHO) and 1958 (ASTM) revisions. Same as AASHO T 99-57, Method A and ASTM D 698-58T, Method A.

Stress, Effective, $\bar{\sigma}$, (Effective Pressure) (Intergranular Pressure)—The average normal force per unit area transmitted from grain to grain of a soil mass. It is the stress that is effective in mobilizing internal friction.

Thixotropy—The property of a material wherein softening occurs on manipulation followed by a gradual return to the original strength when the material is allowed to rest. The phenomenon excludes any changes in moisture content or chemical composition of the soil. The process is completely reversible in a thixotropic material (96).

Unit Weight, γ, (Density)—Weight per unit volume.

Dry Unit Weight, γ_d, (Unit Dry Weight) (Dry Density)—The weight of soil solids per unit of total volume of soil mass.

Effective Unit Weight, γ_e—The unit weight of a soil that, when multiplied by the height of the overlying column of soil, yields the effective pressure due to the weight of the overburden.

Maximum Unit Weight, γ_{max}, (Maximum Density)—The dry unit weight defined by the peak of a compaction curve.

Saturated Unit Weight, γ_{sat}—The wet unit weight of a soil mass when saturated.

Submerged Unit Weight, γ_{sub}, (Buoyant Unit Weight)—The weight of the solids in air minus the weight of water displaced by the solids per unit of volume of soil mass; the saturated unit weight minus the unit weight of water.

Wet Unit Weight, γ_{wet}, (Mass Unit Weight)—The weight (solids plus water) per unit of total volume of soil mass, irrespective of the degree of saturation.

Zero Air Voids Unit Weight, γ_z—The weight of solids per unit volume of a saturated soil mass.

Void Ratio, e—The ratio of (a) the volume of void space to (b) the volume of solid particles in a given soil mass.

Zero Air Voids Curve (Saturation Curve)—The curve showing the zero air voids unit weight as a function of water content.

Index

THE NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare. The ACADEMY itself was established in 1863 under a congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the federal government in scientific matters. This provision accounts for the close ties that have always existed between the ACADEMY and the government, although the ACADEMY is not a governmental agency.

The NATIONAL RESEARCH COUNCIL was established by the ACADEMY in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the ACADEMY in service to the nation, to society, and to science at home and abroad. Members of the NATIONAL RESEARCH COUNCIL receive their appointments from the president of the ACADEMY. They include representatives nominated by the major scientific and technical societies, representatives of the federal government, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the ACADEMY and its RESEARCH COUNCIL thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The HIGHWAY RESEARCH BOARD was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the NATIONAL RESEARCH COUNCIL. The BOARD is a cooperative organization of the highway technologists of America operating under the auspices of the ACADEMY–COUNCIL and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the BOARD are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.