HIGHWAY RESEARCH BOARD

Bulletin 272

Factors That Influence Field Compaction of Soils

Compaction Characteristics of Field Equipment

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Compaction Characteristics of Field Equipment

by

A.W. JOHNSON

and

J.R. SALLBERG

1960

Washington, D.C.

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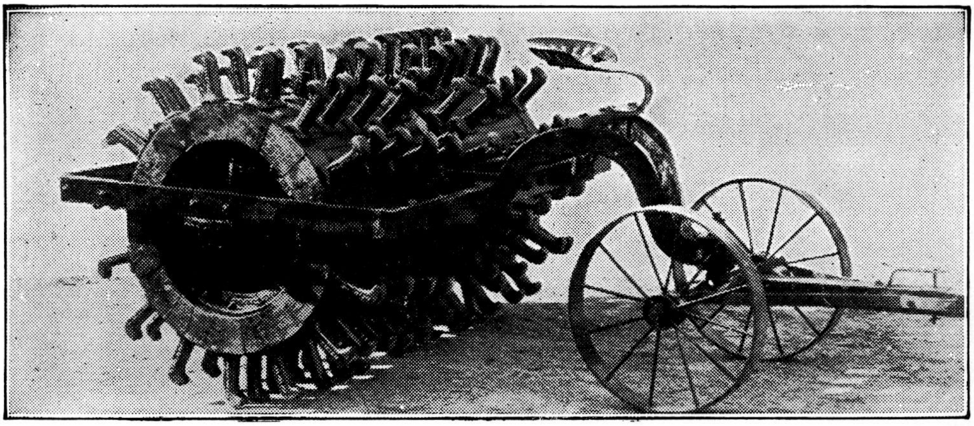

ROLLING TAMPER.

FRONTISPIECE

An early horse-drawn "rolling tamper" made by the Petrolithic Pavement Company of Los Angeles. Diameter 5 ft. Rolling width 8 ft. Made in two sections for easy turning. Iron legs are 7 in. long and have a tamping face 2- x 3-in. Fifteen legs in each of 12 rings or a total of 180 tamper feet. Gross weight about 5,000 lb.

Photo reprinted by permission of Engineering News-Record from "Road Preservation and Dust Prevention," by W. P. Judson, 146 pp. (1908).

Preface

The introductory portions of this bulletin present some historical highlights relative to compaction and state some of the principles that govern compaction in the field as well as in the laboratory. The main body of the text is composed of data that illustrate the compaction and operation characteristics of the several types of compactors on different types of soils. This is followed by brief statements on methods used as aids in the control of moisture content and unit weight in construction.

This bulletin as have previous bulletins of this nature sponsored by the Committee (see Foreward), provides tabulated data on current (as of March 1960) state highway department practices as indicated by specifications governing compaction requirements and compaction equipment. It also includes tabulated data on manufacturers' specifications for compaction equipment, and, for the first time, provides data on permissible loads and tire-inflation pressures for tires used on pneumatic-tired rollers. Thus, this bulletin, which summarizes the results of researches with full-scale equipment and provides other useful data, is prepared specifically for the construction engineer and the project engineer and their technical assistants.

In assembling the data for the main body of the text, the original draft submitted to the Committee was written to include a great amount of detail so as to permit the preparation of a briefer text by deletion of material. However, the Committee elected to recommend publication of the text in its original degree of detail.

The authors regret that because of limited funds and personnel for translation, the literature searched has been limited to those languages with which they are familiar.

The task of assembling the material in this bulletin has been a rewarding one for the authors. Appreciation for the privilege of doing this work is expressed to Mr. Fred Burggraf, Director, Highway Research Board, and to Mr. Harold Allen, Chief, Division of Physical Research, U.S. Bureau of Public Roads. Acknowledgment is made by references, to sources of information given in the list of references. The authors are grateful for the assistance of Dorothy Bright, Librarian for the Highway Research Board, for aid in literature searches and to Marie Koneczny of the Highway Research Board for typing the original manuscript.

A.W. Johnson

John R. Sallberg

Foreword

The value of compaction as a construction process has been attested to by the fact that it has been used by man since he built the earliest earthworks. With the increase in knowledge of the influence of compaction on soil properties has come a better appreciation of the advantages of its use. As this knowledge has increased to permit interpretation and field use, it bears repeating time and again–and with greater emphasis–no other single treatment can be applied to natural soil which produces so marked a change in soil properties at so low a cost as does compaction. The bearing value of some soils may be increased several times by the increases in unit weight which can be produced by present compactors. The volume change of a soil acting as a pavement subgrade can be reduced to relatively narrow limits when compaction and moisture are controlled for optimum conditions. Thus, the control of the moisture content and unit weight of soils has become one of the more significant treatments in the process of constructing highways. As a corollary, the development of more effective compaction equipment also has grown in importance.

This committee has continually recognized the growing importance of compaction. In addition to the sponsorship of numerous papers relative to compaction[1] it has prepared two publications that have summarized knowledge 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. Bulletin 58 was reprinted twice and has been out of print for some time.

The two previous publications briefly outlined knowledge then available on the several facets of compaction. Since the publication of Bulletin 58 the results of numerous researches have been reported. It would not be possible to publish in one Bulletin all of the data that should be available to the user of compaction. Accordingly, this Bulletin is devoted in the main to the performance characteristics of various types of compactors on different soils and methods used in the control of compaction during construction and, in small part, includes data pertaining to general fundamentals of compaction.

There is a large volume of additional published material covering the several facets of compaction in the field and the laboratory, and its influence on soil properties. Consideration of the value of this information has resulted in a decision by the Committee to publish the remaining material in two additional bulletins, one on factors affecting laboratory tests, the other on the effect of compaction on soil properties and design. Much work has already been done in assembling data for these two publications, which will be published as availability of time and personnel permits.

The preparation of this Bulletin has been a task of considerable magnitude requiring many man-months of literature research, of correlation of pertinent data, of organizing of material and, finally of writing the

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[1] In Bulletins 5, 23, 42, 93, 122, 159, 254, Special Report 38, and various volumes of Proceedings of the Highway Research Board.

manuscript. Credit for this time consuming, arduous task belongs to 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 acknowledge and thank Miles D. Catton, W. F. Abercrombie, and Leo J. Ritter, Jr., for their service on a subcommittee appointed to review the first draft of the Bulletin, to consider all review comments offered by members of the Committee, and to approve the final draft for publication.

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

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Early History of Earthwork Compaction

WHAT MAN ACCOMPLISHES concerns first an idea. As that idea develops into a field of knowledge it is accompanied by the development of tools and methods to apply that knowledge. No doubt man has always possessed the idea that the residual compression that was his footprint was, under certain conditions, due to compaction of the soil. No doubt he also knew that compaction gave strength to the soil. Country people have for centuries understood the effect of both moisture content and compaction with relation to soil tilth. The engineer also understood something of the effect of soil moisture on compaction, for depending on the season he was aware that the soil was often too wet or too dry for good results. Whatever the form or extent of his knowledge the engineering literature prior to the 1930's gives no evidence that anyone had established those relationships between moisture content, unit weight and compactive effort that is now spoken of as the fundamental principles of soil compaction.

However, the changing requirements of construction soon demanded that the engineer provide some measure of compaction. According to an early account (18) "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 developed field equipment and methods of consolidating soil samples to determine optimum moisture requirements before construction and subsequently the relative compaction of the completed embankment. This procedure and equipment was adopted as standard in August 1929..." This was the beginning of the "idea." The results of the California work were made known through department publications but were never published in a periodical having nationwide circulation.

The requirements for earth dam construction demanded not only a measure of compaction but also measures of the influence of compaction on shear strength and permeability. As a result, the Bureau of Waterworks and Supply of the City of Los Angeles conducted an extensive study that yielded data on those relationships. The findings were published beginning in August 1933 by R.R. Proctor (11) in a periodical having national distribution. During the period 1927 to 1930 the Silvan Dam for the Melbourne, Australia water supply was constructed. During that construction, Kelso (15) performed experiments that yielded data on soil moisture content-unit weight relationships and thus the idea began to develop into a new field of knowledge that was necessary to the understanding of the behavior of soil.

The development of the tools and methods for compacting soils began long before the principles of compaction were discovered. For a long period before the building of the first road roller, engineers used cattle, sheep and goats to compact soils in the construction of earth dams. Although their use had been largely in Europe and the Mediterranean area, as recently as 1893, one hundred fifteen goats were used to compact the upstream half of an 85-ft high Santa Fe, New Mexico (1) water supply dam.

But a look even farther back must be made to find the first record of mechanical compaction. In 1619, in England (69) a patent was granted to one John Shotbolte for employing "...land stearnes, scowrers, trundlers and other strong and massy engines ...in making and repairing highways and roads." But the learned members of the Royal Society did not look with favor on Shotbolte's invention. In fact, the 1824 edition of John Louden McAdams' book emphasizes traffic compaction rather than rolling. The French, however, after adopting the McAdams' system about 1830 considered rolling an "indispensable concomitant." The first written advocacy in the English language on the economy of rolling was penned by Sir John F. Burgoyne, Royal Engineers, then Chairman of the Board of Works in Ireland.

The first patent for a steam road roller was issued in France in 1859 to M. Louis Lemoine (69) of Bordeaux. The honor for inventing the first successful road roller is credited to Thomas Aveling of England. The "Illustrated London News" of December

16, 1866 described the trial run of the new roller. The first steam road roller used in the United States was purchased by the Central Park Commissioners of New York City on June 19, 1869. A similar machine was also purchased at that time for use in Prospect Park, Brooklyn. They were built in England by Aveling and Porter andwere similar in many respects to some of our present 3-wheel rollers. The English-type roller with horizontal boiler was used here almost exclusively until the development of a vertical boiler with a tandem-type roller by the Julian Scholl Company of New York in 1903 (2). This was followed by the construction of a 12-ton 3-wheel roller by the Austin Manufacturing Company of Chicago. The Austin roller was powered by a 25-hp gasoline engine (4). Additional information pertaining to details of developments of steel-tired rollers of both the 3-wheel and tandem types are given in a paper by C. F. Parker (128).

However, the effectiveness of animals as compactors had not been forgotten. It is said that the first sheepsfoot roller owes its origin to a flock of sheep that crossed a scarified oil-treated road surface in Southern California (92). The first sheepsfoot-type roller was constructed of a log 3 ft in diameter and 8 ft long into which had been driven 7-in.-long railroad spikes (65). But the period 1904-1906 saw further development of the sheepsfoot roller at Santa Monica, California (3, 5, 6, 7, 32). A patent was issued on the "Petrolithic Roller" in 1906 (92). A photo of the Petrolithic roller is shown in the frontispiece. This roller was also known as the Fitzgerald roller, was manufactured in Los Angeles and sold for $750. It was about 5 ft in diameter and 8 ft wide, weighing about 5,000 lb and was horse-drawn. Maximum ground pressure was about 75 psi.

Much of the early rolling was limited to the surface of the subgrade soil and to the metaled surface. Later, although 3-wheel, tandem- and sheepsfoot-type rollers were available, the application of rolling to embankments was not without controversy. It was generally believed that embankments would settle in time. There was some doubt that compaction would wholly prevent settlements. Others simply believed any part of the road structure other than the surface "a waste of money."

In the decade following the introduction of the sheepsfoot roller, the practice of "ponding" became popular. During 1910-1915, 12-in. layers were "ponded" even in earth dam construction (65). During this same decade many highway fills were built by loose dumping the soil and the entire fill "jetted". In some areas jetting was accompanied by surface ponding. Jetting and ponding in highway construction, irrespective of the type of soil, continued in some areas into the late 1930's. A method known as the alternate-ridge and wet-trench method was used in earth dam construction as recently as 1917 (8). The method consisted of dumping the soil in ridges about 5 ft in height separated by trenches. The trenches were then partly filled with water and filled with earth to the level of the ridges. New ridges were then built over the position of the trenches and the procedure repeated.

The use of rollers began to increase following the transition from horse-drawn to tractor-drawn equipment. The sheepsfoot rollers came into widespread use during the 1930's. However, the three-wheel roller continued to be popular in the northeastern states.

This brings this historical summary to the late 1930's and early 1940's when the ideas expressed as "principles of compaction" became widely known and discussed among highway engineers. The "Proctor Curve" was an expression of the times.

Following the publication of Proctor's report, numerous studies were made to increase knowledge of these principles by compacting soil into cylindrical molds by using different sizes of molds and different compaction efforts. Those studies resulted not only in further exploring the moisture content-unit weight-compaction effort relationships but also resulted in the standardization of a test procedure whose results could be used as a basis for comparing with field compaction and thus determining the relative degree of compaction attained in the field. The Committee on Materials of the American Association of State Highway Officials (AASHO) agreed on a test procedure that was published under AASHO Designation: T 99-38. Committee D-18 on Soils for Engineering Purposes of The American Society for Testing Materials (ASTM) approved a similar test procedure under ASTM Designation: D 698-42 T. These early standards provided adequate maximum unit weights for normal highway construction. However, the heavy wheel loads of large military aircraft during World War II required markedly greater compacted unit weights, and the test known as the Modified AASHO Test (as modified by the Corps of Engineers) was developed for use in airfield construction.

The new-found knowledge concerning compaction brought with it problems of administration. The measure of compaction had to be stated in specifications that were a part of the construction contract. There was some apprehension that specifying unit weight would result in excessive costs. Administrators generally were willing to begin by specifying less than "maximum" unit weight obtained in the new standard tests. The problem of measuring unit weights where coarse aggregates were prevalent in embankments and in subbases and bases, in many instances precluded specifying unit weights and much thought was given to specifying equipment and roller hours so the project engineer would be able to control compaction adequately. There has been a strong tendency in the last decade toward specifying compacted unit weight and more specifications each year omit mention of compaction equipment. Tables of state highway specifications given herein and in previous publications of the Highway Research Board attest to this.

As the Standard AASHO T 99 and ASTM D 698 tests provided inadequate unit weights for airfield construction, it became evident during the 1950's that increases in highway wheel loads and number of load applications necessitated increases in unit weight requirements for highway bases, subbases and subgrades. These requirements resulted in the development of new test methods (AASHO T 180-57 and ASTM D 1557-58T) to provide maximum unit weights markedly greater than those provided by AASHO T 99 and ASTM D 698.

Some equipment developed during the late 1930's continues in current use on some projects today. That equipment, as well as examples of more recent equipment — constituting our tools for "putting to work" our new-found knowledge of compaction — are shown in the form of a number of photos throughout the text of this report.

This brief historical account of the development of ideas concerning compaction and the development of construction equipment and methods for their application in construction has, of necessity, included experiences in construction of earth dams and airfields, and their influence on progress. However, in the main, the data presented in this publication pertain to the construction of highways.

Fundamentals of Soil Compaction

THE TERM COMPACTION refers to the act of artificially increasing the unit weight of the soil by manipulation in the form of pressing or ramming or vibrating the soil particles into a closer state of contact. During compaction, air is expelled. Both air and water may be expelled from pervious granular materials as the porosity is reduced by compaction.

The extent to which a soil mass can be made to occupy a smaller volume depends mainly on (a) the nature of the soil and its compactibility; (b) the nature of the compaction effort (that is, the type of effort and the energy expended); and (c) the moisture content at which the soil is compacted. However, before discussing those factors that influence the degree of compaction, it is well to understand the volume-weight relationships that exist for any given unit weight. Knowledge of those relationships is useful in analyzing the degree of compaction in terms of the relative proportions of soil solids, air, and water by weights or by volumes. They also aid in understanding the effect of increasing the unit weight on the properties of the soil mass.

SOIL, WATER AND AIR VOLUME-WEIGHT RELATIONSHIPS

The soil mass is composed of solid particles and interspaces or voids and is termed a porous system. Accordingly, soil has two "densities": first, that of the solid particles which is termed the Specific Gravity (of solids), and second, that of the soil mass which includes solids, water-filled voids and air-filled voids and is termed its unit weight or density and is represented by the symbol γ. (It is recognized that "density" is defined as the mass per unit volume. However, in the field of soil mechanics the term density is often used in place of unit weight. In this publication the terms unit weight and density are used synonymously. However the term unit weight is preferred and is used throughout most of the text. The Greek gamma, γ , has been standardized by the American Society of Civil Engineers (119) and the American Society for Testing Materials (121) and has been accepted on a worldwide basis as a symbol indicating unit weight. See "Definitions" Appendix A.) Although the unit weight may be determined for any moisture content, it is, unless otherwide designated, expressed as dry unit weight, γ_d. A diagrammetric representation of the composition of soil is shown in Figure 1.

The moisture content, dry unit weight, and proportion's of solids, and water-filled and air-filled voids may be determined by means of simple formulas that express the interrelationships involved. These interrelationships are expressed in the "Definitions" Appendix A.

For those who are being introduced to compaction and the calculation of these interrelationships it may be of interest to illustrate the interrelationships here by sample calculations using numerical examples.

Specific Gravity (of Solids), G_s

Given a specific gravity of 2.7, the dry unit weight of solids in soil 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 grams, and W_d = dry weight of a soil mass = 10.6 lb or 4,808 grams, 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 (119). For example, if V = total volume of the soil mass = 0.1 cu ft or 2,832 cu cm, and W_d = dry weight of the soil mass = 10.6 lb or 4,808 grams,

$$\gamma_d = \frac{W}{V} = \frac{10.6}{0.1} = 106 \text{ pcf or, } \frac{4,808}{2,832} = 1.698 \text{ g/cc.}$$

Proportions of Solid and Air and Water Volumes

If n_s = the percent of soil solids,
γ_d = dry unit weight (106 pcf or 1.698 g/cc),
G_s = specific gravity (2.7), and
V_s = volume of soil solids,

$$n_s = \frac{\gamma_d}{G_s} \times 100 = \frac{\frac{106}{62.43}}{2.70} \times 100 = 62.885 \text{ percent}$$

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, and
V_a = volume of air-filled voids,

$$V_v = V - V_s = 1 - 0.6289 = 0.3712 \text{ cu ft total voids.}$$

Also, if W_d = dry weight of soil mass,

$$V_w = \frac{W_d \times w}{100 \times 62.43} = \frac{10.6 \times 17}{100 \times 62.43} = 0.2886 \text{ cu ft of water}$$

and

$$V_a = V - V_w = 0.3712 - 0.2886 = \text{cu ft of air.}$$

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,

$$n = \frac{V_v}{V} \times 100 = \frac{0.3712}{1} \times 100 = 37.12 \text{ percent porosity (percent total voids)}$$

$$n_s = \frac{V_s}{V} \times 100 = \frac{0.6289}{1} \times 100 = 62.89 \text{ percent soil solids}$$

$$n_w = \frac{V_w}{V} \times 100 = \frac{0.2886}{1} \times 100 = 28.86 \text{ percent water-filled voids}$$

$$n_a = \frac{V_a}{V} \times 100 = \frac{0.0825}{1} \times 100 = 8.25 \text{ percent air-filled voids}$$

$$e = \frac{V_v}{V_s} = \frac{0.3712}{0.6289} = 0.5902 \text{ void ratio}$$

For convenience, Table A, giving values of total solids V_s in percent by volume for various values of specific gravity G_s, and dry unit weight γ_d, is included in Appendix B.

In some areas where the soil exists at a moisture content uniformly greater than optimum (81) it may be convenient to compact at the existing moisture content and specify compaction in terms of a maximum percentage of air voids (V_a). The following expression shows the relationship between percent air voids, dry unit weight and other variables:

$$\gamma_d = \frac{\gamma_w\left(1 - \frac{V_a}{100}\right)}{\left(\frac{1}{G_s} + \frac{w}{100}\right)}$$

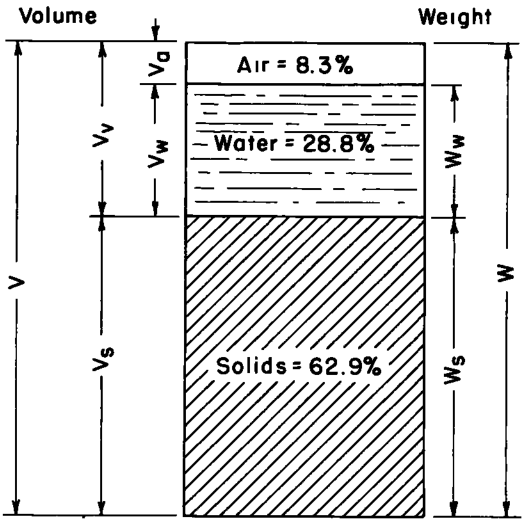


Figure 1. Diagrammatic representation of the composition of soil.

in which

γ_d = dry unit weight of the soil;
γ_w = unit weight of water (62.43 pcf in lb. ft units);
V_a = maximum percent air voids possible (at w = 17 percent) = 8.25 percent;
G_s = specific gravity of soil solids = 2.7; and
w = soil moisture content = 17 percent.

Example:

$$\gamma_d = \frac{62.43\left(1 - \frac{8.25}{100}\right)}{\frac{1}{2.7} + \frac{17}{100}} = 106 \text{ pcf}$$

Zero Air Voids Curve (Line of Saturation)

The curved line showing the unit weight at zero air voids is a function of moisture content (119); that is, the moisture content w (expressed as percent of dry weight of soil) necessary to completely fill 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, and
γ_d = 106 pcf

then the weight of water, W_w, required to fill the voids becomes 0.3712 x 62.43 = 23.17 lb, and the moisture content at saturation

$$w_{sat} = \frac{W_w}{\gamma_d} \times 100$$

$$w = \frac{23.17}{106} \times 100 = 21.86 \text{ percent}$$

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 in g/cc, then

$$w = \left(\frac{62.43}{\gamma_d} - \frac{1}{G_s}\right) \times 100$$

$$w = \left(\frac{62.43}{106} - \frac{1}{2.7}\right) \times 100 = 21.86 \text{ percent}$$

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 2) 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, and

γ_w = unit weight of water = 62.43 pcf or 1 g/cc

$$\frac{w}{100\,\gamma_w} = \frac{1 - \frac{n_a}{100}}{\gamma_d} - \frac{1}{G_s}$$

$$\frac{w}{100 \times 1} = \frac{1 - \frac{10}{100}}{1.698} - \frac{1}{2.7}$$

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 is shown in Figure 2. For convenience, Table B giving values for determining the zero air voids curve, is included in Appendix B.

Percent Saturation, S

In earthwork construction above the groundwater 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 percent 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) (119). The percent saturation, S, may be determined on a volumetric basis, as follows:

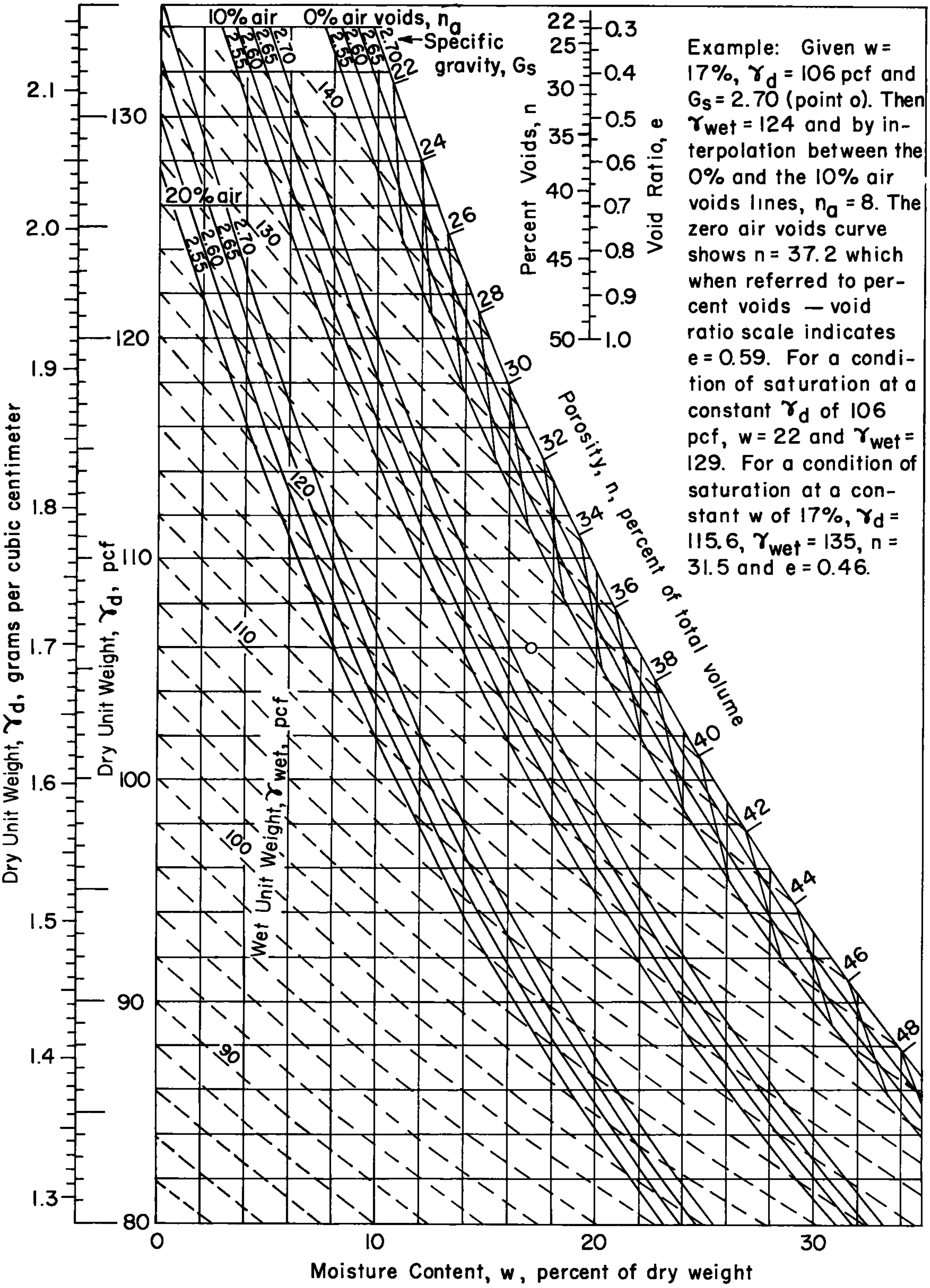
If V_w = volume of water-filled voids = 0.2886 cu ft, and

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



Example: Given w = 17%, γ_d = 106 pcf and G_s = 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 2. Chart of solids-water-voids relations of soil masses (source, Bureau of Public Roads).

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:

$$w = S\left(\frac{e}{G_s}\right)$$

$$17 = S\left(\frac{0.5902}{2.7}\right)$$

$$S = 77.77 \text{ percent}$$

Lines indicating 80 and 90 percent saturation for a soil having a specific gravity, G_s = 2.7 are shown in Figure 3.

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 shown in Figure 2. 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 on chart in Figure 2) 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-Mass Volume-Weight Relationships

Point 0 in Figure 2 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 2, gives e = 0.59.

For a condition of saturation at a constant dry unit weight γ_d = 106 pcf the values obtained in Figure 2 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 and e = 0.46 percent.

THE MOISTURE CONTENT-UNIT WEIGHT-COMPACTION EFFORT RELATIONSHIP

When samples of a given soil are first mixed with different percentages of water and then compacted under identical procedure there results a relationship between unit compacted weight, γ_{wet}, and the moisture content, w. This relationship is expressed in the form of a curve of compacted weight vs moisture content and is known as the wet unit weight curve (Fig. 4). Here the compacted unit weight increases with increase in moisture content to a maximum and then decreases with additional increase in moisture content. The increase in compacted unit weight results in part from the water added and in part from the greater densification obtained by compaction. The relative proportions of the increased wet unit weight due to the water added and that due to compaction are indicated in Figure 4.

Inasmuch as compaction consists of increasing the soil grains per unit of volume it is necessary to express the results of compaction in the form of a relationship between moisture content and dry unit weight. An example of a moisture content-dry unit weight relationship curve (compaction curve) is shown in Figure 3. Here the corresponding wet unit weight curve (Fig. 4) for the same soil is duplicated for comparison. The highest point on the dry unit weight curve represents the maximum unit weight attained with the method of compaction and compaction effort used. The moisture content corresponding to that maximum dry unit weight is known as the optimum moisture content (w_o or OMC). Also shown in Figure 3 are lines of 80 percent and 90 percent saturation, as well as the zero air voids line (line of 100 percent saturation). (These lines of percent saturation are not to be confused with the lines of 10 and 20 percent air voids shown in Figure 2.) The line of 100 percent saturation (zero air voids) represents the theoretical relationship between dry unit weight and moisture content, assuming all the voids to be filled with water. The percent saturation refers to the percent of the total pore volume that is filled with water.

The compaction curves shown in Figures 3, 4, and 5 are "regular" in shape; that is, they are nearly parabolic in form. Certain lateritic soils, uniformly graded sands, and colloidal clays exhibiting very high plasticity indices often result in irregularly shaped curves when compacted by the effort employed in AASHO Designation: T 99, or similar efforts in field compaction. Highly plastic clays usually respond to increase in compaction effort, the shape of their compaction curves changing from irregular to regular on increasing the compaction effort from that of AASHO T 99 to AASHO T 180. That is not necessarily true for some of the other soils. Some of the early tests illustrating regular and irregular curves were obtained in the early studies of soil-cement mistures (17A).

Figure 3 also shows the relationship between the porosity, n (the percent total voids), corresponding to the dry unit weights on the graph. The curve of porosity vs moisture content is a fundamental measure of compaction because it does not reflect the effect of the specific gravity of the soil solids G_s, as does the dry unit weight expressed in pounds per cubic foot (pcf). For any given porosity, n, the dry unit weight, γ_d, increases with increase in the specific gravity of the soil solids, G_s.

There are several general factors that influence the value of unit weight obtained by compaction, whether the compaction be in the laboratory test or in field construction.

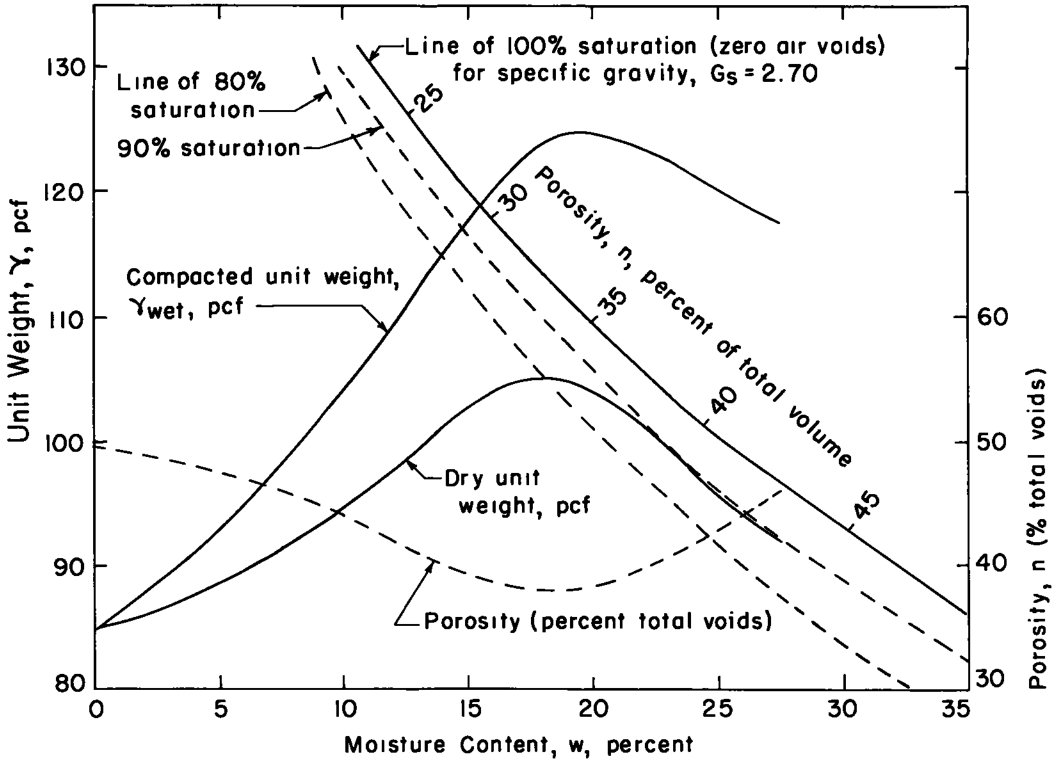


Figure 3. The moisture content-unit weight relationship showing the curves of (1) compacted unit weight, γ_{wet}, vs moisture content, and (2) dry unit weight, γ_d, vs moisture content and porosity corresponding to dry unit weights shown. Soil is a silty clay, LL = 37, PI = 14, compaction effort = AASHO Method T99 (12,375 fp/cf).

The most significant of these are (a) the moisture content of the soil, (b) the type and amount of compaction effort used, and (c) the nature of the soil (that is, its grain size distribution and its physical properties). In addition, (a) the temperature of the soil, (b) the amount and the effectiveness of manipulation during the addition of water, mixing and compaction, or in the removal of water by aeration, and (c) the uniformity of moisture distribution and time period between mixing and compaction, have some influence on the degree of compaction attained.

Influence of Moisture Content

Examination of the moisture content-dry unit weight curve (Fig. 3) resulting from a laboratory compaction test, or of curves developed from full-scale field rolling experiments (Fig. 13) show that for a given soil and a given compaction effort, the moisture content determines the state at which maximum dry unit weight occurs. When the moisture content is low, the soil is stiff, and difficult to compress; low values of dry unit weight and high values of air content are obtained. As the moisture content is increased, the added water decreases surface tension and acts as a lubricant causing the soil to soften and become more workable resulting in a higher dry unit weight and a lower air content. The optimum moisture content at which maximum dry unit weight is attained is the moisture content at which the soil has become sufficiently workable that under the compaction effort used it has permitted the soil to become packed so closely as to expel most of the air. As the moisture content is increased above optimum,

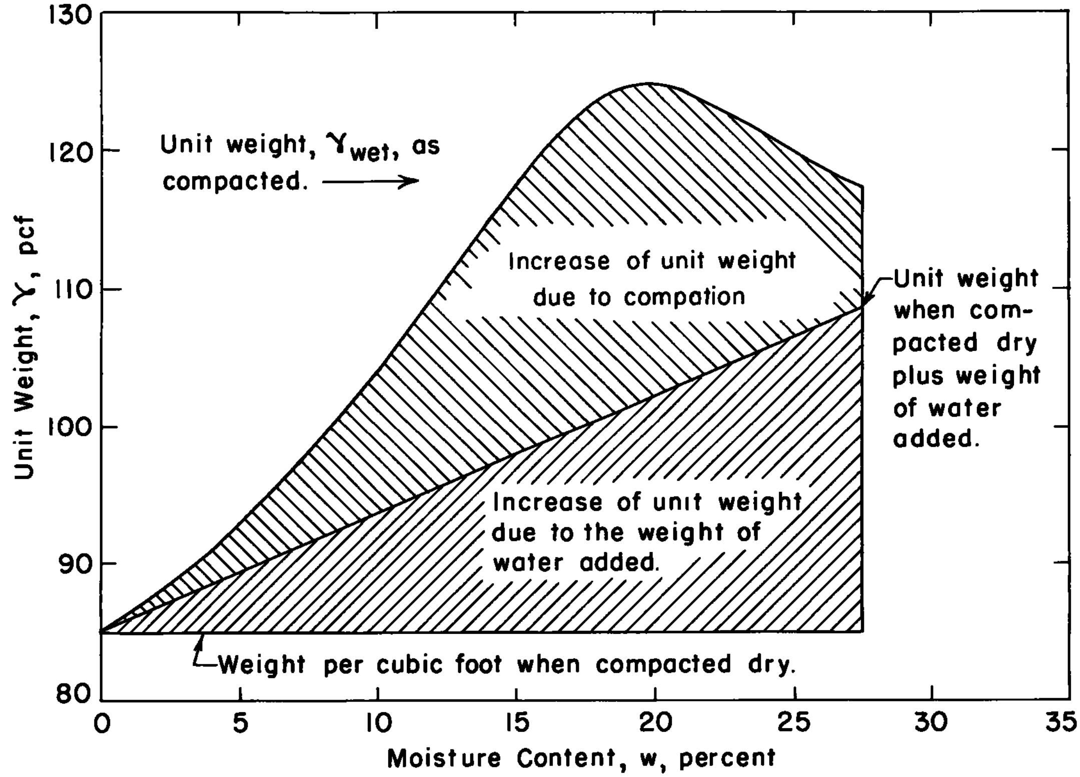


Figure 4. The moisture content-unit weight relationship indicating the increased unit weight resulting from the addition of water and that due to the compaction effort applied. Soil is a silty clay, LL = 37, PI = 14, compaction effort = AASHO Method T99 (12,375 fp/cf) (source (15)).

the soil becomes increasingly more workable but the increased moisture content and the remaining unexpelled air fill the soil voids and prevent closer packing. Thus, the moisture content-unit weight relationship is indicative of the relative workability of the soil at various moisture contents under the compaction effort used.

Influence of Compaction Effort

For all soils, in field or in laboratory compaction, increasing the energy applied per unit volume of soil results in an increase in the maximum unit weight and a decrease in the optimum moisture content. Although the optimum moisture content decreases with an increase in compaction effort for a given soil, that soil is sufficiently workable at the reduced moisture content to be compacted to a higher maximum unit weight at the increased compaction effort. Thus, for each compaction effort applied per unit volume of a given soil, there is a corresponding optimum moisture content and maximum unit weight.

Early studies of the influence of compaction effort on dry unit weight were made by several state highway departments and the Corp of Engineers. The early studies of soil stabilization by the use of portland cement (122A, 122B) explored the effects of different compaction efforts on the properties of the soil-cement mixtures.

The effect of compaction effort on dry unit weight and optimum moisture content for a well-graded clayey sand is illustrated in Figure 5. Here five compaction efforts were used. The magnitude of each effort is given in Figure 5 in terms of foot-pounds per cu in. and also in terms of foot-pounds per cu ft. Note that the values of dry unit weight range from about 11.6 to 127.1 pcf, a total range of about 10.5 pcf, and that the values of optimum moisture content range from 7.7 to 10.5 percent.

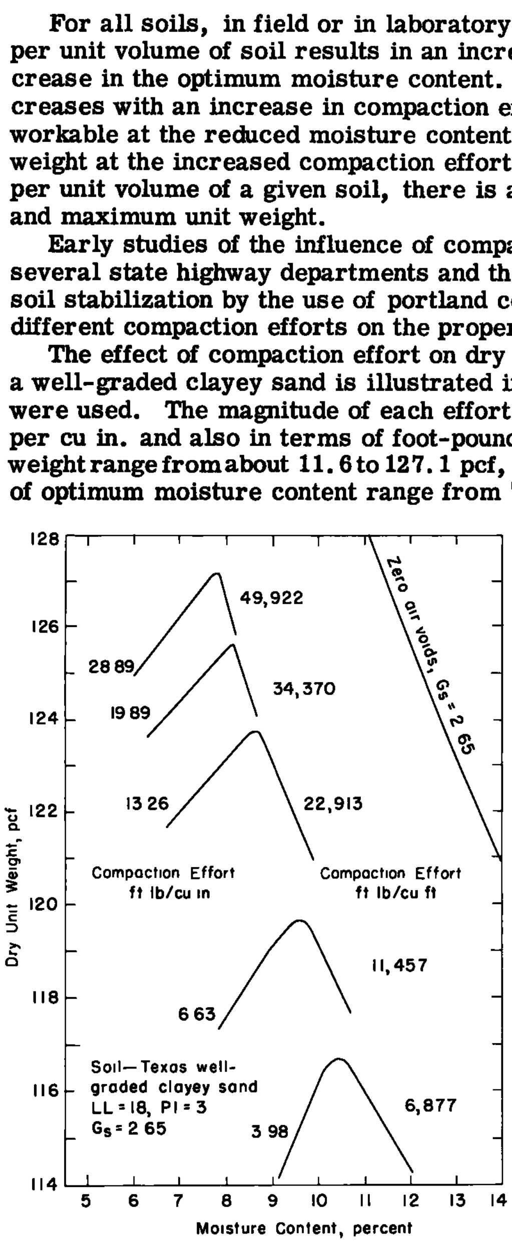


Figure 5. Effect of compaction effort on moisture-unit weight relations for a clayey sand. Note: The compaction effort for Standard AASHO Method T 99-57 is 12,375 fp/cf and Modified AASHO is 56,250 fp/cf (55,986 fp/cf for AASHO Method T 180-57 using 1/13.33 cf mold) (source (106A)).

The effect of compaction effort is often determined by comparing the results obtained with (a) AASHO Designation: T 99-57 (3 layers, 25 blows per layer, 5.5-lb rammer dropping 12 in. in a 1/30-cu ft mold); and (b) the method formerly known as the Modified AASHO Method but which is now AASHO Designation: T 180-57 (5 layers, 25 blows per layer, 10-lb rammer dropping 18 in. in a 1/30-cu ft mold or 56 blows per layer in a 1/13.33-cu ft mold).

Performing both tests on each of several types of soil shows that different soils exhibit different increases in unit weight with increase in laboratory compaction effort. Uniformly graded (one-size) sands may exhibit little (2 to 3 pcf) or in extreme cases no increase in unit weight; well-graded sands 8 to 10 pcf; silty to clayey sands, sandy clays, and silty clays 10 to 18 pcf; and heavy clays may exhibit unit weight increases up to 20 pcf for AASHO Method T 180 compared to that of AASHO Method T 99. Examples indicating the differences in compactibility of two soils in these two laboratory tests that differ so greatly in compactive effort (T 99-57 Method A = 12,375 ft = lb pcf, T 180-57 Method A = 56,250-ft = lb pcf) are illustrated in Figure 6. The absence of different sizes of particles in the fine sand makes it impossible to obtain high unit weights for this soil regardless of method of compaction or compaction effort used in field or laboratory. The silty clay soil, however, responds to compaction effort either in the field or laboratory.

If maximum unit weights for each of several compaction efforts are determined as indicated in Figure 5, and those maximum unit weights are plotted vs compaction effort on a semi-log plot there develops compaction effort vs maximum unit weight curves of the nature indicated in Figure 7. These curves illustrate the very marked effect that changes in the laboratory compaction effort has on some soils compared to a much lesser effect on other soils.

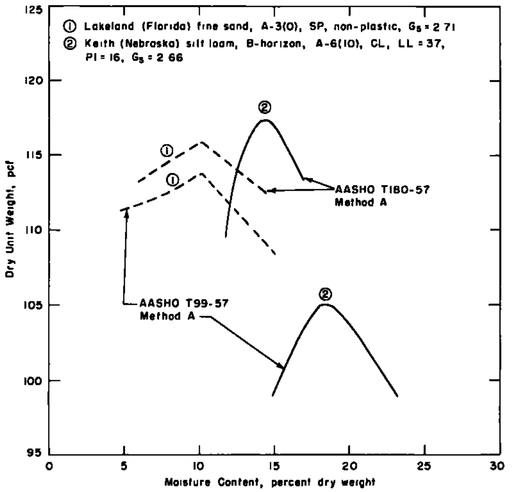


Figure 6. Effect of two different compaction efforts on the unit weights of two different types of soil (courtesy Bureau of Public Roads).

These differences, in response to compaction effort are of practical significance to the engineer who prepares specification requirements for compaction. They are also of significance to the engineer who interprets the results of unit weight tests, particularly when the specification requirements are stated in terms of percent relative compaction (see "Definitions," Appendix A). For example, the percentages appearing above the curves for soils 2, 4, and 7 in Figure 7 show the compaction efforts required to attain unit weights equivalent to 90, 95 and 100 percent of that obtained by AASHO Method T 99-57 (12,375 ft-lb pcf). It may be seen that the compaction effort necessary to attain 90 percent or 95 percent of maximum unit weight varies markedly with soil type, being a function of the slope of the curve. For soil 7, a medium clay, the compaction effort at 90 percent relative compaction is 2,500 ft-lb pcf which is equal to about 20 percent of the compaction effort required to attain maximum unit weight in the AASHO T 99 test. In comparing this with soil 4, it may be seen that the compaction effort needed to attain 95 percent of AASHO T99 maximum dry unit weight is about 20 percent (of 12,375 ft-lb pcf) and that the soil can be poured in the dry state to a unit weight about equal to 90 percent of AASHO T99 maximum dry unit weight. Thus, about the same compaction effort is required to compact the sandy soil to 95 percent relative compaction as is needed to compact the clayey soil to 90 percent relative compaction.

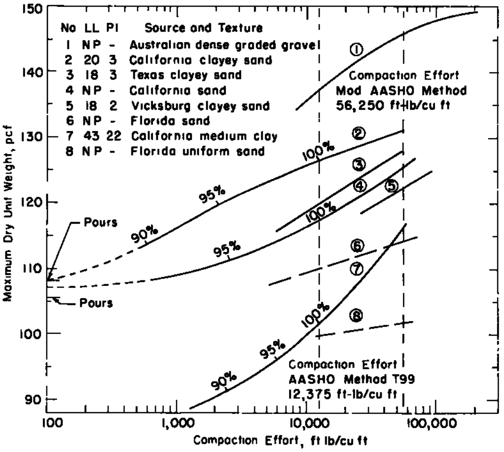
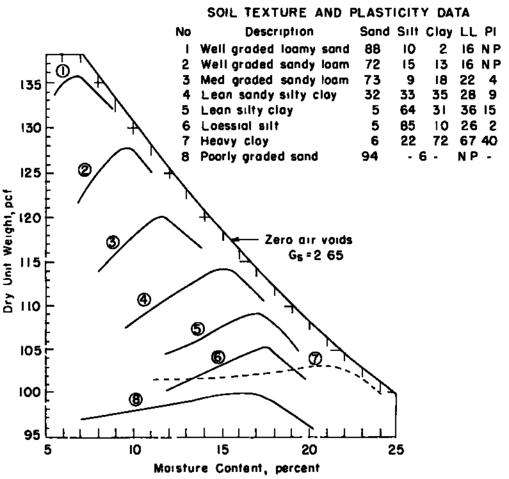


Figure 7. Relationship between compaction effort and the corresponding maximum unit weight obtained at the optimum moisture content for each compaction effort. Sources of data for curves, in order shown: (82A, 42A, 106A, 42A, 53, 63, 42A, 63).

There are differences in methods of applying compaction effort in the field compared with those in the laboratory. Therefore, there are slight differences between field and laboratory relationships between compaction effort and the unit weight attained. However, from the results of full-scale field rolling experiments in several countries, and the comparison of field results with laboratory results there has been found to be a close similarity between trends in the results of field and laboratory compaction. Therefore, the effect of compaction effort is as evident and as significant in field compaction as in the compaction test. In field compaction, unless the roller sinks too deeply in the soil, the effort applied is the product of the drawbar pull and the number of passes for the width and depth of area compacted. This involves the dimensions of the compactor, total weight, size of loaded area, unit contact pressure, lift thickness and number of passes or coverages.



SOIL TEXTURE AND PLASTICITY DATA

No	Description	Sand	Silt	Clay	LL	PI
1	Well graded loamy sand	88	10	2	16	NP
2	Well graded sandy loam	72	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 8. Moisture content-unit weight relationships for eight (8) soils compacted according to AASHO Method T99.

Effect of Soil Type

The values of maximum unit weight and optimum moisture content obtained under a given compaction effort may differ widely for different soil types, depending on the shape of the soil grains, their size distribution, specific gravity and their plastic properties. When compacted under a standard effort (AASHO Method T99), some clayey soils of volcanic origin may have maximum unit weights of the order of 60 pcf or less. Other heavy textured clay soils may exhibit maximum unit weights of the order of 90 to 100 pcf or more. Poorly graded (uniform size) sands may also exhibit unit weights of less than 100 pcf. Improving the distribution of the grain sizes by increasing the sand content and by keeping silt and clay components in proportions approximately sufficient to fill the voids in the sand, markedly increases the unit weight for a given compaction effort.

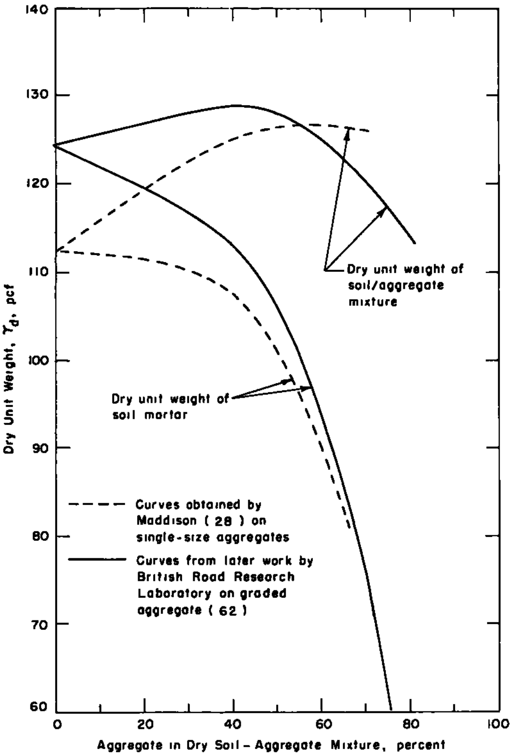


Figure 9. Influence of the proportion of aggregates on the compaction of soil-mortar at optimum moisture content (28, 62).

Examples illustrative of the differences in maximum unit weight and optimum moisture content that result for eight different soils when compacted in accordance with AASHO Method T99 are shown in Figure 8. Here a poorly graded (uniform grain size) sand, No. 8, resulted in the lowest unit weight for the group. Only a slightly higher unit weight was attained for the heavy clay, No. 7. The uniformly graded sand, No. 8, was relatively insensitive to increases in moisture content as is indicated by the small increase in unit weight with increase in moisture content. This is also true for the heavy clay, No. 7. The silty soils showed increased response to change in moisture content, and the sandy soils with relatively small proportions of silt and clay were highly sensitive to changes in moisture content as is indicated by the shapes of their compaction curves. It should be noted in Figure 8 that the zero air voids curve is for a specific gravity G_s of 2.65. Because the specific gravities of the soils differ, their relative position with respect to the zero air voids curve differs. Thus, the actual percent air voids may vary some-

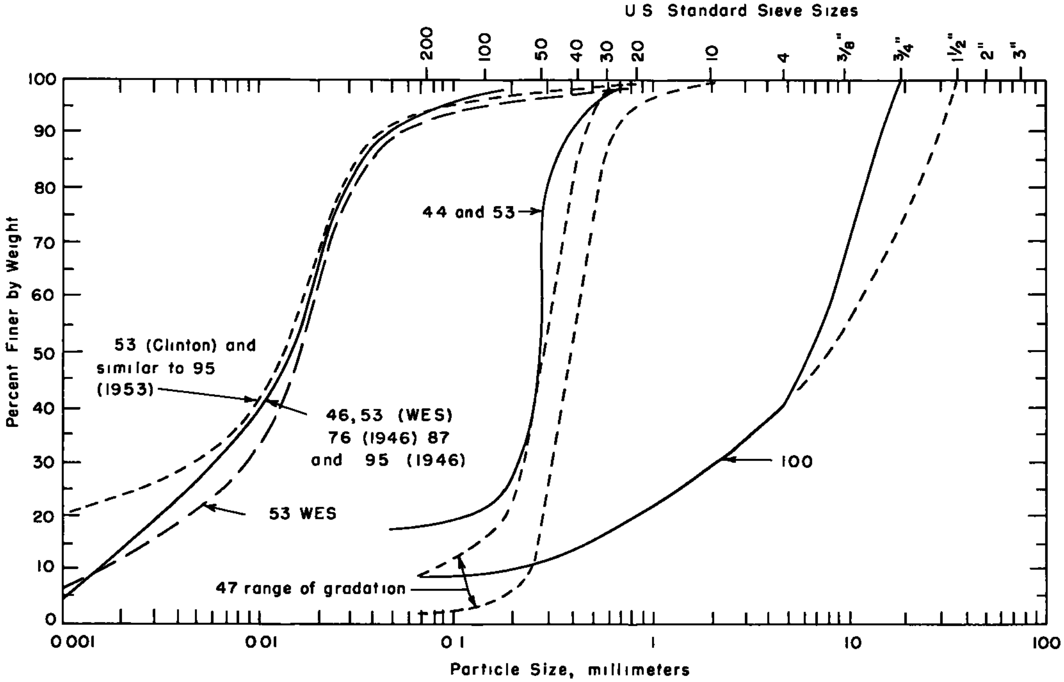
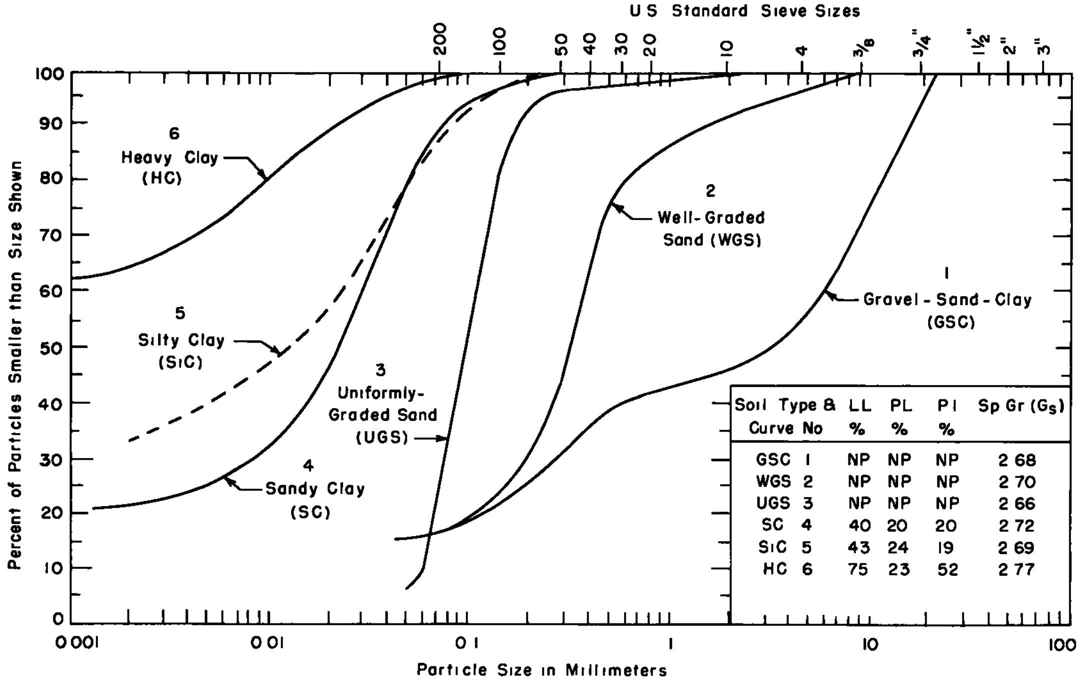


Figure 10. Grain-size distribution of soils used in full-scale compaction experiments by Corps of Engineers. (Note: Numbers beside curves show references from which data were obtained.)

what from that indicated.

The compaction curves in Figure 8 are representative of soils that contain little or no coarse aggregates (material retained on the No. 4 sieve). However, the coarse aggregate, whether it be retained on a No. 4 sieve or the ¾-in. sieve may, like the sand content or the type and proportion of clay, have a strong influence on the compaction characteristics. That influence may differ depending on the nature of the aggregate (natural gravel, crushed gravel, crushed rock, etc.), its maximum size, and its size distribution. The proportion of coarse aggregate determines not only the unit weight of the soil mortar but also the unit weight of the total mix. The effect of coarse aggregate content is significant not because of problems it engenders in obtaining the necessary degree of compaction either in the field or in the laboratory but rather because of the difficulties it presents in the measurement of unit weight and applying those measurements in the control of construction. Measurement is usually based on the unit weight of the material passing the No. 4 sieve or that passing the ¾-in. sieve, although control is sometimes on the basis of the total material. The effect of the proportion of coarse aggregate on the unit weight of the soil mortar and on the total material for two types of coarse aggregate gradings is indicated in Figure 9.

In arriving at the relationships indicated by the dashed lines in Figure 9, Maddison (28) used single size coarse aggregates up to 25 percent of any one size (1 in. to ¾ in., ¾ in. to ½ in., and ½ in. to ⅜ in.). They had but little effect on the compaction of the soil mortar in proportions of less than about 25 percent, the aggregate merely acting as displacers of soil mortar. However, the use of an aggregate graded between the ¾-in. and the British No. 7 standard sieve (62) resulted in decreasing the dry unit weight of the soil mortar on the addition of even small proportions of the aggregate.



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 11. Index properties and grain-size distributions of soils used in full-scale compaction studies in Great Britain (56, 81, 109A, 110, 129).

All coarse aggregates when added to the soil, resulted in increasing the unit weight of the total material to a point of maximum unit weight beyond which further increases in the proportion of coarse aggregate resulted in a decrease in unit weight of the total material.

The influence of coarse aggregate content on unit weight and means for measuring or computing the degree of that influence as it affects or is affected by specification limits has been given much thought and is discussed later.

Other Factors that Influence Compacted Soil-Unit Weight

It has been demonstrated (13, 23) under identical compaction procedures, that increasing the temperature from near freezing to 75 F or more may increase the unit weight of compacted fine-grain soils by three or more pcf. Extreme values range up to 11 pcf (23). Thus, soil temperature may favorably or adversely affect compaction of certain fine-grain soils.

Other factors of a minor nature include manipulation of the type involved in mixing soil and water in either field or laboratory, or that involved in reducing soil moisture content by aeration. These may influence the unit weight particularly of clayey soils. Drying of densely graded granular bases may influence unit weight. Degradation in the form of aggregate breakage under rolling is also a factor. The uniformity of the distribution of the soil moisture and the time period between wetting, mixing and compacting may influence unit weight.

The factors previously mentioned that may influence both the compacted unit weight (and the optimum moisture content) are of general nature and may apply both in field or in laboratory compaction, although not necessarily in the same degree. There are, in addition, a number of factors that are peculiar to testing alone or to field compaction alone that influence the results obtained. These are discussed later.

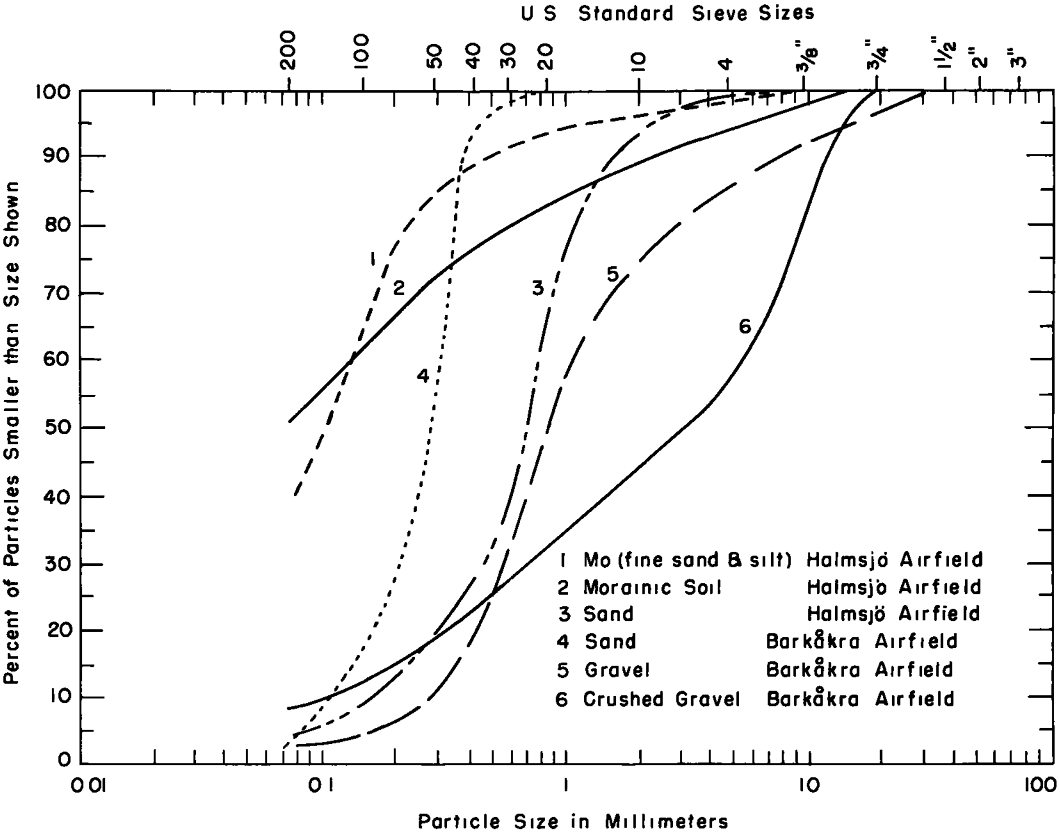


Figure 12. Grain-size distribution curves for soils used in Swedish compaction studies (80).

FACTORS INFLUENCING COMPACTION IN CONSTRUCTION

It has been shown that there are several factors that influence compaction, whether in the laboratory or in the field. The most significant of these are (a) the type of soil, (b) its moisture content, and (c) the nature of the compaction effort. Inasmuch as the soil, and its moisture content, are common to both laboratory and construction compaction, the essential differences between field and laboratory compaction lie in the

TABL

INDEX PROPERTIES OF SOILS USED IN EXPERIMENTAL COMPAC

Line	Reference Number	Textural Soil Type	Mechanical Analysis			Atterberg Limits	
			Gravel and Sand >0.05 mm	Silt 0.05 to 0.005 mm	Clay Smaller Than 0 005 mm	L:L	P.I.
1	29	Indiana silty clay	2-6	57-65	28-40	31-46	13-25
2	29	Ohio sandy silty clay	31-39	38-42	33-36	31-45	12-23
3	37	Macadam base	-[b]	-	-	-	-
4	44, 53	Mississippi clayey sand	82	2	16	18	2
5	46, 76, 95, 53, 87	Mississippi lean clay	5-11	60-68	21-31	36-39	12-18
6	47	Uniformly graded Florida fine sand	96-99	-	-	-	NP
7	56, 127, 110, 129	British sand-gravel-clay	83	-	-	-	NP
8	56, 127, 110, 129	British well-graded sand	83	-	-	-	NP
9	56, 81	British sandy clay	45	29	26	27	8
10	56, 81	British silty clay	22	38	40	43	19
11	56, 110, 129, 81, 127	British heavy clay	3-10	19-26	71	75	47-52
12	55	Washington fine sand (plasters sand)	-[c]	-	-	-	-
13	55	Washington medium sand (building sand)	-[d]	-	-	-	-
14	57	Australian crushed rock	-[e]	-	-	25	9
15	57	Australian fine sand	-[f]	-	-	-	NP
16	61A	C.A.A. crushed limestone	-[g]	-	-	-	-
17	61A	C.A.A gravel	-[h]	-	-	-	-
18	61A	C.A A. sand	-[i]	-	-	-	-
19	61	New Jersey silt-sand-gravel	96[j]	2	2	-	-[k]
20	62	British gravel-sand	-[m]	-	-	-	-
21	62	British sandy soil	-[m]	-	-	-	-
22	62	British sand	-[m]	-	-	-	-
23	60	California medium fine sand	100	-	-	-	NP
24	66	India clayey soil	32-38	48-41	20-21	31-35	13-16
25	66, 104	India silty soil	53	30	17	27-30	10-11
26	66, 104	India sandy soil	62	24	14	26	6
27	80	Swedish moraine soil (Halmsjö airfield)	52[n]	-	-	-	-
28	80	Swedish mo soil (Halmsjö airfield)	40[n]	-	-	-	-
29	80	Swedish medium sand (Halmsjö airfield)	5-8[n]	-	-	-	-
30	80	Swedish sand (Barkåkra airfield)	4[n]	-	-	-	-
31	80	Swedish gravel (Baråkra airfield)	4[n]	-	-	-	-
32	80	Swedish crushed gravel (Barkåkra airfield)	9[n]	-	-	-	-
33	100	1½-in max size crushed limestone	9[n]	-	-	-	NP
34	100	¾-in. max size crushed limestone	9[n]	-	-	-	NP
35	110	British uniformly graded fine sand	-	-	-	-	NP
36	110, 129, 127	British sandy clay	20	54	26	40	20

[a] The British Standard 1377:1948 Test No. 9 is generally similar to AASHO Designation: T 99-57 Method C. [b] Crushed limestone aggregate 3½ in. to 1½ in Limestone screenings fine aggregate ⅜ in to No. 100 sieve. [c] 99% pass No. 10, 35% pass No. 40, 1% pass No. 200. [d] 97% pass No. 4, 85% pass No. 10, 26% pass No. 40, 1% pass No 200 sieve [e] 99% pass ¾ in , 40% pass 3/16 in., 20% pass No. 20, 10% pass No. 52, 7% pass No. 200 sieve [f] 98% pass No. 25, 70% pass No. 52, 4% pass No. 100, 1% pass No. 200. [g] 90% pass ¾ in., 41% pass No 4, 30% pass No. 10, 20% pass No. 40, 15% pass No. 200 sieve. [h] 90% pass ¾ in., 70% pass No 4, 57% pass No. 10, 20% pass No. 40, 8% pass No. 200 sieve. [i] 92% pass No 10, 20% pass No. 40, 3% pass No. 200 sieve [j] 90% pass No. 4, 82% pass No 10, 50% pass No. 40, 8% pass No. 200 sieve [k] A cohesive "sile-gravel-sand" with 6-psi cohesion, angle of internal friction of 31 deg, moisture content = 7% [l] Heavy pneumatic-tired roller. [m] Data not given. [n] Percent passing the No. 200 sieve.

compaction effort; that is, the nature of the compacting equipment and its use. Of principal concern is whether or not a piece of equipment is able to compact the soil to the degree desired, and, if so, under what conditions of thickness of lift, number of passes, and moisture content, the compaction can be accomplished. These constitute the compaction characteristics of a compactor. Also of concern is the productive capacity (output) of a compactor in terms of cubic yards of soil compacted in a given period. The output involves (a) the width of the compacted strip; (b) its depth; (c) the speed of travel; (d) the number of passes required to attain the desired unit weight; (e) the maneuverability of the compactor and its ability to operate over rough terrain (original ground), near or on the side slopes of fills, etc; and, (f) its adaptibility, in terms of variability of weight, to compact a wide range of soil types under varying soil conditions.

Test Results From Full-Scale Field Experiments

The origin of the compaction test (10, 11, 15, 18) served as a strong stimulus toward the study of compaction in construction. Engineers became concerned with how closely the moisture content-dry unit weight relationships produced in the compaction test were being simulated under rolling. This resulted in full-scale compaction experiments being conducted over a period of years on the principal types of compaction equipment available at the time. Some of the earliest of these tests were conducted during the late 1940's and the results were given in part in HRB Bulletin 58. Full-scale compaction experiments have been conducted in several countries since that time. Reports are available from tests performed in Canada, Great Britain, India, Sweden, and the United States.

A review of the test reports from the full-scale closely controlled field tests re-

E 1

TION TESTS WITH VARIOUS TYPES OF COMPACTION EQUIPMENT

Laboratory Compaction Data					Types of Compactors Tested On Soil						
AASHO T99 or Its Near Equivalent[a]		Modified AASHO or Its Near Equivalent									
Max. Dry Unit Weight (pcf)	O M.C. (%)	Max Dry Unit Weight (pcf)	O.M C (%)	Specific Gravity Gs	3-Wheel Roller	Sheepsfoot Roller	Pneumatic Tired Roller	Vibrating Base-Plate-Type Vibratory Compactor	Vibrating Roller	Track-Type Tractor	Explosion-Type Tampers
102-107	17-22	-	-	-	x	x	x	-	-	-	-
106-110	17-20	-	-	-	x	x	x	-	-	-	-
-	-	-	-	-	x	-	-	x	x	-	-
116	11.5	122	10	2.68	-	x	x	-	-	x	-
105-108	17-18	117-118	14-15	2.72	-	x	x	-	-	x	-
-	-	103-111	-	-	-	-	x	-	-	x	-
129	9	138	7	2.68	x	x	x	x	x	x	x
121	11	130	9	2 70	x	-	x	x	x	x	x
115	14	128	11	2 70	x	x	x	x	x	x	x
104	21	120	14	2 69	x	x	x	-	x	x	x
97-99	24-26	113-116	16-17	2.77	x	x	x	x	x	x	x
96.6	-	-	-	-	-	-	-	x	-	-	-
-	-	-	-	-	-	-	-	x	-	-	-
-	-	141	7	2.76-2 80	x	-	x	-	x	-	-
-	-	107	13	-	-	-	-	-	x	-	-
126	6.6	140	6.3	-	-	-	-	x	-	-	-
135	8	142	6.2	-	-	-	-	x	-	-	-
121	13.2	133	8.2	-	-	-	-	x	-	-	-
120	7	-	-	-	-	-	-	x	x[1]	-	-
129	6.5	-	-	-	-	-	-	x	x	-	-
121	10.4	-	-	-	-	-	-	x	x	-	-
115	10.5	-	-	-	-	-	-	x	x	-	-
-	-	98	12.7	-	-	-	-	x	-	-	-
116-124	10-13	129	9	-	x	x	-	-	x	-	-
117-121	11-12	127	9	-	x	x	x	-	x	-	-
116-121	10-11	131	9	-	x	x	x	-	x	-	-
129	8	134	8	-	x	x	x	x	x	-	-
123	12	126	10	-	x	x	x	x	x	-	-
114	11	122	11	-	-	x	x	x	x	-	-
-	-	107	14	-	x	x	-	x	-	-	-
-	-	130	9	-	x	x	-	x	-	-	-
-	-	135	8	-	x	x	-	x	-	-	-
-	-	148	5	-	-	-	x	-	-	-	-
-	-	146	5	-	-	-	x	-	-	-	-
-	-	-	-	2.66	-	-	-	-	x	-	-
109	16	126	12	2.72	-	-	x	x	x	-	-

vealed a great amount of data on different types of equipment used in compacting a variety of soil types. Effort has been made to select numerous examples of data that may be of value to engineers interested in learning of fundamental relationships between the soil type, soil moisture content and the nature of the field compaction equipment. The Committee has selected insofar as is practical, data representative of soils, conditions, and equipment that are most nearly applicable in the United States.

Types of Soils Compacted in Full-Scale Compaction Experiments

The field compaction experiments employed a wide variety of textural soil types ranging from heavy clays to cohesionless sands and gravels. The principal index properties of the soils are given in Table 1. Included, where available, are data on percentages of sand, silt and clay, liquid limit and plasticity index, as well as maximum laboratory dry unit weight and optimum moisture content for one or two compaction efforts, the AASHO T 99 effort or its near equivalent and the Modified AASHO effort. The term "Modified AASHO" is used throughout the text because AASHO Designation: T 180-57 did not exist as a standard during the period when the tests were performed.

In order that the reader may more fully appreciate the nature of each soil tested in the principal series of tests, graphs indicating grain size distribution are provided for some of the soils on which the greatest amount of testing of compaction equipment was done. Grain size distributions for soils tested by the Corps of Engineers are shown in Figure 10, those for Great Britain in Figure 11 and those tested in Sweden in Figure 12. The soils tested by the Corps of Engineers include a number of soils in the Vicksburg area. The soils are of loessial origin and are quite uniform. Therefore, it has been found possible to represent these clayey silt, silty clay and lean clay soils by the three grain size distribution curves shown in Figure 10. In Table 1 they are represented by the Mississippi lean clay on a single line giving the ranges of values of the various index properties.

Full-Scale Field Tests on 3-Wheel Power Rollers

THE EFFECTIVENESS of a smooth-wheel roller of the three-wheel type, tested in competition with other types of rollers was first observed on experimental embankment construction projects in Indiana and Ohio in 1938. Since that time additional tests have been performed in Great Britain, India and Sweden. Weights and dimensions of the rollers employed in the tests are given in Table 2. Data obtained in the tests are given under appropriate subject matter in the following.

ROLLER MAXIMUM DRY UNIT WEIGHT VS MOISTURE CONTENT

The Indiana-Ohio experiments (29) were aimed at measurement of the amount of compaction needed to satisfy specification requirements of dry unit weight and moisture content based on the then newly standardized compaction test, AASHO T 99-38, on two construction projects. Efforts were not made to develop roller compaction curves. The Indiana tests, made on a silty clay soil with a 10-ton roller showed that no difficulty was experienced in attaining 100 percent relative compaction on 9- and 12-in. loose lifts in about 2 to 2.5 coverages. However, the Indiana soils ranged from one to almost four percentage units wet of optimum. The Ohio tests were all performed at moisture contents from one to two percentage units dry of optimum. Rolling of 6- and 9-in. loose lifts with a 10-ton roller showed that average values of relative compaction ranging from 101 to 105 percent were attained under 2.6 to 3.3 coverages on the 6-in. loose lift thickness and 4.1 coverages on the 9-in. loose lift.

The tests by the British Road Research Laboratory (56, 81, 129) were the earliest that developed roller compaction curves for a 3-wheel roller. They developed dry unit weight vs moisture content relationships for two weights of 3-wheel rollers (3.08- and 9.5-ton) on each of five soils ranging from a heavy clay to a gravel-sand-clay. All tests were performed on 9-in. loose lifts. Each was fully compacted—that is, compacted to refusal or by 64 passes of the roller. Similar tests were performed in India with rollers of 6.72- and 7.97-tons weight.

TABLE 2

CHARACTERISTICS OF THREE-WHEEL ROLLERS USED IN TESTS

Test	Gross Weight[a] (Tons)	Diameter of Rolls (in.)		Width of Rolls (in.)		Max. Comp. (lb/in. Width of Rolls)	
		Front	Rear	Front	Rear	Front	Rear
Ohio (29)	10	-	-	-	20	-	350
Indiana (29)	10	-	-	-	23	-	325
Great Britain (56)	3.08	34	36	24	15	80	142
Great Britain (56)	9.5	42	54	42	18	186	311
India (66)	7.97	44	55.5	40	20	98	294
India (104)	6.72	34	51	48	18	-	-
Sweden (80)	13.2	47	63	36.6	19.7	241	448

[a] All values in United States units.

Examples of the moisture content vs dry unit weight relationship for full compaction by rolling each of five soil types are shown by the roller curves in Figure 13. To the construction engineer, 64 passes of the roller may seem wholly impractical, yet only by the application of many passes can the limitations of a roller be fully determined.

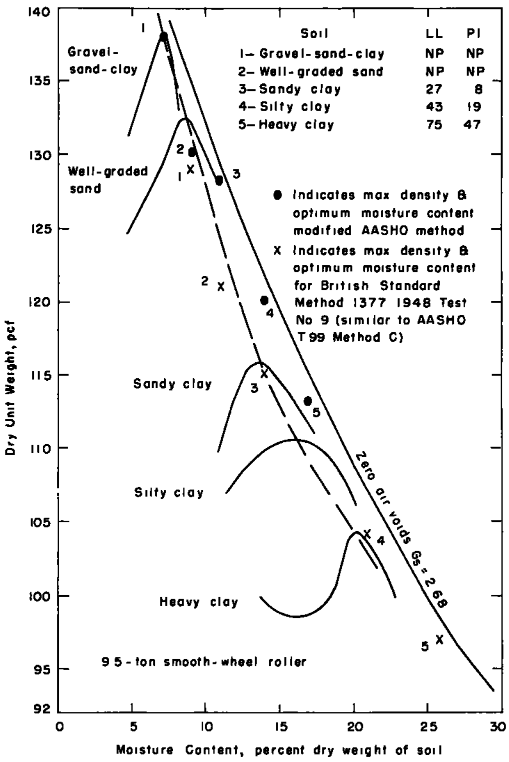


Figure 13. Comparison of roller compaction curves and roller lines of optimums for fully compacted soils (64 passes) with points of maximum unit weight and optimum moisture content from laboratory compaction tests on five different types of soils. Roller was of 3-wheel type weighing 19,012 lb, and having a compression under drive-rolls of 311 lb per in. of tire width (56).

Examinination of the roller compaction curves shows them to be approximately parabolic in shape, not unlike those from the laboratory compaction test. However, the roller maximum dry unit weights bear no consistent relationship to the corresponding laboratory values obtained in either the standard test or the Modified AASHO test. This is to be expected because of differences in compaction areas and forces, and is consistent with differences found in laboratory tests involving various compaction forces as has been mentioned previously. This is discussed further under "Comparison of Results of Roller Compaction and Laboratory Compaction" for various types of rollers. The peak values from the roller curves markedly exceed the peak values from the standard test in almost every instance but are less than peak values from the Modified AASHO test for all but the sand and the gravel-sand-clay soils. A summary of the results of the British tests (56, 81) on two weights of rollers, each tested on 9-in.-thick loose lifts, is given in Table 3. The results of the tests made in India (66, 104) on alluvial soils differed somewhat in that the lighter-weight rollers did not produce dry unit weights so greatly in excess over laboratory maximum values as did the heavy roller (9.5-ton) employed in the British tests.

INFLUENCE OF NUMBER OF PASSES ON DRY UNIT WEIGHT

Two sets of observations on the influence of number of passes on the dry unit weight of the soil were made in the British tests (56, 81). In one group the soil moisture content in the 9-in. loose lifts was adjusted to the optimum moisture content for the individual roller. Dry unit weight was then determined after increasing numbers of passes of the roller. In the other group tests were made to determine the effect of number of roller passes on dry unit weight at several different moisture contents.

The results of the first group of tests made at the optimum moisture content for the roller are shown in Figure 14 for the same five types of soils for which roller compaction curves were developed. Except for the heavy clay the fine-grain soils attained near maximum dry unit weight for the 9.5-ton roller after about 8 passes. There was a progressive gain in unit weight for the heavy clay and the gravel-sand-clay up to about 15 passes of the roller, indicating the greater difficulty of compacting heavy clays and gravels. Other tests (104, 80) yielded generally similar results, except lighter-weight rollers required a greater number of passes to attain similar degrees of compaction for the same lift thickness.

Figure 14 also indicates the number of passes required by the 9.5-ton 3-wheel roller to attain 95 and 100 percent of AASHO T 99 maximum unit weight for each of the five soils. Ninety-five percent was attained by an average of about two passes for four of the five soils. On only the heavy clay was a greater number of passes (6)

TABLE 3

COMPARISON OF MAXIMUM DRY UNIT WEIGHTS AND OPTIMUM MOISTURE CONTENTS FOR FIVE SOILS COMPACTED BY TWO SIZES OF ROLLERS IN 9-IN. LOOSE LIFTS

Test	Heavy Clay, CH[a]		Silty Clay, CL[a]		Sandy Clay, CL[a]		Sand, SW[a]		Gravel-Sand-Clay, GW[a]	
	Max Dry Unit Wt (pcf)	OMC (%)	Max Dry Unit Wt (pcf)	OMC (%)	Max Dry Unit Wt (pcf)	OMC (%)	Max Dry Unit Wt (pcf)	OMC (%)	Max Dry Unit Wt (pcf)	OMC (%)
British std. comp. test[b]	97	26	104	21	115	14	121	11	129	9
Modified AASHO test[c]	113	17	120	14	128	11	130	9	138	7
9.5-ton 3-wheel roller	104	20	111	16	116	14	132	9	138	7
3.08-ton 3-wheel roller	96	21	110	17	114	16	131	9	137	7

[a] Cavagrande classification.

[b] Similar to AASHO T 99 Method C.

[c] Differs only slightly from AASHO T 180 Method C.

required to attain 95 percent relative compaction. However, the attainment of 100 percent compaction required a wider range in number of passes, ranging from a minimum of three for the sand to eight for the heavy clay.

The second series, to determine the effect of number of passes at various moisture contents on rolled unit weight, was performed only on the silty clay soil. The results are shown in Figure 15. Dry unit weights continued to increase with increase in number of passes for moisture contents less than to slightly greater than optimum for the roller. At a moisture content 1.4 percentage units greater than laboratory optimum the soil became so easily workable that the maximum unit weight for the roller (at that moisture content) was attained in three passes.

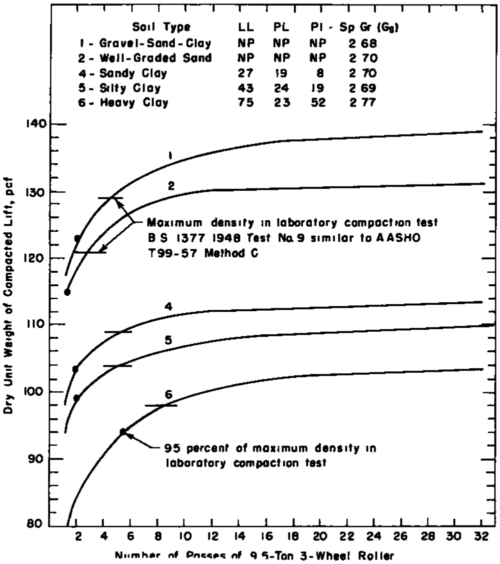


Figure 14. Effect of number of passes of a 9.5-ton 3-wheel roller on unit weights of five soils at optimum moisture contents for the roller in 9-in. loose lifts. Values of 100 and 95 percent of laboratory maximum unit weights are shown to indicate relation to number of passes required for field compaction (56, 81, 129).

EFFECT OF SPEED OF TRAVEL OF THREE-WHEEL ROLLER

Tests performed on the Indiana project at 180 fpm and 360 fpm (2.05 and 4.09 mph) showed that "...the compaction was undiminished at the higher speed ..." No other data on effect of speed of 3-wheel rollers have been found.

DEPTH VS PRESSURE RELATIONSHIPS FOR 3-WHEEL ROLLERS

For all rollers, the degree of compaction that is attained bears a relationship to the pressure that is applied over the contact area and the distribution of that pressure with depth. Much thought has been given to the computation of load pressures at various depths and at distances away from a point of load application. Because this is so intimately related to depth of compaction (proper lift thickness), it is of direct interest here in association with other data on compaction characteristics of three-wheel rollers.

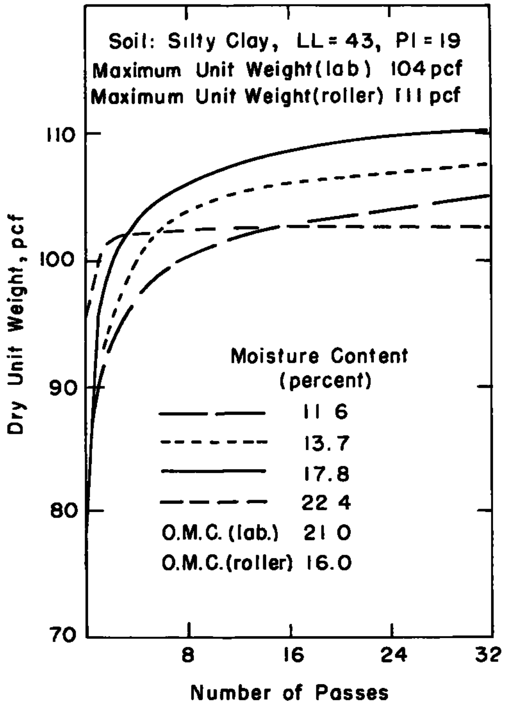


Figure 15. Relationship between dry unit weight and number of passes of 9.5-ton 3-wheel roller when compacted in 9-in. loose layers at different moisture contents. O.M.C. (roller) is optimum moisture content for 9.5-ton roller on silty clay soil in 9-in. loose lifts (56).

for depths of 0-4 in. and 0-6 in. The dry unit weight of the bottom 2 in. was then computed from the two sets of in-place tests. The results showed that the dry unit weight of the lower one-third of the compacted lift was 5.7 pcf less than the unit weight of the upper two-thirds of the total depth. The lower one-third was 8.6 pcf less for the silty clay; 7.6 pcf less for the sandy clay but only 2.3 and 4.3 pcf less for the sand and the gravel-sand-clay, respectively, indicating that the granular soils are not only easier to compact to higher percent relative compaction (in some instances with less effort) but also that a satisfactory unit weight can be attained to a greater depth. Actual values of dry unit weight expressed to the nearest whole number for the upper and lower portions are given in Table 4.

These early findings (56) of marked differences in dry unit weight between the upper and lower portions of a compacted

Transient pressures were measured under rollers as a part of the British study of compaction (74, 81). The measurements were made on a sandy clay and a silty clay. (Table 1 and Fig. 11). The depth of loose soil was 25 in. Measurements of pressure-depth relationships, were made after repeated (12 to 14 double passes) movements back and forth by the front roll which developed a ground pressure of 186 lb per inch of width. Measurements were made at several soil moisture contents.

Figure 16 shows the limiting values of peak pressures at various depths for a given moisture content for each of two soils. Laboratory values of maximum unit weight and optimum moisture content were not given but moisture contents may be compared with the plastic limits. A significant feature of the depth vs pressure relationship is that for a given moisture content the pressure vs depth relationship bears a relation to the unit weight of the compacted soil. This is indicated in Figure 17 which shows the relation between unit weight, depth, and pressure for the two soils at the same moisture contents shown in Figure 16.

DEPTH VS UNIT-WEIGHT RELATIONSHIPS FOR 3-WHEEL ROLLERS

In the early British experiments (56) in-place tests for measuring unit weight were

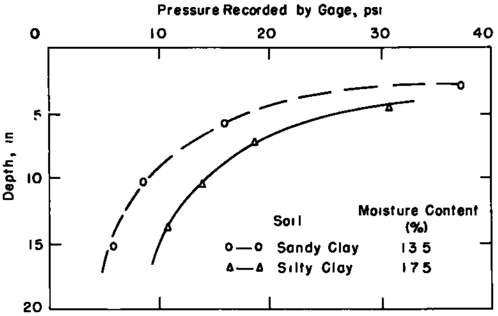


Figure 16. Relationship between pressure and depth in soil under 3-wheel 9.5-ton roller. Soils nearly identical to soils Nos. 4 and 5 in Figure 11. Index properties are as follows (74):

Soil	Particle Size Distribution, %				LL	PL	PI
	Gravel	Sand	Silt	Clay			
Silty Clay	0	17	49	34	40	20	20
Sandy Clay	0	40	36	24	34	17	17

lift led to a more comprehensive study of the unit weight vs depth gradient. Soils were compacted in 24-in. loose lifts at each of three moisture contents ranging from several percentage units dry of optimum to approximately optimum. Typical results are shown in Figures 18 and 19. The relationship between depth and dry unit weight at various moisture contents illustrates the significance of compacting at moisture contents that closely approximate optimum if the greatest degree of uniformity with depth is to be obtained. The effect of compacting at a moisture content consistent with high unit weight at maximum depth on the economy of compaction should not be overlooked. The tests in India (66) and those in Sweden (80) provided data that support those shown in Figures 18 and 19.

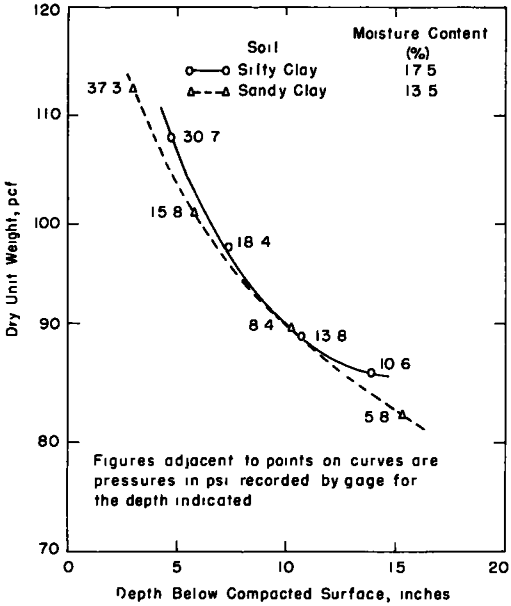


Figure 17. Relation between density, depth below compacted surface, and pressure under a 3-wheel 9.5-ton roller (74).

Depth vs dry unit-weight relationships of the nature illustrated in Figures 18 and 19 represent the normal relationships encountered where soil moisture contents are approximately at optimum or dry of optimum. If soil moisture contents are excessively high (well above optimum), it is entirely possible even on lifts of 12-in. thickness, to produce dry unit weights in the lower half of the lift that exceed those in the upper half of the lift. This may be associated with a cracked or "checked" loosened condition that often occurs in compacting very wet soils that exhibit "springing" and produce a wave of uplifted soil immediately ahead of and behind the rolls. The checked, loosened upper portion may be of lower dry unit weight than the lower part of the lift (29).

TABLE 4

COMPARISON OF DRY UNIT WEIGHTS IN UPPER AND LOWER PORTIONS OF FULLY COMPACTED LIFTS OF 9-IN. LOOSE DEPTH (56)

Soil Type and Weight of Roller	Dry Unit Weight (pcf)			
	Upper Half	Lower Half	Upper Two-Thirds	Lower One-Third
Indiana silty clay, 10-ton 3-wheel roller	103	107	-	-
British heavy clay, 9.5-ton 3-wheel roller	-	-	106	100
British silty clay, 9.5-ton 3-wheel roller	-	-	114	105
British sandy clay, 9.5-ton 3-wheel roller	-	-	119	110
British well-graded sand, 9.5-ton 3-wheel roller	-	-	133	130
British gravel-sand-clay, 9.5-ton 3-wheel roller	-	-	140	134

COMPARISON OF RESULTS OF ROLLER COMPACTION AND LABORATORY COMPACTION

The Indiana-Ohio tests (29) showed that no difficulty was encountered in compacting to 100 percent or more of AASHO T 99 maximum dry unit weight in up to 12-in. loose

Figures beside curves are moisture contents at which soils were compacted with 3-wheel 9.5-ton smooth-wheel roller

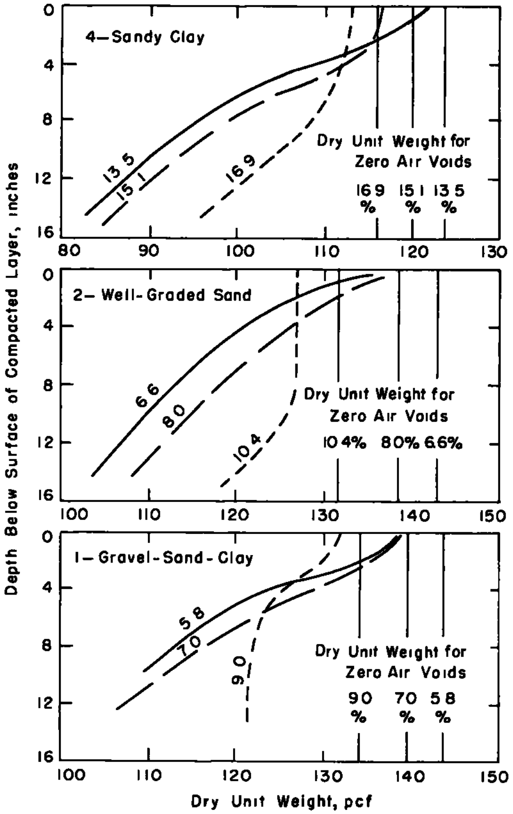


Figure 18. Relation between dry unit weight and depth for sandy clay, clay, and gravel-sand-clay soils when compacted in loose layers, 24 in. thick, by 32 passes of a 9.5-ton smooth-wheeled roller. Optimum moisture contents and maximum unit weights for roller and laboratory compaction are (56, 81, 129):

	Roller Compaction		Laboratory Compaction	
	O M C, %	Max Un Wt, pcf	O M C, %	Max Un Wt, pcf
Sandy Clay	15	116	16	109
Well-Graded Sand	9	132	11	121
Gravel-Sand-Clay	7	138	9	129

Figures beside curves are moisture contents at which soils were rolled with 3-wheel 9.5-ton smooth wheel roller

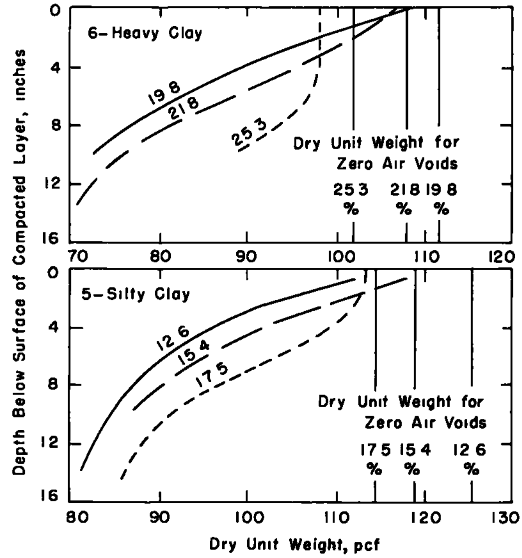


Figure 19. Relation between dry density and depth for heavy clay and silty clay soils when compacted in loose layers, 24 in. thick, by 32 passes of a 9.5-ton 3-wheel roller. Optimum moisture contents and maximum densities for roller compaction and laboratory compaction are (56, 81):

	Roller Compaction		Laboratory Compaction	
	O M C, %	Max Un. Wt, pcf	O M C, %	Max Un Wt., pcf
Heavy Clay	20	104	24	99
Silty Clay	16	111	21	104

(56) (81)

lifts at moisture contents above optimum with two to three passes in Indiana, and in up to 9-in. loose lifts at moisture contents up to 2 percentage units less than laboratory optimum with 3 or 4 passes in Ohio. Similar results were obtained at roller optimum (which was up to 4 percentage units below the laboratory optimum) with 4 to 5 passes in Great Britain (56) (Fig. 14).

The roller tests bring out a significant relationship between roller maximum dry unit weight and optimum moisture content and the corresponding values obtained in the standard laboratory test. Examination of the values for full compaction given in Table 3 and for one roller (9.5 ton) in Figure 13 show that the greatest differences between maximum roller and maximum laboratory dry unit weights are for the sand and gravel-sand-clay. It is evident from Figure 14 that the number of passes required for a given percent relative compaction is less for the lighter textured soils. Contrary, the greatest differences between roller optimum and laboratory optimum moisture content are for the clayey soils, the roller optimum being 6- to 7-percentage units less than corresponding values for the standard laboratory test. This may or may not be desirable, depending on soil-use requirements; the lower roller optimum moisture contents no doubt providing greater strength (for a given dry unit weight) but also providing greater possibilities for soil swell for expansive clayey subgrade soils.

Having compared results between roller-produced and laboratory-produced moisture content unit-weight relationships by using the average unit weight for the entire depth of the compacted lift, it is of interest to learn how nearly the optimum moisture content for each produces an acceptable unit-weight gradient in the compacted lift. Examination of Figures 18 and 19 shows marked decreases in dry unit weight with depth below the surface of the compacted lift. Further examination shows that the nature of the reduction is related to moisture content—the greater the moisture content, the lesser the difference between unit weights in the upper and lower portions of a given lift thickness.

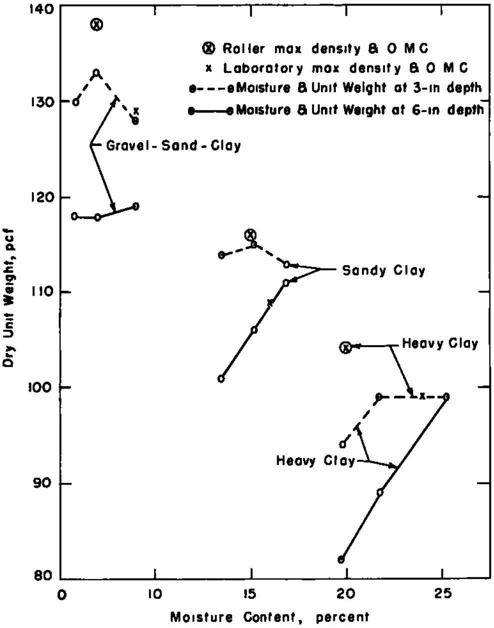


Figure 20. Comparison of unit weights at depths of 3 and 6 in. below compacted surface with values of maximum unit weight and optimum moisture content for 9.5-ton 3-wheel roller and for laboratory compaction test (British Standard 1377: 1948 Test No. 9) similar to AASHO T99-57 Method C (56).

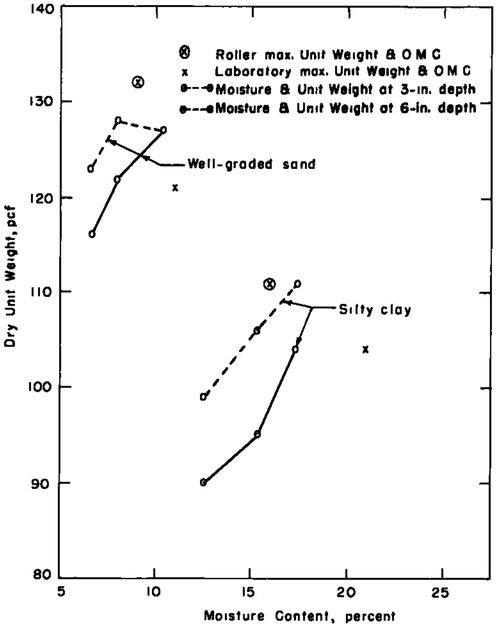


Figure 21. Comparison of unit weights at depths of 3 and 6 in. below compacted surface with values of maximum unit weight and optimum moisture content for 9.5-ton 3-wheel roller and for laboratory compaction test (56).

Figures 20 and 21 make it possible to compare quickly the roller-produced moisture content-unit-weight relationships at depths of 3 and 6 in. below the compacted surface for five soils (56) with the maximum roller values. The unit weights at the 6-in. depth may be 10 pcf or more less than at the 3-in. depth at moisture contents well below roller optimum. At roller optimum differences in roller compacted unit weights at the 3- and 6-in. depths range from 3 to 15 pcf whereas at laboratory optimum the differences range from 0 to 9 pcf. These differences in unit weight with depth show that while the greatest average dry unit weight for the compacted lift occurs at roller optimum, the more uniform compaction vertically in the lift occurs at laboratory optimum. This is evident on inspection of Figures 18 and 19.

The maximum roller dry unit weights for "full compaction" far exceeded those obtained by the standard laboratory test. This lack of correlation is by no means unexpected. The intent of the original Proctor test, on which AASHO T 99-38 was based (AASHO T 99 substituted a 12-in. drop of the rammer for a 12-in. firm blow), was to produce a dry unit weight that provided a given strength and permeability and which could be produced by rolling a nominal number of passes of the roller. Inspection of results in Table 3 shows that although roller unit weights exceeded maximums produced in the standard test, only for the sand and gravel-sand-clay did roller unit weights equal or exceed those maximums produced by the Modified AASHO test.

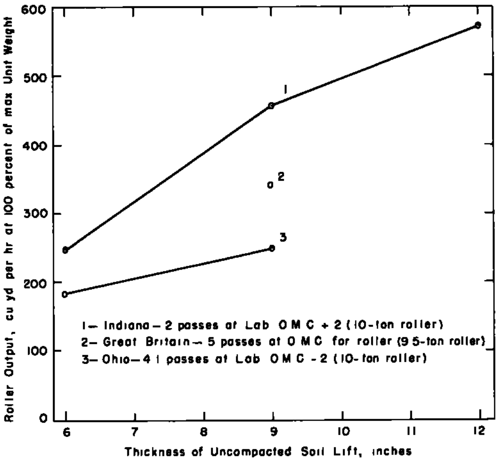


Figure 22. Comparison of output of 3-wheel rollers for three different thicknesses of uncompacted silty clay soils (29, 56, 81).

The individual laboratory optimum moisture contents for each soil showed no consistent relationship with those obtained under "full compaction" by rolling. This is evident on examination of the peaks of the roller curves and the points representing laboratory values in Figure 13. These differences may be attributable to differences in the response of the soils to the energy applied. However, inasmuch as lines drawn through points of maximum unit weight and optimum moisture contents for various field and laboratory compaction efforts lie very close together, it is indicated in Figure 13 that the soils react similarly in field and laboratory provided compaction efforts are comparable. The line of optimum moisture contents through the peaks of the roller curves lies approximately on a similar line drawn through the peaks of the standard test but lies on the dry side of a line drawn through points of optimum moisture content for the Modified AASHO test.

TABLE 5

OUTPUT IN CUBIC YARDS PER HOUR FOR A 9.5-TON 3-WHEEL ROLLER COMPACTING 9-IN. LOOSE LIFTS (56, 81)

Soil Type	Percent Relative Compaction[a]		
	90	95	100
Heavy clay	570	340	240
Silty clay	1710	570	340
Sandy clay	860	340	53
Well-graded sand	1710	860	570
Gravel-sand-clay	1710	860	340

[a] Percent of British Standard 1377:1948 Test No. 9 maximum dry unit weight. The British test is generally similar to AASHO T 99 Method C.

PRODUCTIVE CAPACITY (OUTPUT) OF 3-WHEEL ROLLERS

The output of a roller is expressed in terms of cubic yards of soil compacted per hour. The output depends on the dimensions and ground pressures of the rolls, speed of travel, the nature of the soil and its moisture content, and the thickness of the lift (which determines the number of passes required) to produce the degree of compaction specified. Soil type influences output in that the lighter textured, sandy soils require less number of passes than do the heavy clays. The lower the moisture content the greater the number of passes required (Fig. 15). Inasmuch as data are not available that indicate any effect that speed of travel may have on rolled unit weight, output is directly related to speed of travel.

The direct effect of lift thickness is shown in Figure 22 for two silty clays and a sandy silty clay. Here, the roller compacted soil in Indiana (29) was compacted to about 100 percent relative compaction at an average moisture content about 3 percentage units wet of optimum, and the Ohio soil (29) to an average of 103 percent relative compaction at two percentage units dry of optimum. Production in the British tests was based on the requirement of 5 passes to produce 100 percent relative compaction (340 cu yd per hour) for the silty clay (Fig. 14).

Data were compiled to show the direct effect of number of passes on output for compaction to a required percent relative compaction. Figure 14 shows that the number of passes required to compact 9-in. loose lifts to 100 percent relative compaction, ranged from 3 for the sand to 8 for the heavy clay. Values of output for 90, 95, and 100 percent relative compaction for five soils when compacted in 9-in. loose lifts by a 9.5-ton roller are given in Table 5.

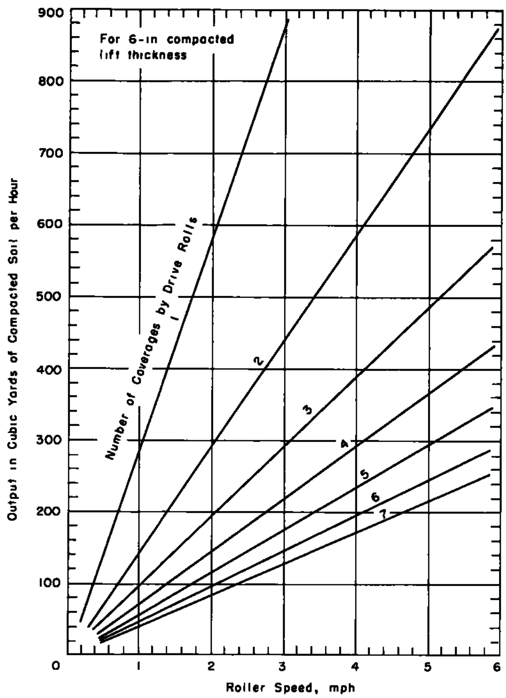


Figure 23. Maximum productive capacity of a 10-ton 3-wheel roller for coverage by drive rolls only. (Based on 20-in. wide drive rolls, spaced 36 in. apart and complete coverage by drive rolls. Continuous operation. Six-inch compacted lift.)

The maximum possible output for a 3-wheel roller may be calculated as follows:

$$\text{Maximum Output} = \frac{\text{Width of compacted strip (ft)} \times \text{Depth (ft)} \times \text{Roller Speed (ft per hour)}}{27}$$

For example, a 10-ton, 3-wheel roller equipped with 20-in. drive rolls spaced 36 in. apart, rolling with a 1-in. overlap on each side of rear roll, provides a width of compacted strip of 18 in. for each drive roll and for both rolls, a compacted strip of 3 ft. For a 6-in. (0.5-ft) compacted lift thickness one pass, and a speed of 1 mph, the

$$\text{Maximum Output} = \frac{3 \times 0.5 \times 5280}{27} = 293 \text{ cu yd per hour.}$$

Figure 23 permits rapid estimates to be made of maximum possible output. The chart is based on continuous operation. Deductions can be made for time lost. It is possible that the guide roll may for a given number of passes provide satisfactory compaction. For the roller in the example, the full width is 76 in. Effective rolling width then becomes 76 in. less overlap of about 4 in. or 72 in. This is twice the effective width of drive rolls only, and the maximum possible output per pass shown in Figure 23 is doubled.

Full-Scale Field Tests on Sheepsfoot-Type Rollers

TYPES OF SHEEPSFOOT ROLLERS

THERE IS a tendency to class all rollers with protruding feet as "sheepsfoot" rollers although some prefer to describe them as "tamping" rollers. However, the literature does make an effort to distinguish differences in different sheepsfoot-type rollers on the basis of the shapes of the feet. Some of the more commonly described types are (a) the taper foot, (b) the clubfoot, (c) the pegfoot, and (d) the sheepsfoot. The shapes of these different classes of feet are shown in Figure 24.

Manufacturers' specifications and additional data on contact unit pressures for sheepsfoot rollers employed in full-scale rolling experiments are, insofar as data permitted, given in Table 6.

FULL-SCALE TESTS ON SHEEPSFOOT-TYPE ROLLERS

There have been two extensive full-scale experimental tests of sheepsfoot rollers to determine the influence of the different variables of design on their characteristics as compactors. The Corps of Engineers performed a series of tests on large (60-in. diameter drums) rollers to determine the effect of contact area, contact unit pressure and number of passes on the dry unit weight largely on a single type of soil (46, 53, 76, 87). The British Road Research Laboratory conducted tests on 48-in.-diameter drum rollers to determine their effectiveness as compactors on several different types of soil (56). Tests of a similar nature but on a smaller scale were performed in India on alluvial soils (66) and in Sweden (80).

ROLLER MAXIMUM DRY UNIT WEIGHT VS MOISTURE CONTENT

Because moisture content (in addition to soil type and compactive effort) has so great an influence on the dry unit weight of compacted soils, engineers, following the development of the laboratory compaction test, were anxious to learn if sheepsfoot rollers would as did smooth-wheel rollers, also produce compaction curves that would be similar to those produced in the laboratory test, provided that all variables except moisture content were held constant. The first full-scale closely controlled tests (44, 46, 47, 49, 56) showed that roller-produced moisture content-dry unit-weight relationships did simulate those produced by the laboratory test in that they were similar in shape although their maximum dry unit weights and optimum moisture contents did differ in magnitude. Examples of roller-produced moisture content vs dry unit-weight relationship curves for soils fully compacted (compacted to refusal or by 64 passes) are shown in Figure 25. In addition to illustrating the effect of moisture content on dry unit weights, Figure 25 also shows the very strong effect of soil type in determining what the moisture content vs dry unit-weight relationships shall be for each soil, whether it be compacted in a mold or rolled by a sheepsfoot roller.

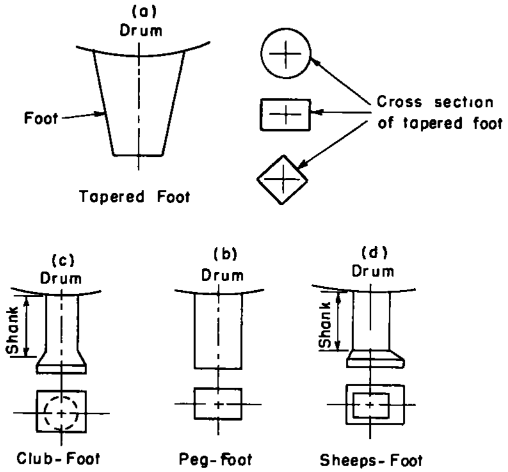


Figure 24. Sketches of different types of roller feet (not drawn to scale (59A)).

Examination of Figure 25 and comparing laboratory-produced curves with roller-produced curves on identical soils shows that

TABLE 6

CHARACTERISTICS OF SHEEPSFOOT-TYPE ROLLERS EMPLOYED IN FULL-SCALE ROLLING EXPERIMENTS

Source of Data	Dimensions of Drums		Data on Roller Feet							Gross Weights (lb)			Contact Pressure (psi)[d]		
	Length[a] (in)	Diameter[b] (in)	Type of Foot	Number per Drum	Area of Foot (sq in)	Sq in of Foot Area per sq ft of Drum Area	Foot Contact Area[m] (%) of Total Area of Cylinder Generated	Length of Feet (in)	No [c] on Ground	Empty	Loaded With Water	Loaded With Wet Sand	Empty	Loaded With Water	Loaded With Wet Sand
Indiana (Type A roller) (29)	48	40	Sheepsfoot	88	5 5	11 5	5 9	7	4	5, 100	9, 200	-	116	209[e]	-
Ohio (Type A roller) (29)	48	40	Clubfoot	88	5 5	11 5	5 9	7	4	6, 250	9, 800	-	142	223[f]	-
Corps of Engineers (44)	66	60	Sheepsfoot	120	7	9 7	5 5	7	4	10, 640	-	-	190	250[g]	450[g]
Corps of Engineers (48)	66	60	Sheepsfoot	120	7	9 7	5 5	7	4	10, 640	-	-	190	250[g]	500[g] 750[g]
Corps of Engineers (53)	78	72	Special[h]	136	9 4	10 4	4 8	18	4	9, 700	-	40, 750[g]	-	-	1, 087[g]
Great Britain (56)	48	42	Clubfoot	64	12	17 5	9 1	7	4	7, 085	10, 010	-	74	115	-
Great Britain (56)	48	42	Taperfoot	88	5 1	10 1	5 1	7 75	4	6, 115	10, 080	-	151	249	-
India (66)	48	42	Taperfoot	64	5 1	7 4	3 8	7	4	7, 940	10, 100	-	193	249	-
Corps of Engineers (76)	66	60	Sheepsfoot	120	7, 14, 21	9 7, 19 4, 29 1	5 5, 10 9, 16 4	7	4	-	-	-	-	250[e]	-
Sweden (80)	60	42	Taperfoot	120	5	10 9	5 5	7 9	5	3, 505[j]	5, 512	-	105	200	-
Bur of Reclamation (77, 92)	48-60	60 min	Variable	Note[k]	7 to 10[k]	-	-	9	2	-	-	k	-	417	-
Corps of Engineers (87)	66	60	Sheepsfoot	120	14	19 4	10 9	7	4	-	-	-	-	125[l] 375	-

[a]Length of each drum [b]Diameter of drum only [c]Per drum [d]Based on one row of feet in contact with ground [e]Loaded to 184-psi contact pressure for major portion of tests [f]Fully loaded with water in most of tests [g]Loaded with Baroid to obtain pressures shown [h]Approaches shape of section of an I-beam [i]Weight adjusted to provide constant contact pressure of 250 psi for different foot-contact areas [j]For single drum roller [k]Cross-section must be equal or less than 10 sq in at a distance of 6 in from surface of drum but not greater than 10 in at a distance of 8 in One tamper foot per 100 sq in of drum surface Weight fully loaded with sand and water not less than 4, 000 lb per foot length of drum [l]Total roller weight controlled by loading with Baroid to weights and unit pressures shown [m]Percent of total area of a cylinder generated by the limits of the faces of the tamper feet

moisture content-dry unit-weight relationships produced by the sheepsfoot roller are generally similar in shape to those produced by the standard laboratory test. However, the maximum dry unit weights, as were those produced by the three-wheel roller, bore no consistent relationship to the maximum values produced in the laboratory test, even though the conpaction effort was constant although not identical in the laboratory compaction test, and in the field rolling experiment. Peak values from the roller-produced curves in Figure 25 markedly exceed peak values from the standard laboratory compaction test for all soils except the gravel-sand-clay soil.

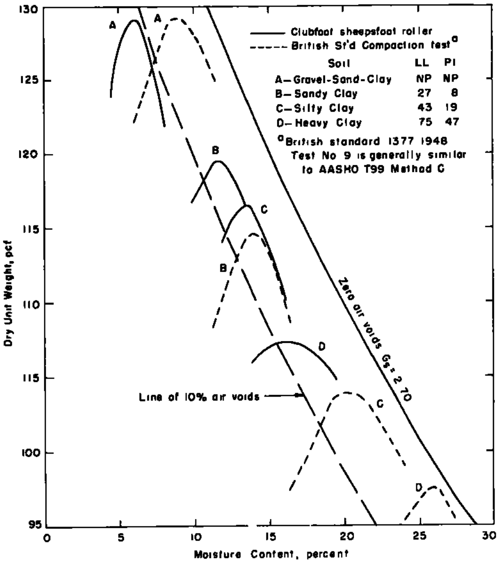


Figure 25. Comparison of roller curves for clubfoot-type sheepsfoot roller and laboratory compaction. Roller curves are for full compaction (64 passes) by roller having 12-sq in. contact area and maximum contact pressure of 115 psi (56).

The influence of changes in roller compaction effort are clearly shown in moisture content vs dry unit weight relationships in Figure 26. Any change in the roller that changes the applied compaction effort changes the moisture content-unit-weight relationships. Changes in effective contact unit pressure should produce a change in the compaction curve provided pressures are within a range where such changes actually do produce a change in compaction effort. In most cases the contact unit pressures sufficiently exceeded the bearing capacities of the soils that changes in unit pressures had little or no effect. This is discussed later under "Contact Area and Contact Unit Pressure."

Any change in the magnitude of the contact area and the number of passes produces marked changes in the roller compaction curves. These statements are verified by data shown in Figure 26 in which roller compaction curves are shown for three sheepsfoot rollers (76) equipped with tamping feet of three different contact areas. Each roller is applied in the compaction of a silty clay soil using three different numbers of passes (6, 12, and 24 passes). The contact unit pressure was constant for all rollers at 250 psi. Thus, it may be seen that the greater the contact area and the greater the number of passes the greater the compaction effort applied. Examination of Figure 26 shows that increasing the number of passes for a given area of tamper foot increases the roller-produced maximum dry unit weight and reduces the optimum moisture content. Increasing the area of the tamper foot while holding the contact unit pressure constant also increases the compaction effort. Comparison of the three sets of plots in Figure 26 shows the effect of increasing the contact area of the tamper foot.

Thus, the roller maximum dry unit weight vs moisture content curve varies according to soil type (Figure 25) and responds to compaction effort (Figure 26) in a manner generally similar to that of the laboratory compaction test. Differences that occur between field (roller) curves and laboratory curves are discussed in more detail later.

OBTAINING ROLLER CURVES FROM TEST SECTIONS

It is practicable to prepare roller compaction curves from job test sections without imposing the rigid controls necessary in a full-scale test of the type referred to here. The development of roller compaction curves involves performing a sufficient number of tests for in-place moisture content and dry unit weight after various numbers of passes on soils differing in moisture contents so the resulting data can be analyzed statistically. This involves the use of a uniform-type soil or adequate identification of soil samples by type as testing progresses. Examples of the application of statistical methods are available (92). This pertains especially to the development of roller curves from test sections. Roller curves can be developed to show graphically the variation of rolled dry unit weight from maximum laboratory dry unit weight, as well as the variance of fill moisture content from the laboratory determined optimum moisture content.

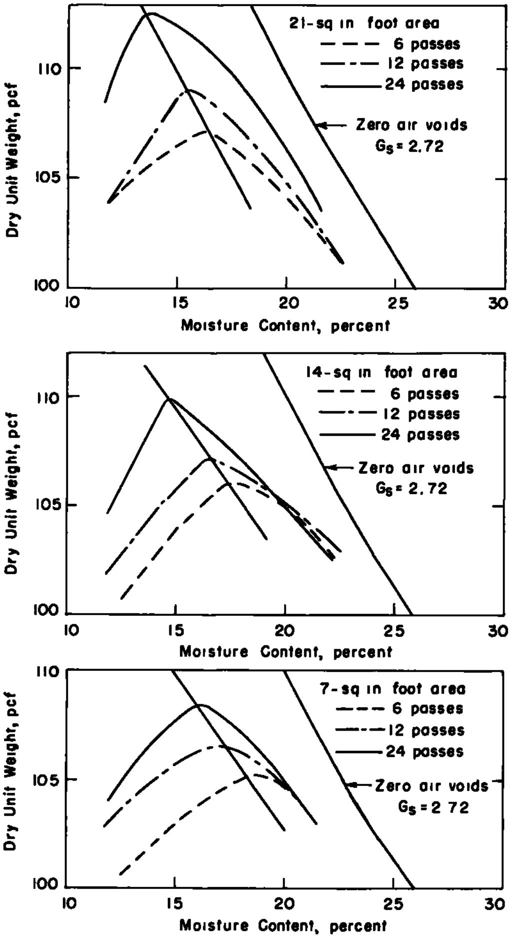


Figure 26. Roller compaction curves for a lean (silty) clay soil for sheepsfoot rollers having 7-, 14-, and 21-sq in. foot contact area, a constant maximum contact pressure of 250 psi for 6, 12, and 24 passes (76).

EFFECT OF NUMBER OF PASSES ON DRY UNIT WEIGHT

The number of passes required to attain a given unit weight depends in part on those characteristics of the roller that determine percent coverage per pass and the compaction effort per pass. These characteristics are the contact area of each tamper foot and its relation to the total area at the periphery of the feet, the contact unit pressure, and the effective or pitch diameter of the drum plus tamper feet. The number of passes required are also related to the lift thickness employed. Finally, the number of passes required are related to soil type, soil moisture content and the degree of compaction required. Because data on direct relationships of some of these factors to number of passes are not available, only the effect of soil type, soil moisture content, degree of compaction required, and the dimensions of the tamper feet on the number of passes necessary to attain compaction are discussed here. The other factors on which few data are available are discussed under "Productive Capacity (Output) of Sheepsfoot-Type Rollers."

For a given sheepsfoot roller, compacting at optimum moisture content, the soil type largely determines the number of passes required. This is well illustrated in Figure 27 which indicates the number of passes required by a clubfoot-type sheepsfoot roller having 64 tamper feet per drum, each foot having a contact area of 12 sq in. (9.1 percent of total peripheral area) and a maximum contact pressure of 115 psi (see Table 6 for data on roller).

The effect of soil type is evident directly in Figure 27 in terms of response in increase in dry unit weight with increase in number of roller passes. The effect of soil type becomes even more evident in some instances in the relative numbers of passes required to compact some soils to a given percent relative compaction when compared to other soil types. An example of this is shown in Figure 27 in comparing the numbers of passes required to compact the sandy clay and the silty clay to 95 percent relative compaction. The sandy clay was compacted to 95 percent relative compaction (109.3 pcf) in 13 passes. It required only 7 passes to compact the silty clay to 95 percent relative compaction (98.8 pcf).

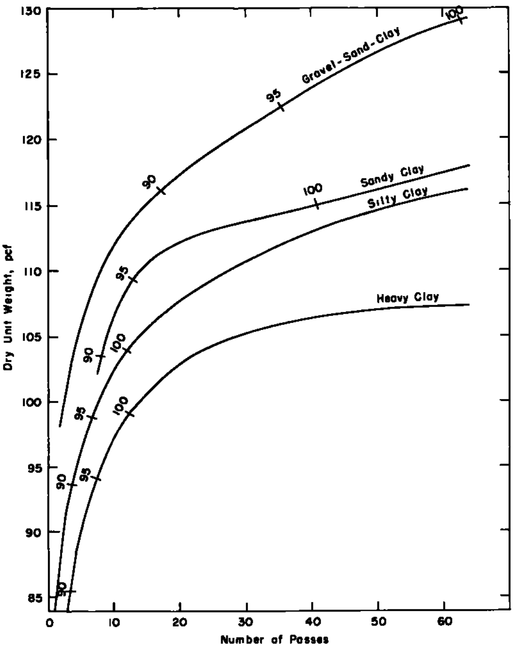
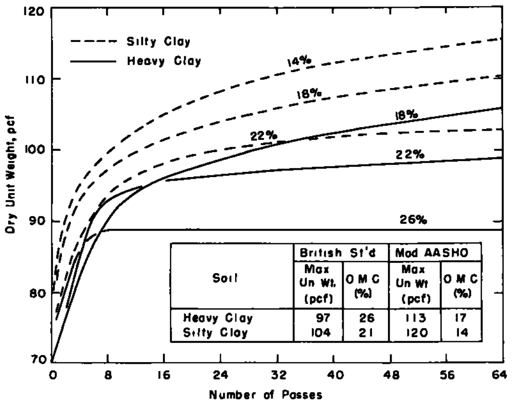


Figure 27. Number of passes of a clubfoot-type sheepsfoot roller required to compact four different types of soils to 90, 95 and 100 percent relative compaction (56).

Figure 28 illustrates that the effect of soil moisture content has a strong influence on the number of passes required by a taperfoot sheepsfoot roller having small tamper foot contact area to compact two types of soils, one a silty clay, the other a heavy clay. Increasing the soil moisture content sharply reduced the dry unit weights attained in the heavy clay. However, near maximum dry unit weights, for the moisture contents given in Figure 28, were attained after progressively lesser numbers of passes as the soil moisture content was increased. In other words, for the heavy clay rolled at 26 percent moisture content no additional gain in weight was attained after 8 passes. Contrary, approximately 95 percent relative compaction was realized after 12 passes at 22 percent moisture content (100 percent after 64 passes). As the moisture content was decreased to 18 percent, 95 percent relative compaction was attained after about 13 passes, but the maximum possible dry unit weight at full compaction increased to about 106 pcf. (Note that roller maximum dry unit weight and optimum moisture content were 107 pcf and 15 percent, re-



Soil	British St'd Max Un Wt. (pcf)	British St'd O M C (%)	Mod AASHO Max Un Wt (pcf)	Mod AASHO O M C (%)
Heavy Clay	97	26	113	17
Silty Clay	104	21	120	14

Figure 28. Relationship between dry unit weight and number of passes of a taperfoot sheepsfoot roller for two soils when compacted in 9-in. loose lifts at different moisture contents. Roller has 88 feet per drum, 5 1/16-sq in. contact area per foot and contact pressure of 249 psi when fully ballasted with water (56).

spectively). The silty clay soil followed a somewhat similar behavior pattern of number of passes vs dry unit weight with variation in moisture content (56).

The dimensions of the tamper feet (contact area) and the proportion of that total area in percent of total peripheral area generated by the faces of the tamper feet also influence the number of passes for they determine the percent of the ground surface covered by each pass of the roller and also influence the compaction effort. The relationships between maximum dry unit weight produced by the roller and number of passes are illustrated in Figure 29 for three sizes of tamper feet. Examination of Figure 29 shows that the larger the contact area the greater the dry unit weight and the lesser the optimum moisture content for a given number of passes. Also, for a given dry unit weight requirement, the smaller the foot contact area the greater the number of passes to satisfy a given dry unit weight requirement.

For example, in the left-hand plot in Figure 29, if it is desirable to compact the lean clay soil (76) to 108-pcf dry unit weight, that requirement may be satisfied by 9 passes of a 21-sq in. foot contact area roller, by 15 passes of a 14-sq in. foot contact area roller, or by 22 passes of a 7-sq in. foot contact area roller. The total peripheral areas, generated by the tamper foot for the 21-, 14-, and 7-sq in. tamper feet are 16.4, 10.9 and 5.5 percent, respectively. Contact area in percent of total area at the periphery of the roller feet is determined as follows:

$$\frac{\text{Number of feet per drum x contact area of one foot in sq in.}}{(\text{Diameter of drum in inches} + 2 \text{ x length of feet in in.}) \text{ x } (3.1416 \text{ x length of drum in in.})}.$$

It may be seen that if the contact unit pressure is held constant, increasing the contact area of the tamper foot increases compaction effort proportionately—more or less, depending on soil type and moisture content.

EFFECTS OF WEIGHTS AND DIMENSIONS OF ROLLERS

The principal sheepsfoot roller characteristics related to dimensions and weights that influence compaction are the contact unit pressure, the contact area of the individual feet, and the contact area in percent of the total peripheral area of the cylinder generated by the faces of the tamper feet.

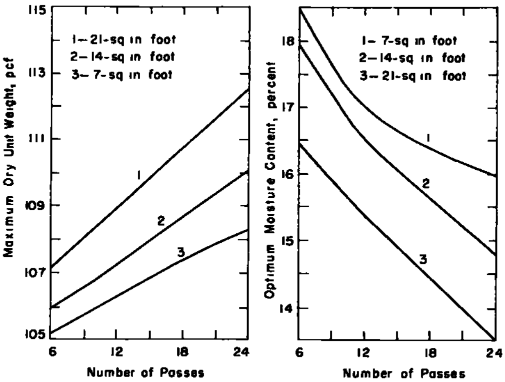


Figure 29. Effect of contact area of foot and number of passes of sheepsfoot roller on unit weight and optimum moisture content for the roller. Soil is a lean (silty) clay (LL = 38, PI = 18). Unit contact pressure 250 psi, AASHO and Modified AASHO maximum unit weights are 107.9 and 117.8 pcf (76).

CONTACT UNIT PRESSURE

The contact unit pressure for a sheepsfoot roller is determined by dividing the total weight of the roller (empty or loaded depending on how it is used) by the product of the number of feet in one row and the contact area per tamper foot. Thus contact unit pressure is an arbitrary maximum unit pressure and may bear no relationship to the unit pressures actually impressed on the soil.

Rollers built in the 1950's provided for increasingly greater unit pressures. Users hoped or expected that the use of greater pressures would hasten compaction and produce greater unit weights. A number of closely controlled full-scale experiments were conducted to measure the effect of total pressure and unit pressure applied by tamper feet (44, 46, 53, 76, 87). One series performed on a clayey sand (LL = 18, PI = 2) (44) employed unit pressures of 250 and 450 psi on a tamper foot having a contact area of 7 sq in., and also employed the same lift thickness and number of passes. There resulted, for practical purposes, no difference in dry unit weight. In a second series (46), unit pressures of 250, 500, and 750 psi were produced by the same roller (by loading with Baroid) and applied in compacting a silty clay (LL = 37, PI = 14). The roller had 120 ft per drum, each foot having a contact area of 7 sq in. The results of these tests are shown in Figure 30. Examination of Figure 30 shows that only minor differences occurred in maximum dry unit weight and optimum moisture content for the three different unit pressures, although the same lift thickness and number of passes were employed in each test.

A third series of tests (87) was performed on a similar soil (a lean clay having a LL = 36, PI = 15) from the same general area. This test was performed with a roller also equipped with 120 ft but each foot having a contact area of 14 sq in. Twelve passes were applied. Two unit pressures (125- and 375-psi) were employed. Again, there was no difference in maximum dry unit weight.

In addition to the foregoing tests similar tests were performed in Great Britain (56) employing lighter-weight rollers having unit pressures of 115 and 249 psi. (Tamper foot areas were 12 and 5.06 sq in. and total contact areas in percent of the periphery generated by the face of the tamper feet were 9.1 and 5.1 percent, respectively.) Here again, the maximum dry unit weights produced by the two rollers were in every instance equal or differed by less than one percentage unit (of laboratory maximum dry unit weight) for a given soil type. Because of the interest in the effect of contact unit pressure as an influencing factor in soil compaction it is believed worthy of reproducing in tabular form the results of the described tests.

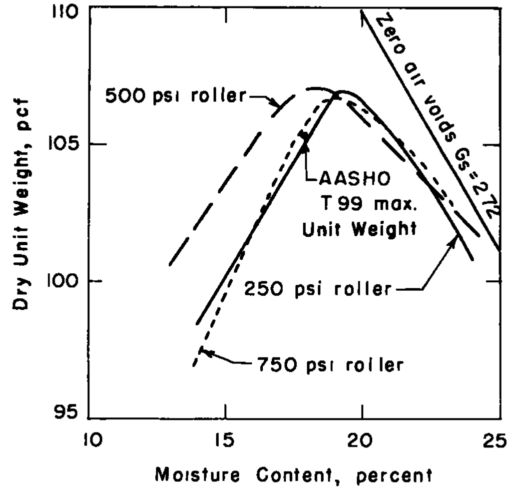


Figure 30. Roller compaction curves on a silty clay soil. Unit weights measured for 12- to 21-in. depth in a 4-ft fill. Sheepsfoot roller had 120 feet per drum, 7-sq in. contact area and was loaded to produce maximum contact pressures of 250, 500 and 750 psi (46).

Table 7 shows that for a given soil and for the range of foot contact area and number of passes observed in the tests, doubling or tripling the contact unit pressure had small, if any, influence on roller compacted dry unit weights. This statement apparently holds for a wide range of soil types as is indicated by the range for which data were provided in Table 7. Thus, unit pressure when adequate, has small influence on soil compacted near optimum moisture content. Unit pressure appears from Figure 30 and also from graphical representation of data from other tests (44, 87) to have little or no effect at moisture contents several percentage units wet or dry of optimum.

Data are insufficient to define the lowest unit pressure that will satisfactorily compact a soil in lifts of nominal thickness to the required unit weight because contact area is also a factor that cannot be entirely separated from unit pressure (Fig. 26). However, for the soils given in Table 7 it is apparent that a unit pressure of the order of 115 to 150 psi should be adequate to provide compaction for rollers with small tamper foot area. Pressures of a greater range may be desirable for larger foot areas especially when compacting soils dry of optimum or soils that otherwise depend on internal friction for bearing capacity.

TABLE 7

THE EFFECT OF CONTACT UNIT PRESSURE ON MAXIMUM DRY UNIT WEIGHT (FROM ROLLER COMPACTION CURVES)

Source Reference	Soil Type	Contact Area of Each Foot (sq in.)	Contact Unit Pressure (psi)	Compacted Lift Thickness (in.)	Number of Passes	% of Mod AASHO Max Density	% of AASHO T 99 Max Density
44	Clayey sand	7	250	6	9	94	99
44	Clayey sand	7	450	6	9	93-95	99
46	Silty clay	7	250	6	6	92	102
46	Silty clay	7	500	6	6	91-92	101
46	Silty clay	7	750	6	6	91-92	101
87	Lean clay	14	125	6	12	93	101
87	Lean clay	14	375	6	12	93	101
56	Heavy clay	12	115	6[a]	64	92	108
56	Heavy clay	5.06	249	6[a]	64	92	108
56	Silty clay	12	115	6[a]	64	97	112
56	Silty clay	5.06	249	6[a]	64	96	111
56	Sandy clay	12	115	6[a]	64	93	104
56	Sandy clay	5.06	249	6[a]	64	94	104
56	Gravel-sand-clay	12	115	6[a]	64	94	100
56	Gravel-sand-clay	5.06	249	6[a]	64	93	99

[a] 9-in. loose lifts which produced compacted lifts approximately 6 in. thick.

CONTACT AREA

The influence of contact area on the compaction characteristics of a roller has been discussed under "Effect of Number of Passes on Dry Unit Weight." The families of roller curves produced at a constant unit pressure of 250 psi by varying the contact area (and number of passes) is illustrated in Figure 26 and in the plots showing the relationship between number of passes and maximum dry unit weight shown in Figure 29. If the contact unit pressure is not kept constant as in the tests described (76), then adjusting the contact area is a means for adjusting contact unit pressure. It is also a means for changing percent coverage; that is, the percent of the total ground area traversed by the roller that comes into contact with the tamper feet with each pass of the roller. For soils developing most or all of their strength through friction the unit bearing capacity decreases with decrease in size of loaded area. Thus, a small variation in size of loaded area (even if unit pressure is constant) may represent a substantial variation in bearing capacity.

Figure 29 shows that increasing the foot size can increase the compacted dry unit weight for a given number of passes or decrease the number of passes and increase the productivity of rollers in a lean clay soil over that obtained with smaller size tamper feet. The area of the tamper foot should be as large as practicable and yet be compatible with adequate unit pressure and proper spacing for cleaning purposes.

SPACING OF FEET

For a given size foot, decreasing the spacing between feet increases the percent coverage per pass and reduces the number of passes to obtain coverage. Percent coverage may be determined as follows:

$$\text{Percent Coverage} =$$

$$\frac{\text{Number of feet per drum x contact area of one foot expressed in sq in.}}{(\text{Diameter of drum in in.} + 2 \text{ x length of (feet) in in.}) \text{ x } 3.1416 \text{ x length of drum in in.}} \text{ x } 100$$

Increasing the spacing also increases the unit pressure. There is a limit to the closeness of spacing of tamper feet that is dictated in part by contact unit pressure and in part by the ability of the roller to keep itself clean. Without doubt, self-cleaning feet can be designed that can be spaced more closely and that can be shaped to better conform with contact area requirements and yet enter and withdraw from the soil easily and thus permit higher travel speeds.

EFFECT OF SPEED OF TRAVEL ON COMPACTED DRY UNIT WEIGHT

Only two experimental projects included observations on the effect of speed of travel of sheepsfoot rollers on compacted dry unit weights. Data from one of these (29) indicated some reduction in dry unit weight in increasing the roller speed from 200 fpm to 350 fpm. However, the results were inconclusive. In a second study (36) sheepsfoot rollers were operated at 2 and 5 mph (176 and 440 fpm) in compacting a sandy clay soil. The roller was a taperfoot type having 88 feet per drum, each tamper foot having a contact area of 5.06 sq in. Tests were made at numbers of passes up to 32. At no number of passes did the difference in compacted dry unit weight for the two speeds differ by more than one pcf.

DEPTH OF COMPACTION BY SHEEPSFOOT-TYPE ROLLERS

The depth of compaction by sheepsfoot-type rollers in commercially manufactured weights and sizes has been measured under several different conditions. These include measurement of unit weights (a) at different intervals in a compacted lift of nominal thickness (for example a 6-in. thick compacted lift); (b) at various depths in thick lifts (up to 5 ft thick) initially placed in a loose state; and (c) measurement of dry unit weights that result from adding and compacting overlying lifts as in constructing embankments. In addition, sheepsfoot rollers specially designed with long feet and great foot contact unit pressures have been constructed for the purpose of increasing the dry unit weight of natural subgrade soils or the upper portions of previously constructed fills.

TABLE 8

COMPARISON OF DRY UNIT WEIGHTS IN UPPER TWO-THIRDS AND IN LOWER ONE-THIRD OF SHEEPSFOOT ROLLER COMPACTED LIFTS (56)

Soil Type	Depth[a] (in.)	Sheepsfoot Roller[b] Clubfoot Dry Unit Wt (pcf)	Sheepsfoot Roller[b] Taperfoot Dry Unit Wt (pcf)
Heavy clay	0-4	107	107
	4-6	94	94
Silty clay	0-4	116	115
	4-6	95	103
Sandy clay	0-4	119	120
	4-6	95	108
Gravel-sand-clay	0-4	129	128
	4-6	129	110

[a] Depth in inches below surface of compacted lift.
[b] See Table 6 for data on sheepsfoot rollers.

An early test on a sandy clay (36) showed that the dry unit weight of a sheepsfoot roller compacted soil exhibited a relative compaction of approximately 100 percent near the surface but a relative compaction of only 90 percent at a depth of 4 in. This no doubt prompted a second series of tests on four soils compacted by two different types of sheepsfoot rollers (clubfoot and taperfoot) (56). This test also exhibited rather large differences in dry unit weights between the upper two-thirds and lower one-third portions of a 6-in. compacted lift (Table 8). These data exhibit decrease in unit weight for the clubfoot-type roller for the bottom 2 in. of the compacted lift for all but the gravel-sand-clay soil but somewhat lesser differences for the taperfoot-type roller. These values are for lifts that were 9 in. thick before being compacted.

Tests have also been performed by compacting thick loose lifts (80) to determine the effective depth of compaction under these conditions. Tests were performed on a morainic soil and on a mo (fine sand and silt) soil by a taperfoot-type roller having 120 tamper feet per drum, each foot having a contact area of 5 sq in. and a total contact area of 5.5 percent of the total area generated by the periphery of the face of the feet. Two of the soils were compacted at unit pressures of 200 psi, and a third at 105 psi. The results of the tests are shown in Figure 31. Examination of the results shows very small decrease in unit weight for these dominantly sandy soils for about the top 10 in. of compacted depth for the 200-psi roller but marked decrease in unit weight for the 105-psi roller below a depth of about 4 in. Percent compaction in Figure 31 is in percent of Modified AASHO maximum dry unit weight.

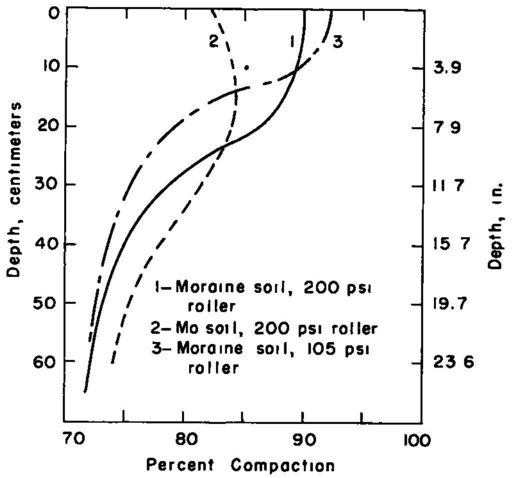


Figure 31. Relationship between depth of compaction and percent of Modified AASHO maximum unit weight when fully compacted by a taperfoot-type sheepsfoot roller with feet having contact area of 5 sq in. and maximum contact pressure of 105 psi empty and 200 psi loaded. Mo and moraine soils have 40 and 52 percent passing the No. 200 sieve, respectively (80).

Engineers have long been concerned about the effect of sheepsfoot roller compaction on the unit weights of the underlying lifts. In compacting a 5-ft test embankment of a clayey sand (44) in 6-in. compacted lifts, it was found that there resulted a slight increase in dry unit weight of the underlying lifts. The roller had a foot area of 7 sq in. and a maximum unit pressure of 250 psi. Maximum dry unit weights were 114.5 pcf at an 18-in. depth, 113.2 pcf at 12 in., and 112.4 at a depth of 6 in. The roller compaction curves of the lifts nearer the surface were more rounded in the vicinity of optimum than those for underlying lifts. A similar trend was found for construction lifts for the 450-psi roller. The increase in unit weight and nature of the curves at different depths for the 250-psi roller are shown in Figure 32. The depth effect did not extend below 18 in.

Deep compaction of subgrades in cut sections, in shallow fill sections or at grade points, or deep compaction of old fills that are inadequately compacted to satisfy current design requirements are problems confronting engineers. In only one instance has a sheepsfoot roller been expressly designed to accomplish these purposes (53). Tamping feet 18 in. long with a 9.4-sq in. foot contact area were attached to a drum 78 in. long and 72 in. in diameter. Loaded, the roller produced a maximum unit pressure of 1,087 psi.

The roller was tested in (a) a natural (Vicksburg, Miss.) clayey silt (LL = 37, PI = 12) subgrade; (b) in a clayey sand (LL = 18, PI = 2) previously constructed subgrade (44) that had been rolled by a 250-psi sheepsfoot roller; and (c) a loose silty clay fill constructed for the tests.

The natural subgrade had a natural dry unit weight of 84 percent of Modified AASHO at the surface decreasing to 74 percent at 5 ft. An increase in unit weight of 2½ to 5 pcf was attained for depths of 12 to 20 in., the top 12 in. being left in a loose state. The previously constructed clayey sand fill (44) was subjected to 18 passes of the 1,087-psi roller, increasing the dry unit weight over that previously obtained with the 250-psi

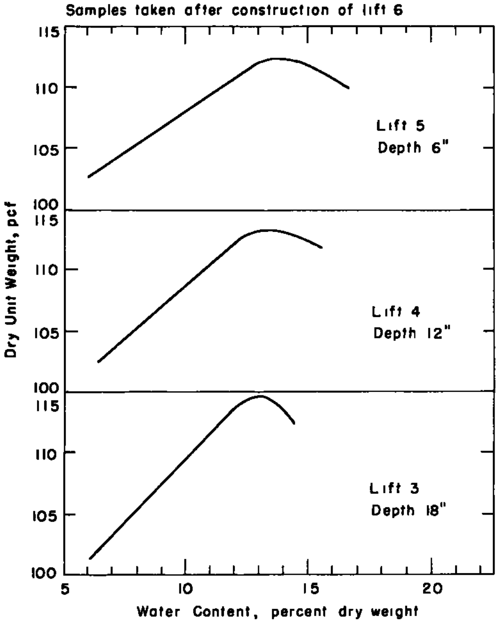


Figure 32. Typical moisture content-unit weight data showing increase in unit weight and "sharpening" of peaks of curves for lifts 3 and 4 following construction of lifts 5 and 6. Each lift was compacted by 9 passes of sheepsfoot roller having contact area of 7 sq in. and contact pressure of 250 psi. Soil is a clayey sand (LL = 18, PI = 2) (44).

roller for a depth of 18 to 54 in. The maximum dry unit weight attained by the 1,087-psi roller was 99 percent of Modified AASHO at a depth of 51 in. compared to 94 percent obtained with the 250-psi roller. In increasing the dry unit weight a family of compaction curves for various numbers of passes was developed. The 4-ft-high loose silty clay fill constructed for the tests, was subjected to 0, 6, 12, and 18 passes of the 1,087-psi roller. A substantial increase in dry unit weight occurred from a depth of 12 in. downward throughout the fill, the maximum increase being 11 pcf. The final dry unit weight ranged from 78 to 84 percent of Modified AASHO maximum. These values are much lower than those for the previously compacted fill suggesting that precompaction to a certain minimum may be necessary to absorb the energy provided by the heavy roller as is advocated by proponents of stage compaction. Typical dry unit weight gradients with depth and relationships with numbers of passes and dry unit weight are shown in Figure 33.

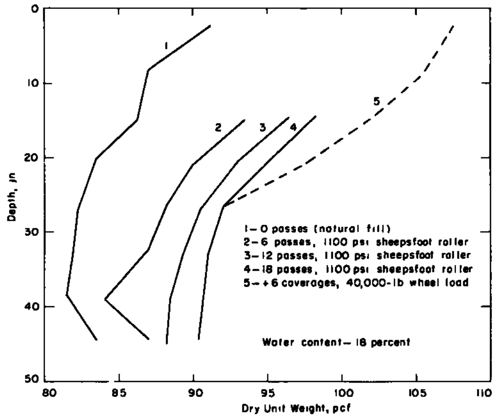


Figure 33. Effect of number of passes on dry unit weight at various depths in a 4-ft loose silty clay fill by a 1,100-psi sheepsfoot roller and by a 40,000-lb wheel load (53).

In summarizing "Depth of Compaction by Sheepsfoot Rollers," it may be said that some engineers are not in agreement that a marked disparity in dry unit weight should occur between the upper and lower portions of a compacted lift. The claim has often been repeated that a sheepsfoot-type roller compacts from the bottom upwards, as it "walks up" or "walks out" in the rolling process. However, for any load on the earth's surface, the unit pressure diminishes with depth. All other types of compactors exhibit decrease in dry unit weight with depth.

BOND BETWEEN LIFTS

The occurrence of "compaction planes," laminations, or other smooth surfaces within or between construction lifts resulting directly from a tamper foot, or a tire, or a smooth-wheel roller has been of some concern to engineers. This is especially true in compacting certain types of stabilized bases. Efforts have been made to insure against their occurrence near the surface (by sacrifying) where they might otherwise result in raveling or spalling. Some experimenters have commented on this occurrence in or between earthwork construction lifts in fine-grain soils. In rolling tests (87) on a lean clay soil (LL = 36, PI = 15), the soil was compacted by a sheepsfoot roller equipped with tamper feet of 14-sq in. contact area per tamper foot. Maximum unit pressures were 125 and 375 psi. A good bond was obtained between the drier lifts in all test sections compacted by sheepsfoot rollers. In sections where the soil was wet of optimum, slight laminations were noticed.

It is held (98) that laminations in a compacted soil are produced primarily by excessive "springing" of the lift under compacting equipment regardless of type, and that excessive occurrence of laminations occurred in a sheepsfoot compacted loess fill in which the soil was deliberately compacted at two percentage units on the wet side of optimum. However, tests showed that shear strength and permeability along the laminations were not significantly different from those at right angles or diagonal to the laminations. In other observations (92) it was found that a tendency existed for the tamping feet to mask the boundary between successive layers. Compaction by sheepsfoot rollers on the dry side of optimum results in the absence of smooth surfaces between layers. A number of local shear surfaces were encountered in the backfilled cutoff trench of a certain dam foundation. (Soil, a clayey loess, LL = 28, PI = 10, 95 percent pass No. 200 sieve, G_s = 2.67, maximum dry unit weight 106.5, OMC = 18, Proctor penetration = 700 psi.) However, these surfaces were found only in samples compacted wet of optimum.

The aforementioned accounts of observations indicate the occurrence of laminations or smooth surfaces that could have some detrimental effect, has been limited to soils compacted at moisture contents considerably in excess of optimum.

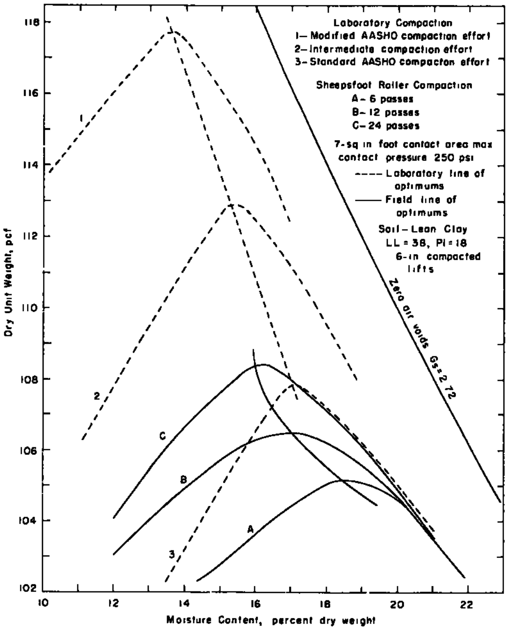


Figure 34. Comparison of lines of optimum moisture content from laboratory compaction (in 6-in. diam. molds) with those obtained from full-scale tests on a sheepsfoot roller having 7-sq in. foot contact area and contact pressure of 250 psi (76).

COMPARISON OF RESULTS OF SHEEPSFOOT ROLLER AND LABORATORY IMPACT COMPACTION

In most instances roller compacted dry unit weights are compared with dry unit weights from the laboratory compaction tests. This is also true of optimum moisture contents. One reason for this is lack of adequate data on which to base other comparisons. First of all, it must be recognized that comparison is being made between impact compaction and a "kneading" compaction. Much study has been given to the relative effects of the two types on the properties of soils but for reasons of selection of scope of subject matter those findings are not given here. Second, laboratory compaction is done in a cylinder in which the soil is in much greater restraint or interference than in rolling. In fact, the restraint is no doubt so great that the measured dry unit weight may include not only a permanent residual compression but for some clays, some elastic compression as well. Sidewall interference no doubt prevents some lateral movements to provide the maximum dry unit weight for some gravelly soils, while the effect of an impact blow on cohesionless soils in so shallow a layer must certainly prevent effective compaction. Layers in the compaction test are shallow permitting rapid expulsion of air. Roller compaction is in thicker lifts tending to make air release slower. Be all these items as they may, in any instance there exists a disparity between laboratory and field results that differs with soil type.

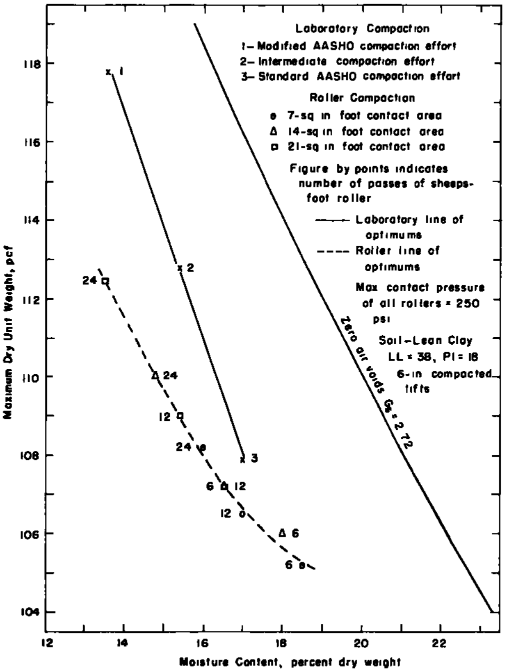


Figure 35. Comparison of lines of optimum moisture content from laboratory compaction (in 6-in. diam. molds) with those obtained from full-scale tests on sheepsfoot rollers. Field compaction efforts resulted from applying 6, 12, and 24 passes of rollers having 7-, 14-, and 21-sq in. contact area and constant maximum contact pressure of 250 psi (76).

Comparison between laboratory and field results can be made on the basis of simple comparison of field values in terms of laboratory values (percent relative compaction). This comparison becomes most useful when it includes both dry unit weights and optimum moisture contents. Other comparisons can be made in terms of comparable compaction efforts required to obtain in field rolling a dry unit weight equivalent to 100 percent (or some other percentage) of laboratory maximum dry unit weight.

There are few comparisons between laboratory and sheepsfoot roller compaction more revealing than a simple comparison of their moisture content-dry unit-weight relationships. Consider the roller compaction curves and laboratory compaction curves for the lean clay shown in Figure 34 (76). The dashed lines represent laboratory compaction curves for (a) the Modified AASHO compaction effort; (b) an intermediate effort; and (c) the AASHO T 99 effort. The line drawn through their optimum moisture contents represents the optimum that might be expected for a range of compaction efforts.

The three solid line compaction curves represent 6, 12, and 24 passes of a 250-psi roller having a contact area of 7 sq in. on each tamper foot. Note that the roller optimum for a given dry unit weight is less than for the laboratory test and also that about 22 passes (Fig. 29) were required to attain a dry unit weight equal to the maximum dry unit weight from the AASHO T 99 test. A graphical summary of maximum dry unit weights from 6, 12, and 24 passes of rollers having 7-, 14-, 21-sq in. foot contact areas compared directly with maximum dry unit weights and optimum moisture contents for three laboratory compactive efforts is shown in Figure 35. All of the foregoing tests were performed with dual-drum sheepsfoot rollers in which each drum was 66 in. wide, 60 in. in diameter, each was equipped with 120 tamper feet per drum, and loaded to a constant contact unit pressure of 250 psi (Table 6).

From these data it is evident that the limiting rolled dry unit weight for 24 passes is only slightly greater (100.3 percent) than AASHO T 99 maximum unit weight. However, examination of Figure 29 and Figure 35 shows that equipping the roller with larger foot contact area permits compaction to maximum dry unit weights up to 104.3 percent of AASHO T 99 maximum although at a roller optimum somewhat less than laboratory optimum. The above comparisons have been made for a single type soil, a lean (silty) clay that lies about midway in the range of compactibility between a heavy clay and a sand.

Similar observations of test results have also been made on four types of soils (56). Separate lines through points of maximum dry unit weight and optimum moisture content are shown in Figure 36 for four different soil types for both the standard and the modified laboratory tests. Roller compaction was "full" compaction by means of a clubfoot-type roller having a tamper foot area of 12 sq in. and a maximum contact unit pressure of 115 psi. Figure 36 shows that the roller optimums lie on the curve for the standard test whereas roller optimums for the clay and the gravel-sand-clay were dry of laboratory optimum, indicating lower roller optimums for those soils. (Results from the taperfoot roller (5$\frac{1}{16}$-sq in. foot area and 249-psi maximum contact pressure) were almost identical to results from clubfoot-type roller.) Figure 36 shows that field values for full compaction are greater than laboratory values indicating the greater compactive effort by the roller.

When data on drawbar pull are available, they furnish a means for comparing the relative effort required to compact a soil in the field with that required in the laboratory test. Proctor (41, 42) held that drawbar pull ranged from 25 to 40 percent of the weight of the roller, the smaller value applying to the lighter textured sandy (and presumably silty) soils. For example, for the silty clay (76) the drawbar pull based on a value of 25 percent would be 250 psi x 7 sq in. x 4 feet in a row x 2 drums = 14,000 lb, 14,000 lb x 0.25 = 3,500 lb drawbar pull. If 22 passes were required to attain 100 percent of AASHO T 99 maximum dry unit weight, the field compactive effort would be

$$\frac{3,500 \times 22 \times 2 \text{ (6-in. layers to make 1 ft of depth)}}{11 \text{ (roller width)}} = 14,000 \text{ ft lb/cu ft}$$

which does not differ significantly from the value of 12,375 ft lb/cu ft compactive effort in the AASHO T 99 laboratory compaction test.

Measurements of drawbar pull were made in another series of tests (56) by measuring power input into an electric moter (of known efficiency) employed in towing the sheepsfoot rollers. Drawbar pulls were measured (a) during the first pass with the soil at approximately the highest moisture content employed in the tests; and (b) after 12 passes with the soil at about roller optimum moisture content. Values of drawbar pull were of the order of about 10 percent of the roller weight for (a) and about six percent for (b). It seems entirely reasonable to use values midway between (a) and (b) to represent the average drawbar pull during compaction of a soil. On that basis the roller compactive efforts needed to attain 100 percent of maximum dry unit weights as determined by the standard test are as given in Table 9.

It is possible that the values of drawbar pull given in Table 9 may, because of test conditions, be somewhat lesser than would be encountered in normal field construction. In any instance the drawbar pulls given in Table 9 show marked differences in the field compaction efforts required to compact the soils to a required percent relative compaction. Similar data prepared for the taperfoot roller showed that the silty clay required the least effort, then the heavy clay, the sandy clay and the gravel-sand-clay in that order.

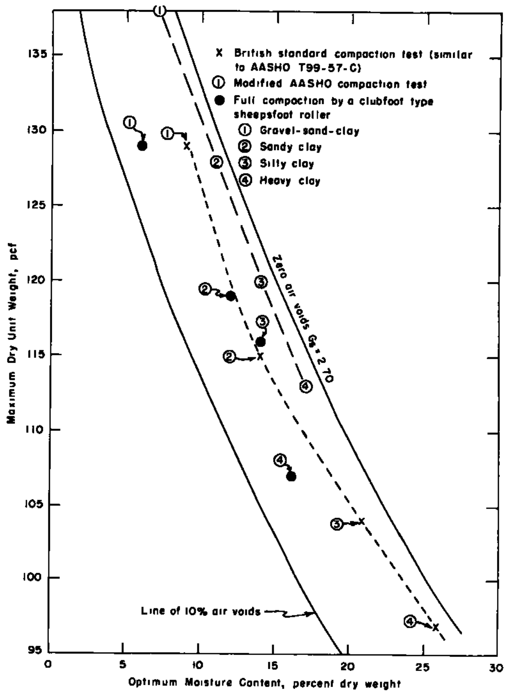


Figure 36. Comparisons of maximum dry unit weights and lines of optimum moisture contents from roller and laboratory compaction curves. Roller of clubfoot type, 12-sq in. foot contact area and 115-psi maximum contact pressure. Rolling to full compaction (56).

TABLE 9

COMPARATIVE DRAWBAR PULLS REQUIRED FOR A SHEEPSFOOT ROLLER[a] TO ATTAIN 100 PERCENT RELATIVE COMPACTION (56)

Soil Type	Drawbar Pull (lb)	No. of Passes to Attain 100% Relative Compaction	Roller Compactive Effort (ft lb/cu ft)
Heavy clay	795	10	1,987
Silty clay	775	13	2,519
Sandy clay	680	38	6,460
Gravel-sand-clay	930	64	14,880

[a] Clubfoot type—12-sq in. foot area, 115-psi contact pressure.

No other comparison between field rolling results and results of laboratory tests is as useful as comparison of actual rolled unit weights and moisture contents with those determined by the laboratory test. This is especially true if the records are extensive, and are carefully kept for a variety of soil types and conditions. Engineers of the Bureau of Reclamation—Esmiol (77) and Holtz (92)—have reported on the use of their sheepsfoot roller (see Table 6) in the construction of 39 earth dams, representing about 50 million cu yd of impervious material compacted by a roller designed to satisfy Bureau requirements. Some 28,000 in-place unit-weight tests were analyzed. A summarization of the data reported by the Bureau of Reclamation is made here according to soil type to show the relation between average soil moisture content and average variation from laboratory optimum, and variation in dry unit weight from dry unit weight at fill moisture contents, as well as variation from laboratory maximum dry unit weight. The results are summarized in Table 10.

Table 10 shows that all fine-grained soils were rolled to average dry unit weights within the range of +0.2 and -0.5 pcf of laboratory maximum dry unit weight. All soils of the fine-grained groups (CL, SM, ML, and SC groups of the Unified Classification) were compacted at average moisture contents ranging from 0.8 to 1.7 percentage units dry of optimum. Nevertheless the fine-grain soils produced average dry unit weights ranging from 1.3 to 2.7 pcf greater than laboratory dry unit weight at fill moisture content. The coarser-grained soils of the GC, GC-SC, GM, and GM-SM groups produced dry unit weights about 2.5 pcf less than laboratory maximum although they were compacted at moisture contents more closely approaching laboratory optimum. The compaction effort of the Bureau of Reclamation laboratory test method is equivalent to that of AASHO T 99 (12,375 ft lb/cu ft). (The report (92) provides data indicating 90 percent confidence limits, and also includes data on standard deviation for the three principal items in Table 10 for the soil in each dam.)

FACTORS INFLUENCING THE PRODUCTIVE CAPACITY (OUTPUT) OF SHEEPSFOOT ROLLERS

The output of a sheepsfoot roller depends on its compaction characteristics as well as on its operating characteristics. The compaction characteristics are those attributes inherent to the roller that determine the dry unit soil weights it can produce under certain limiting conditions. They include diameter and width of drum, size of and spacing of tamping feet, foot contact pressure and how effective these items are in compacting different soil types.

The operation of a roller, the lift thickness, whether or not precompaction is employed, the degree of compaction required, the speed of travel, the manner in which the operators dump, spread and roll before soil drying interferes with compaction, the manner and degree of moisture control (prewetting in cut or borrowpit or sprinkling in the fill) individually and collectively determine output in terms of cubic yards of soil compacted per hour. It is obvious that all of these factors cannot be evaluated

TABLE 10

RESULTS OF SHEEPSFOOT ROLLER COMPACTION ON 38 DAMS CONSTRUCTED BY THE BUREAU OF RECLAMATION (92) (COMPACTION RESULTS ARE BASED ON THE MINUS NO. 4 FRACTION)

			Dry Unit Weight (pcf)	
Soil Type	No. of Dams Having Soils in Group	Avg Moisture Content, w. Variation from Laboratory Optimum (% of dry Weight)	Avg Variation From Laboratory Dry Unit Weight At Fill Moisture Content	Avg Variation From Lab. Maximum Dry Unit Weight
CL (inorganic clays of low to medium plasticity, gravelly, sandy, silty and lean clays)	12	-1.7	+2.7	-0.5
SM (silty sands and poorly graded sand-silt mixtures	7	-1.8	+2.3	+0.3
ML (inorganic silts and very fine sands, rock flour, and silty and clayey fine sands with slight plasticity)	5	-1.4	+1.3	-0.4
SC (clayey sands, and poorly graded sand-clay mixtures)	9	-0.8	+1.6	+0.2
GC and GC-SC (clayey gravels and poorly graded sand-clay mixtures)	3	-0.5	+1.1	-2.5
GM and GM-SM (silty gravels, and poorly graded gravel-sand-silt mixtures)	2	-0.2	-0.7	-2.4

in terms of direct influence on productive capacity of the roller. Therefore only those items on which some data have been produced are discussed in detail here.

Compaction Characteristics

Contact Unit Pressure and Contact Area.—The minimum foot contact unit pressure that can be used has not been established for various contact areas for various soil types. Results indicate that excessive pressures in several hundreds of pounds per square inch are not only not necessary but may be detrimental to high output especially if small tamper feet are employed. In any instance, the contact pressure should be as great as the bearing capacity of the soil will permit. If the contact pressure is too great, the roller simply sinks deeper, placing more feet in contact with the soil (and even the drum if necessary) to reduce the unit pressure to that which can be accommodated by the soil. Thus there is an upper or maximum contact pressure for effective rolling. This can be judged if the roller "walks out;" that is, sinks less deeply with increase in number of passes. Perhaps "walks up" is a more fitting description. Rollers that "walkup" so the feet penetrate 20 to 50 percent of their length do not have excessive contact pressure.

The roller having the largest tamping foot area and a spacing yielding the largest percentage of coverage of the periphery generated by the feet, also yields the greatest percent coverage and thus should require the smallest number of passes. Thus it should produce the greatest output, provided the roller has adequate contact pressure and can be kept clean when rolling wet soils containing roots, etc. However, for soils developing most or all of their strength through friction, the unit bearing capacity decreases with decrease in the size of the loaded area. Thus, for sandy soils, a small variation in contact area (if the unit pressure is constant) may represent a substantial variation in the load the soil will support. It has been shown (76) that increasing the size of the foot can increase the soil dry unit weight for a given number of passes, or decrease the number of passes and increase the productivity of rollers in silty clay soils over that obtained with a smaller tamper foot. The size of the tamper foot should be as large as is practicable and yet compatible with adequate contact pressure and proper foot spacing for cleaning purposes.

It is obvious that the percent coverage per pass influences the number of passes required. Coverage is determined by the area of the tamper foot and the relationship of that area to the total area of an imaginary cylinder generated by the periphery at the face of the feet. Insofar as is known, only one study has been made (56) to determine both by actual measurement and by computation using statistical methods, the percent coverage by two sheepsfoot rollers having different numbers of feet per unit of drum area, and different sizes of tamper feet. For the actual measurements, a fine tilth of moist soil about 1 in. thick was placed on an area having a compact surface. The roller was then operated over the surface and observations of percent coverage made after various numbers of passes. This was done for a taperfoot roller (42-in. diameter drums, 48 in. long, 88 feet per drum, $5\frac{1}{16}$-sq in. tamper foot area) and for a clubfoot roller (same size drums but with 64 feet per drum and a foot contact area of 12 sq in.). After observing the actual percent coverage in rolling, computations of the coverage that might be expected from true random rolling were made. The results are given in Table 10A.

TABLE 10A

COVERAGE OBTAINED IN ROLLING FOR DIFFERENT NUMBERS OF PASSES OF TWO SHEEPSFOOT ROLLERS (56)

Number of Passes	Clubfoot Coverage (%) Observed in Rolling	Clubfoot Coverage (%) Computed for Random Rolling	Taperfoot Coverage (%) Observed in Rolling	Taperfoot Coverage (%) Computed for Random Rolling
4	35	32	20	19
8	63	53	36	34
16	83	78	57	56
32	94	95	80	81
64	98	100	91	96

It may be seen from Table 10A that the tests on the clubfoot roller with the 12-sq in. foot contact area (the 64 feet occupied 9.1 percent of the peripheral area generated by the face of the feet) effected a coverage of 63 percent in 8 passes compared to 36 percent for the taperfoot roller. Were it possible to prevent duplication of coverage, the clubfoot roller would have covered 8 x 9.1 = 72.8 percent of the area in 8 passes and 100 percent in 12 passes and the taperfoot 8 x 5.0625 = 40.5 percent of the area in 8 passes and 100 percent in 19.75 passes.

Soil Type.—In only one series of tests (56) were sheepsfoot rollers tested on several types of soil to determine values that would be indicative of output. Here the two types of rollers previously described were employed on each of four types of soils. The clubfoot-type roller had a unit pressure of 115 psi. The taperfoot roller had a unit pressure of 249 psi. The numbers of passes of the two types of rollers necessary to compact a

9-in. loose lift to 95 and 100 percent of standard compaction are indicative of the relative difficulty of compacting these different soil types with the two types of rollers employed. The relative numbers of passes required are given in Table 11. The relative compaction efforts computed from drawbar pull required to compact to 100 percent relative compaction are given in Table 9.

TABLE 11

NUMBER OF PASSES REQUIRED TO ROLL FOUR TYPES OF SOIL TO 95 AND 100 PERCENT RELATIVE COMPACTION IN 9-IN. LOOSE LIFTS AT ROLLER OPTIMUM MOISTURE CONTENT (56)

Soil Type	No. of Passes Required to Obtain Relative Compaction (%)	Clubfoot Roller	Taperfoot Roller
Heavy clay	95	6	13
	100	10	24
Silty clay	95	7	7
	100	13	15
Sandy clay	95	14	19
	100	38	44
Gravel-sand-clay	95	32	28
	100	64	64

It is not surprising that the silty clay compacted "easier" than did the heavy clay for the taperfoot roller, but it is somewhat unexpected that the heavy clay required lesser numbers of passes of the clubfoot roller than did the lighter textured silty clay. Sandy clays are apparently difficult to compact, a high number of passes being required to attain 100 percent relative compaction. Comparison of results of nine passes of a 250-psi roller on a clayey sand (44) showed a maximum dry unit weight of 98.5 percent whereas six passes of the same roller on a silty clay (46) yielded a maximum dry unit weight equivalent to 101.9 percent of AASHO T 99 maximum dry unit weight.

Dimensions of the Roller.—The greater the width of the roller the greater is the volume of compacted soil. However, it is believed that the diameter of the drum has influence on the rolling radius or pitch diameter. Shape of feet may also have some influence. Usually the greater the diameter of the drum the greater is the ease of manipulation. The longer the tamper feet, the greater is the permissible lift thickness although length of tamper feet and lift thickness are limited by other factors.

Effective or Pitch Diameter, Rolling Radius.—The effective diameter of a roller is determined by the number of revolutions of the roller to traverse a given distance. Observations (46) have shown that effective diameter is greater than the over-all diameter (diameter of drum + 2 x length of foot). This indicates that the roller slides forward slightly while being towed. Some determinations of effective diameter made during rolling tests on a lean clay (76) are given in Table 12. The drum of the roller was 60 in. in diameter. Metal plates welded to the feet to increase contact area account for the difference in foot length. Measured over-all diameters for the different foot sizes and values of effective roller diameters are given in Table 12.

The data in Table 12 indicate that at the 6th pass the effective diameter was slightly greater than the over-all diameter of the roller when equipped with the 7-sq in. feet and considerably greater than when equipped with the 14- and 21-sq in. feet.

The maximum effective diameter occurred when the roller was equipped with 14-sq in. feet. The effective diameter decreased with an increase in number of passes. For the range of foot contact areas and number of passes tested, the maximum increase above the over-all diameter was about 8 percent, an amount that may significantly influence output.

TABLE 12

EFFECTIVE ROLLER DIAMETER FOR THREE FOOT SIZES AFTER 6, 12, 18, AND 24 PASSES (76)

Contact Unit Pressure (psi)	Foot Contact Area (sq in.)	Foot Length (in.)	Measured Overall Roller Diameter (in.)	Effective Roller Diameter			
				6th Pass	12th Pass	18th Pass	24th Pass
250	7	7.0	74	75.0	74.1	73.8	73.5
250	14	7.375	74.75	80.6	79.5	77.7	76.9
250	21	7.625	75.25	78.3	77.7	76.5	76.2

Roller Walkout.—Differences of opinion exist among engineers and also among contractors concerning the desirability for a sheepsfoot roller to "walkout," particularly as it concerns output. Insofar as is known, only the Bureau of Reclamation has recorded data based on a qualitative description of the amount of roller walkout and its influence on compaction. For example, if the roller feet penetrated the lift at least 4 in. less on the 12th pass than during the first pass it was considered to have "walked out" and designated by the word "yes" in Table 13. If the walkout was less than 2 in. the notation "no" was made. Walkout of between 2 and 4 in. was designated by the word "some."

TABLE 13

COMPARISON OF AVERAGE RESULTS OF COMPACTION FOR THREE DIFFERENT DEGREES OF ROLLER WALKOUT (92) (COMPACTION RESULTS BASED ON MINUS NO. 4 FRACTION)

Moisture Content, w, Variation from Laboratory Optimum (% of Dry Weight)		Dry Unit Weight (pcf)				
		Variation from Lab. Dry Unit Weight at Fill Moisture Content		Variation from Lab. Maximum Dry Unit Weight		
Average[a] $\bar{X}$	Standard Deviation σ	Average[a] $\bar{X}$	Standard Deviation σ	Average[a] $\bar{X}$	Standard Deviation σ	Roller Walkout
-1.7 ± 0.15	1.60	+2.0 ± 0.39	4.00	-1.2 ± 0.39	4.11	Yes
-0.9 ± 0.14	1.44	+1.0 ± 0.39	3.79	-0.5 ± 0.39	3.83	Some
-1.48 ± 0.10	1.82	+1.8 ± 0.16	2.83	0.0 ± 0.18	3.10	No

[a] The ± entry indicates 90 percent confidence limits.

An effort was made to determine if any strong trend in degree of compaction was associated with roller walkout. Average values of variation of moisture content from optimum; variation of dry unit weight from laboratory unit weight at fill moisture content; and variation of dry unit weight from laboratory maximum dry unit weight, were determined for each of the three degrees of roller walkout. Those averages and variance from those averages within 90 percent confidence limits are given in Table 13. Although the moisture content and variation in dry unit weight at fill moisture content are not significantly different for the three degrees of walkout, the variation in dry unit weight from laboratory maximum dry unit weight is different. It shows the smallest average variation from laboratory maximum and smallest standard deviation when "no" roller walkout is recorded.

"No" roller walkout was recorded for four dams, each constructed of the ML group (inorganic silts and very fine sands and silty or clayey sands with slight plasticity). Eighteen dams were reported as showing "some" roller walkout. The soils were 3-CL, 4-SM, 2-SM-SC, 1-SC-SM, 1 SC, 2 ML, 1 ML-CL, 1-GM, 1-GC-SC, 1-GM-SM. Twelve dams were reported showing the maximum walkout (the "yes" group). The soils in these dams were 6-CL, 3-SC, 2-SM and 1-GC-SC. Average values of plasticity index for the "yes," "some," and "no" groups were 12.0, 4.4, and 2.1, respectively.

The differences in variation from laboratory dry unit weights associated with degree of sheepsfoot roller walkout are very small. Walkout alone cannot be a satisfactory measure of compaction efficiency. A very light roller having contact unit pressure markedly less than the bearing capacity of the soil would walk out quickly and leave a soil of low compaction. However, the values of contact unit pressures at which this would occur are not known. Walkout has one advantage in that it is said to require less drawbar pull than a roller with no walkout.

The preceding discussion has pertained to the compaction characteristics of sheepsfoot rollers to indicate how those characteristics might influence output. The output of a roller depends heavily on how it is operated. If for example, the tamping feet are spaced so they "track" (fall into the same depressions from previous trips) during successive passes, the operator has but little choice in routing his travel so this cannot occur. Few rollers are operated at the optimum lift thickness for the roller and the soil type; that is, the lift thickness at which compaction is adequate and maximum output occurs. That is a problem of trial and error that can be solved only by a cooperative team of inspector and operator.

Insofar as is now known increasing the speed of travel does not result in commensurate reduction in compacted unit

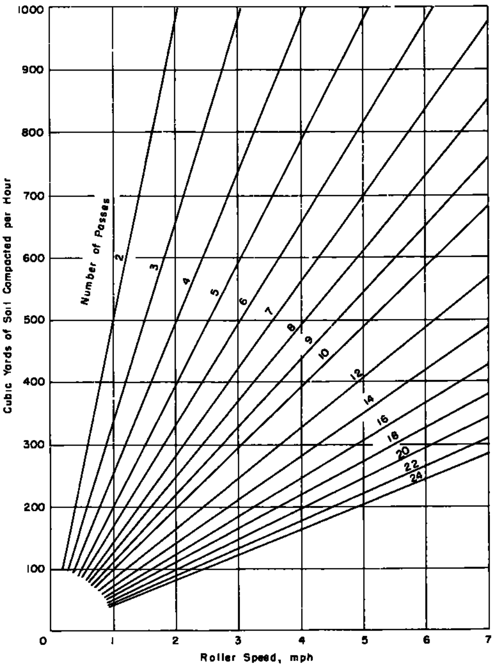


Figure 37. Maximum output of a sheepsfoot roller. (Based on a 10-ft compacted width, 6-in. compacted lift and continuous operation with no overlap.)

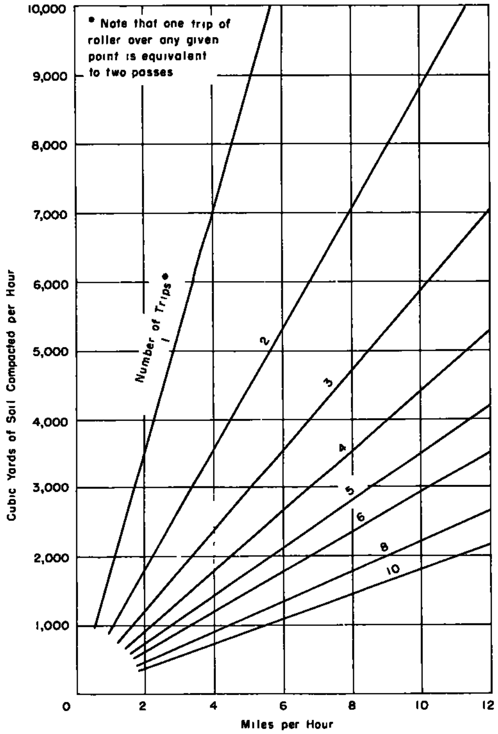


Figure 38. Maximum possible output for self-propelled sheepsfoot roller having two pairs of 6-ft drums in tandem. Output is based on 12-ft wide compacted strip of 9-in. compacted depth, continuous operation with no allowance for overlap.

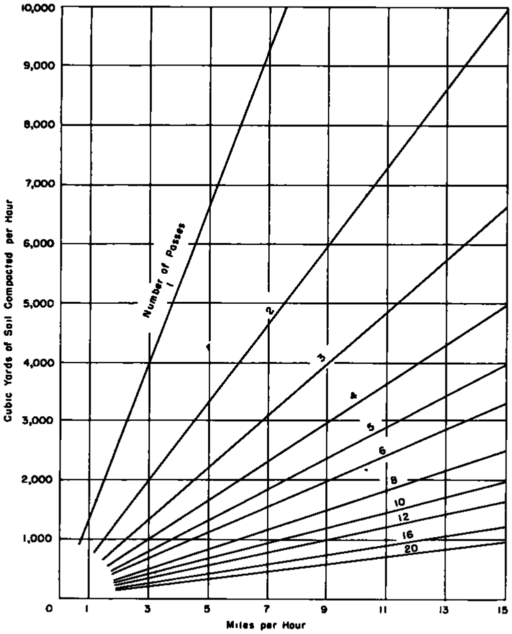


Figure 39. Maximum possible output of a tamping-type roller which is claimed to be designed for high-speed operation. Output is based on a strip 10 ft 2 in. wide of 8-in. compacted depth, continuous operation with no allowance for overlap.

weight, therefore an increase in speed of travel means a gain in output. Some sheepsfoot rollers are specifically designed for increased speed. This of course involves smoothness of spread as well. If soils are difficult to compact due to roller sinkage, some light precompaction may aid.

The one single greatest influence on output is moisture content. Its use and economy of use may markedly alter the final cost. Finally, due to rapid developments in equipment, attention needs to be given to the type of equipment that is best suited to the job. It should be kept in mind that there is no one universal machine that provides the highest unit weights and does so at the least cost for all types of soils and conditions.

For a roller having given characteristics the maximum possible output may be calculated as follows:

$$\text{Output (cu yd/hr)} = \frac{\begin{array}{c}\text{Width of roller in feet}\\ \text{x speed in ft per hr x}\\ \text{thickness of lift in feet}\end{array}}{\text{Number of passes x 27}}$$

For example, for a roller compacting a strip 10 ft wide, traveling 3 mph, and rolling a lift of 6 in., compacted thickness to satisfactory density in 8 passes.

$$\text{Output (cu yd per hr)} = \frac{10 \times 3 \times 5280 \times 0.5}{8 \times 27} = 367$$

A chart showing maximum output for a towed-type roller compacting a strip 10 ft wide, 6 in. deep and operating continuously, is shown in Figure 37. A similar chart has been drawn for a self-propelled roller equipped with two pairs of dual six-foot drums compacting a 12-ft strip 9 in. deep, and based on continuous operation with no overlap (Fig. 38). A third chart has been prepared for another type of self-propelled tractor-roller unit whose manufacturers claim it is designed for high-speed (up to 15 mph) operation (Fig. 39).

Full-Scale Field Tests on Pneumatic-Tired Rollers

TYPES OF ROLLERS TESTED

FIRST AMONG the types tested were the 9-, 11-, and 13-wheel two-axle lightweight rollers (29, 36, 44, 56, 57, 66, 80, 127, 129). These rollers were usually equipped with 7.50 x 10, 7.50 x 15, 10.50 x 20 or 11.00 x 12 tires with a rated tire inflation pressure ranging between 25 and 35 psi. These included the "standard" and also the "wobble-wheel" lightweight rollers and were used in compacting earthwork and granular base courses. A very few were equipped with tires permitting pressures of 50 psi or more.

During the early 1940's heavier rollers permitting heavy wheel loads at moderately high tire pressures were not available for study with regard to the needs for greater wheel loads and tire inflation pressures anticipated for airfields planned and under construction. This necessitated that the Corps of Engineers (44, 46, 47, 53) adapt tractors and earth hauling equipment (mainly loaded Tournapull-scraper combinations) as "rollers" having wheel loads and tire-inflation pressures greater than employed heretofore. These tests employing haul equipment were followed by a series of tests by the Corps of Engineers (87, 100, 95) and by the British Road Research Laboratory (127, 129) employing medium weight and heavy weight pneumatic-tired rollers in which tire inflation pressures ranged from 80 to 150 psi. Information on the individual rollers insofar as data are available, are given in Table 14.

ROLLED MAXIMUM DRY UNIT WEIGHT VS MOISTURE CONTENT

The first pneumatic-tired rollers consisting of the lightweight two-tandem axle multiple-wheel type were tested widely on a number of different soils. With the exception of some very limited testing by the Corps of Engineers (44) and the Swedish Road Institute (80) performed at a nominal number of passes, the remainder of the testing was at "full compaction" for the roller; that is, the soil was rolled to refusal or by 32 or 64 passes of the roller. Also, a large proportion of the tests were performed at a loose lift thickness of 9 in. which the results show was obviously too great a lift thickness for producing the greatest dry unit weight and likewise not the most desirable lift for economical operation for the lightweight units.

The roller-dry unit weight vs moisture content curves were not unlike those produced by other rollers or by laboratory tests except that they produced maximum dry unit weights at slightly different optimum moisture contents. The principal data from the tests are reproduced here in tabular form to indicate the practical limitations of this group of rollers. Standard laboratory maximum dry unit weight, and optimum moisture content, and test data for these lightweight rollers in terms of wheel load, tire inflation pressure, lift thickness, numbers of passes and roller maximum dry unit weight (in percent of AASHO T 99 maximum dry unit weight) are given in Table 15.

It is significant from the data presented in Table 15 that the Clinton clayey sand (44) was compacted by a nominal number of passes (6) in a 3-in. compacted lift and yet attained a relative compaction of about 100 percent of AASHO T 99 maximum dry unit weight. This verifies a fact known to many that lightweight equipment can attain satisfactory results if proper lift thickness and moisture content are employed. Except for the Swedish tests (80), the remaining Indian (66) and British (56, 127) tests were performed on the 9-in. loose lift thickness almost universally used to provide a 6-in. compacted depth. The low tire inflation pressure of 25 psi was evidently inadequate in the Indian tests to attain a dry unit weight of 100 percent of British standard maximum except for the non-plastic sand. The Swedish tests were admittedly performed on lifts

TABLE 14

CHARACTERISTICS OF PNEUMATIC-TIRED ROLLERS USED IN FULL-SCALE ROLLING EXPERIMENTS

			Data on Roller Dimensions			Data on Roller Weights and Pressure Intensities					
						Gross Weights			Tire Pressure and Contact Area		
Source of Data	Reference Number	Type of Roller	Rolling Width (in)	Tire Size and Ply Rating (in) (no)	Center to Center Wheel Spacing (in.)	Per Inch of Tire[a] Width (lb)	Roller[b] Weight (lb)	Wheel Load[b] (lb)	Inflation Pressure (psi)	Contact Pressure (psi)	Contact Area (sq in)
Indiana-Ohio tests	29	9-wheel, two-axle	60			225	13,500[c]	1,500[c]	35		
Corps of Engineers	44	13-wheel, 2-axle wobble wheel					19,440	1,495	40		
Corps of Engineers	44	4-wheel super C tournapull					80,000	20,000	55	65	308
Corps of Engineers	44	32-cu yd tournapull					160,000	40,000	57	69	580
Corps of Engineers	46	DW-10 tractor[d]						10,000	60	64	155
Corps of Engineers	47	8-cu yd tournapull	{21.00 x 24 (front)			28,000	7,000	45		
Corps of Engineers	47	8-cu yd tournapull		16.00 x 21 (rear)			60,000	15,000	38-45		
Corps of Engineers	47	"Large" tournapull		30 00 x 40			140,000	35,000	45		
Corps of Engineers	47	"Large" tournapull		30 00 x 40			240,000	60,000	45		
British Road Res. Laboratory	56	9-wheel, two-axle	82	11 00 x 12	18		26,880	2,987	36	39	
Australia Country Roads Board	57	11-wheel, two-axle					18,350	1,668	50		
India Central Road Res Inst	66	13-wheel, two-axle	102	10.50 x 20			18,565	1,428	25		
Swedish Road Institute	80	13-wheel, two-axle		7.50 x 15			30,953	2,381	35		
Swedish Road Institute	80	5-wheel, two-axle	76 8	17 00 x 16 - 10	28.6		55,115	11,023	43		
Corps of Engineers	87	4-wheel		18.00 x 24	28⅞		63,500	15,875	50	52	305
Corps of Engineers	87	4-wheel		18.00 x 24	28⅞		100,000	25,000	90	82	305
Corps of Engineers	87	4-wheel		16.00 x 21	26		125,000	31,250	150	120	260
Corps of Engineers	100	4-wheel		e	e		100,000	25,000	90	e	e
Corps of Engineers	95	4-wheel		18 00 x 24[f]	f		100,000	25,000	90	82	305
Corps of Engineers	95	4-wheel		16 00 x 21[f]	f		125,000	31,250	150	120	260
British Road Res Laboratory	127	9-wheel, 2-axle	82	11.00 x 12 - 5	18		26,880	2,985	36		
British Road Res. Laboratory	127	9-wheel, 2-axle	84	9 00 x 20 - 14	18		44,800	4,978	80		
British Road Res Laboratory	127	4-wheel	93	16 00 x 21 - 36	30[g] 18		44,800	11,200	90		
British Road Res. Laboratory	127	4-wheel	93	16 00 x 21 - 36	30[g] 18		44,800	11,200	140		
British Road Res Laboratory	127	4-wheel	93	16 00 x 21 - 36	30[g] 18		89,600	22,400	90		
British Road Res Laboratory	127	4-wheel	93	16 00 x 21 - 36	30[g] 18		89,600	22,400	140		
British Road Res. Laboratory	129	4-wheel	93				100,800	25,200	140		

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[a] Per inch of tire width in contact with the ground. [b] Weights used in tests. [c] Total weights not given but assumed to be 60 in. wide x 225 lb per inch of tire width = 13,500 lb. [d] Load furnished by rear wheels of a DW-10 tractor [e] Although the report does not state values, they are assumed to be similar to those for the 90-psi roller previously described. [f] Assumed to be the same as for the 90- and 150-psi rollers previously described [g] 30-in. applies to outer pair and 18 in. applies to inner pair

TABLE 15

TEST RESULTS ON LIGHTWEIGHT PNEUMATIC-TIRED ROLLERS

Soil Types	Reference No.	AASHO T 99 or Its Near Equivalent		Wheel Load (lb)	Tire Inflation Pressure (psi)	Lift Thickness[a] (in.)	No. of Coverages	Maximum Percent Relative Compaction from Roller Compaction Curve (%)	Roller OMC (%)
		Max. Dry Unit Wt (pcf)	OMC (%)						
Clinton Clayey sand	44	116.2	11.5	1,495	40	3-C	6	99.7	12.3
India Clayey soil	66	124	10	1,428	25	9-L	64	89.1	12.0
India Silty soil	66	121	11.4	1,428	25	9-L	64	96.3	8.3
India Sandy soil	66	120.5	11.0	1,428	25	9-L	64	93.4	11.0
India sand	66	101	15.5	1,428	25	9-L	64	99.5	11.0
Swedish moraine	80	128.5	8.2	2,381	35	29.6-L	6	81.9	-
Swedish mo	80	122.6	11.8	2,381	35	29.6-L	6	83.8	-
British Heavy clay	127	99.8	22.8	2,985	36	9-L	32	100.9	23.2
British Silty clay	56	104.0	21.0	2,985	36	9-L	64	100.0	20.0
British Sandy clay	127	109.4	16.5	2,985	36	9-L	32	101.2	17.8
British Well-Graded Sand	127	124.4	10.2	2,985	36	9-L	32	101.9	9.7
British Gravel-sand-clay	127	129.5	9.2	2,985	36	9-L	32	102.1	8.2

[a] C = compacted, L = loose.

of excess thickness. The British test data (scaled directly from roller compaction curves) show that 100 percent of the British standard maximum dry unit weight (similar to AASHO T 99 Method C) can be attained by 32 passes or less of the lightweight roller on a 9-in. loose lift. From this it appears that 100 percent of standard dry unit weight may not have been attained at a nominal number of passes normally employed in earthwork construction. It would have been of interest to have observed the number of passes vs maximum dry unit weight for thicknesses less than 9 in. for these lightweight rollers.

During the early testing it was believed that the wheel load had substantial influence on compaction. Accordingly, inasmuch as heavy rollers were not available, three "rollers" of different wheel loads (44) were selected for test on a clayey sand soil. They were (a) a 13-wheel "wobble wheel," 1,495-lb wheel load two-axle-type roller with 40-psi tire inflation pressure; (b) a 20,000-lb wheel load on a 4-wheel Super C Tournapull with tire inflation pressure of 55 psi; and (c) a 40,000-lb wheel load on a 32 cu yd Tournapull with a tire inflation pressure of 57 psi. The 1,495-lb roller was tested with 6 coverages on 3-in. compacted lifts (Table 15) and the others were tested with 4 coverages on 6-in. compacted lifts. The two heaviest of the rollers should have applied about the same unit pressure to the surface and differences in stresses at a 6-in. depth should have been small. Only at greater depths should the increased stresses due to weight have resulted in increased pressures and correspondingly increased unit weights. The results of these experiments are shown in Figure 40 where it may be seen that the magnitude of the wheel load has small influence on either the maximum dry unit weight or the optimum moisture content for the thickness of the lift employed.

A comparison of dry unit weights at various depths in the embankment revealed that slightly greater dry unit weights (for the 1,495-lb roller) were encountered in the lifts immediately below the surface indicating an effect from the compacting of the superimposed layers. A similar gradient was incountered in the embankments compacted by the sheepsfoot rollers. However, the increases were limited to the upper 18 in. of the compacted embankment.

The experience in rolling the clayey sand (44) led to another and similar series of tests on a loessial silty clay soil (46) (LL = 37, PI = 14). Here wheel loads of 10,000, 20,000, and 30,000 lb having tire inflation pressures of 60, 55, and 57 psi, respectively, were applied in six coverages in constructing a test fill of 6-in. compacted lifts. The soil moisture contents closely bracketed AASHO T 99 optimum. The results are given in Table 16. Here again, the experiments resulted in almost identical maximum dry unit weights resulting from the rolling with the 10,000-, 20,000-, and 30,000-lb tire loads having almost identical tire inflation and measured contact pressures.

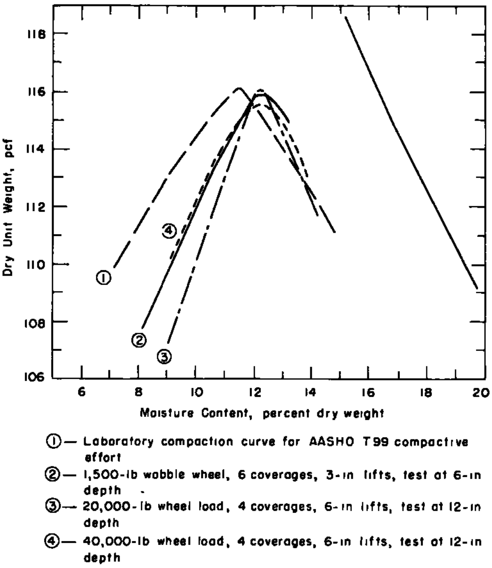


Figure 40. Comparison of roller compaction curves for different weights of pneumatic-tired rollers for a Clinton, Miss. clayey sand (LL=18, PI=2). Tire inflation pressures for 1,500-, 20,000-, and 40,000-lb wheel loads are 40, 55, and 57 psi, respectively (44).

Following these preliminary tests a third series (87) of experiments was performed in which wheel loads, number of coverages and inflation pressure were the principal variables. The soil was a lean clay similar to that used in previous tests (46). A four-wheel roller was fitted with 18.00 x 24-in. tires for the 15,875-lb wheel load and 50-psi inflation pressure and the 25,000-lb wheel load and 90-psi inflation pressure. Tires 16.00 x 21 in. were employed for the 31,250-lb wheel load and 150-psi tire inflation pressure tests.

The families of roller compaction curves for the three wheel loads, and three tire inflation pressures and for three different numbers of coverages are shown in Figure 41. Here it may be seen that increasing the roller compaction effort by increasing the contact unit pressure and number of coverages results in increasing the maximum dry unit weight and decreasing the optimum moisture content in a manner quite similar to that which takes place on increasing the compaction effort in the laboratory compaction test. The influence of the magnitude of the wheel load is discussed under "Depth of Compaction."

During rolling operations (87) noticeable rutting or springing did not occur under a wheel load of 15,875 lb and 50-psi inflation pressure except in the unit rolled wet of optimum. Slight movement occurred during the fourth coverage (8th pass). (The term "springing" as used here indicates an elastic behavior where the soil compresses under load and rebounds as the load moves forward.) Springing increased with increase in coverages until the material was "spongy" after 16 coverages. Action under the 90-psi loading was generally similar to that for the 50-psi loading. In the 150-psi unit some springing occurred at or slightly wet of optimum. In the test units 4 to 5 percentage units wet of optimum, material was moving from 4 to 6 ft in front and 1 to 2 ft at the side of the roller.

The relationships between wheel load, tire inflation pressure, lift thickness, number of coverages, and moisture content hold for all types of soil—or for that matter for crushed rock. Therefore it is of interest to include data on pneumatic-tire rolling of crushed rock of high stability (100). An example of the influence of these variables on dry unit weight is summarized in part in Figure 42. This figure shows (a) the results of the Modified AASHO laboratory compaction test; (b) the dry unit weight-moisture content relations observed in rolling by a 25,000-lb wheel load with a tire inflation pressure of 90 psi in lifts of 4-in. compacted thickness (in other words the roller compaction curve); and (c) the results of traffic compaction by 500 coverages of a 50,000-lb wheel load roller having a tire inflation pressure of 200 psi. Note: in Figure 42 the

TABLE 16

WHEEL LOADS, TIRE PRESSURES, AND ROLLER COMPACTION IN CONSTRUCTING FILLS OF SILTY CLAY IN 6-IN. COMPACTED LIFTS (46)

Wheel Load (lb)	Tire Inflation Pressure (psi)	Measured Contact Pressure (psi)	Contact Area (sq in.)	Number of Coverages	AASHO T 99 Test Data: Maximum Dry Unit Weight (pcf)	AASHO T 99 Test Data: OMC (%)	Roller Compaction Data: Max Dry Unit Wt in % of AASHO T 99 Max	Roller Compaction Data: OMC (%)
10,000	60	64	155	6	105.3	17.9	102.3	19.5
20,000	55	65	308	6	105.3	17.9	102.9	19.6
30,000	57	69	580	6	105.3	17.9	103.5	19.3

very marked increase in dry unit weight for any moisture content for the roller with the higher inflation pressure.

The maximum dry unit weight in the rolling tests (100) occurred at the maximum moisture content, which represents a "flushed" condition. If the percentage of fines is adequate this develops a "slush" of fines on the surface as in rolling waterbound macadams having adequate fine aggregate content (screenings). This excess moisture content is permissible where the subgrade soil is of a type in which the water (from the "flushed" condition) will not have a deleterious effect, or where the subgrade is adequately protected.

Recent tests have been completed in Great Britain (127, 129) on medium weight (22.4-ton) and heavy weight (50.4-ton) pneumatic-tired rollers (Table 14). Four soils were employed in recent tests and retests were made on a lightweight roller (Fig. 11). The rollers were tested to full compaction at 32 passes. The maximum dry unit weight vs optimum moisture content relationship for the 36-psi, 2,985-lb wheel load; the 80-psi, 4,978-lb wheel load; the 90-psi, 11,200-lb wheel load; and, the 140-psi, 22,400-lb wheel load are shown in Figure 43.

These data illustrate the effect of not only tire inflation pressure, but in the case of

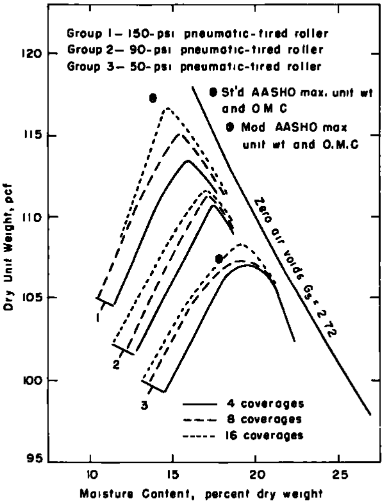


Figure 41. Roller compaction curves for 4, 8 and 16 coverages of pneumatic-tired rollers having wheel loads of 15,785, 25,000 and 31,250 and tire inflation pressures of 50, 90, and 150 psi, respectively, on 6-in. compacted lifts of a lean clay soil (LL=36, PI=15). (Note: Two passes required for one coverage.) (87)

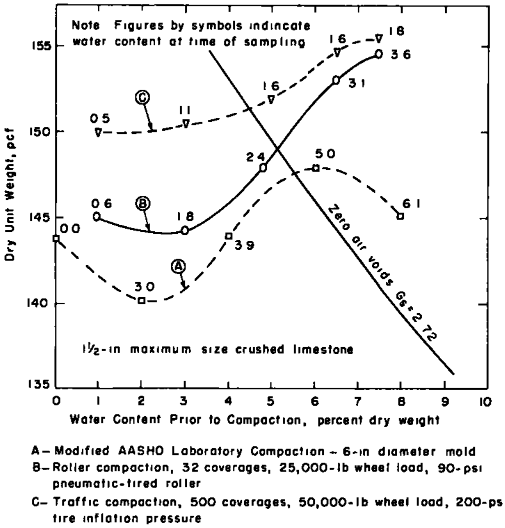


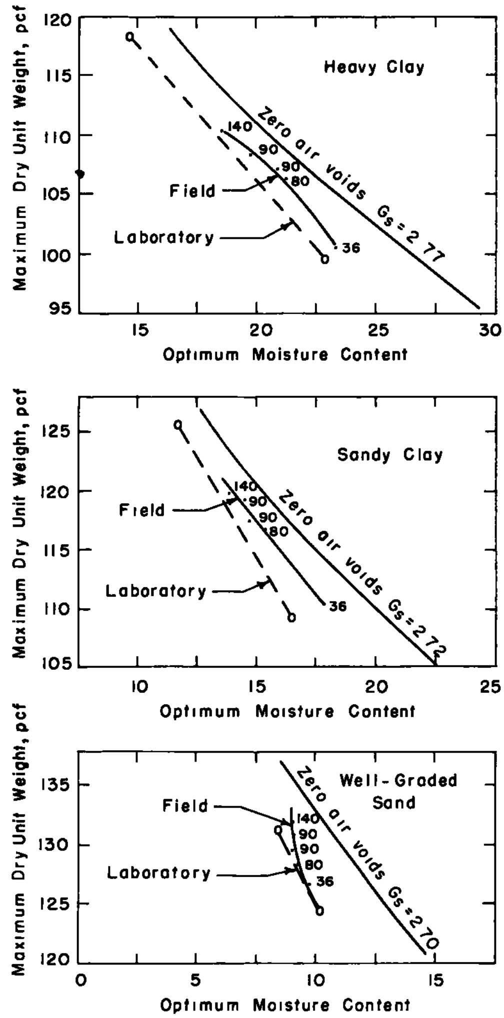
Figure 42. Comparison of field and laboratory compaction data for a $1\frac{1}{2}$-in. maximum size crushed limestone base course. The base course was covered with a double asphaltic surface treatment prior to commencement of traffic. (Note: Data on specific gravity not available. Value of 2.72 selected arbitrarily to indicate approximately the line of saturation for water content prior to compaction. Roller wheel load 25,000 lb.) (100)

the 90-psi tire inflation pressure, the effect of increasing the wheel load from 11,200 to 22,400 lb. As the tire inflation pressure is increased, the maximum dry unit weight is also increased with a reduction in optimum moisture content.

The effect of increasing the wheel load and tire inflation pressure is greatest on the clayey soils and least on the well-graded sand. At moisture contents wet of optimum the difference in state of compaction produced by rollers of different weight and tire pressure tends to decrease with increase in moisture content. Thus, there is no gain in employing heavy rollers for fine-grained soils wet of optimum. It is usually not possible to operate heavy pneumatic-tired rollers with high inflation pressures on uniformly (one-size) graded non-cohesive sands and other poorly graded non-cohesive soils. Pressures as low as 25 psi with wheel loads as low as 1,500 lb are sometimes necessary on these soils if rutting and tracking are to be prevented. Stage compaction using light rollers followed by heavier equipment may be employed to advantage. Vibration may be an effective method for compacting these light textured soils.

EFFECT OF NUMBER OF PASSES OR COVERAGES ON DRY UNIT WEIGHT

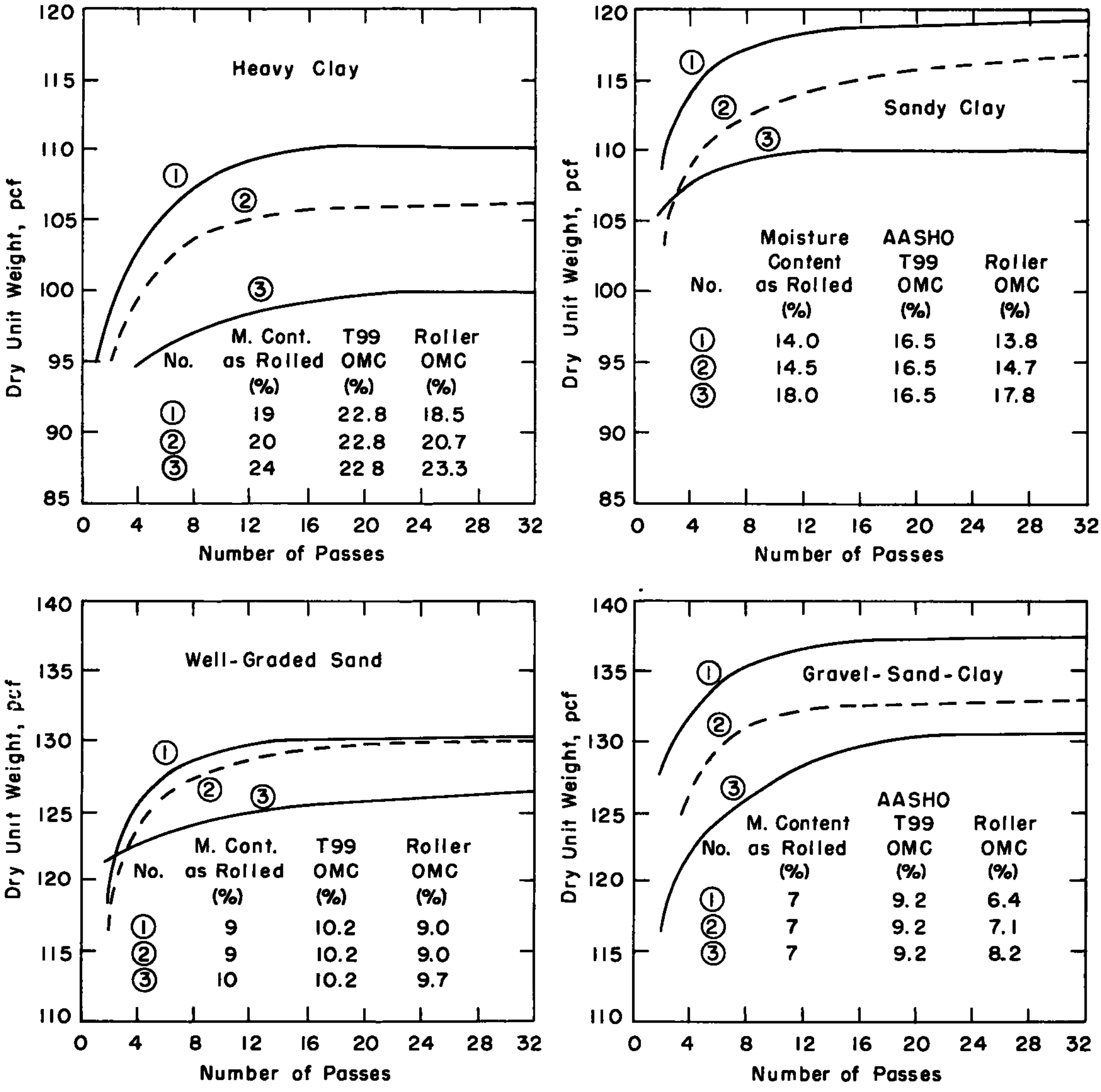
The number of passes required for pneumatic-tired rollers depends on (a) the tire widths and the spacing of the wheels, (b) whether or not axles are in tandem, (c) the contact unit pressure, (d) the wheel load, (e) the lift thickness, (f) the soil type, and (g) the moisture content. The close spacing of wheels and the use of tandem axles as on the 7-, 9-, 11-, and 13-wheel lightweight rollers insure one coverage per pass. Some of the medium and heavyweight rollers with larger spacing between tires and between sets of tires (on different oscillating axles) may produce one coverage per pass insofar as deep compaction is concerned but certainly not for compaction of the upper few inches of soil. It should be noticed that under "Roller Maximum Dry Unit Weight vs Moisture Content" some rollers are shown as requiring two passes per coverage.



Note Figures beside field curves are tire inflation pressures for various rollers.

Figure 43. Comparison of laboratory and roller optimum moisture contents and maximum unit weights for three soils after each has been compacted by 32 passes of pneumatic-tired rollers in 9-in. loose lifts (36-psi roller) or 12-in. loose lifts (heavier rollers). All unit weights are for top 6 in. of compacted soil (127).

The number of passes also depends on wheel loads and tire inflation pressure. It is difficult to discuss interrelationships between dry unit weight and moisture content without illustrating the effect of tire inflation pressure and number of passes. However, those relationships with coverage as shown in Figures 41 and 42 are indirect as compared to those shown later. In a series of tests on Florida fine sand (47) 25 coverages of a 15,000-lb wheel load with a tire inflation pressure of 45 psi produced a dry unit weight of 98.8 percent of Modified AASHO maximum dry unit weight while 25 coverages of a 60,000-lb wheel load with a similar inflation pressure produced a dry unit weight equivalent to 103.8 percent. In a more recent series (127) with rollers of four weights on four types of soil the interrelationships of wheel load, tire inflation pressure and type of soil on number of passes to attain very small further increases in unit weight are shown in Figure 44. Curves for only three of the four rollers are shown, the values



Heavy Clay

No.	M. Cont. as Rolled (%)	T99 OMC (%)	Roller OMC (%)
①	19	22.8	18.5
②	20	22.8	20.7
③	24	22 8	23.3

Sandy Clay

No.	Moisture Content as Rolled (%)	AASHO T99 OMC (%)	Roller OMC (%)
①	14.0	16.5	13.8
②	14.5	16.5	14.7
③	18.0	16.5	17.8

Well-Graded Sand

No.	M. Cont. as Rolled (%)	T99 OMC (%)	Roller OMC (%)
①	9	10.2	9.0
②	9	10.2	9.0
③	10	10.2	9.7

Gravel-Sand-Clay

No.	M. Content as Rolled (%)	AASHO T99 OMC (%)	Roller OMC (%)
①	7	9.2	6.4
②	7	9.2	7.1
③	7	9.2	8.2

Curve No.	Roller Rating (tons)	Wheel Load (lb)	Tire Inflation Pressure (psi)	Loose Lift Thickness (in.)
①	46.8	22,400	140	12
②	46.8	11,200	90	12
③	13 44	2,985	36	9

Figure 44. Relation between dry unit weight of upper 6 in. of compacted soil and number of passes of pneumatic-tired rollers (127).

for the 4,978-lb wheel load and 80-psi tire inflation pressure being omitted because in most instances the curves fall so close to curve No. 2 as to make it difficult to distinguish their relative positions. These tests were performed at moisture contents approximately equal to the roller optimum for each soil. The curves in Figure 44 exhibit the same general shape. The minor variations in form are probably due more to differences in design of tires and in wheel arrangement than to total load and tire inflation pressure. Very small increases in dry unit weight occurred after 16 passes.

The curves of dry unit weight vs number of passes for rolling at a given moisture content produces relationships that show rather strongly the effect of number of passes for most soils. However, the relationship is more obscure when the maximum dry unit weights for a given roller are plotted vs the number of coverages for a lean clay soil. Figure 41 illustrates this relationship for the three weights of rollers for which roller compaction curves are shown. Here rather marked changes in numbers of coverages of rollers, differing greatly in contact unit pressure and considerably in wheel load, result in small changes in maximum dry unit weights for this lean clay soil, a not entirely unexpected phenomenon for this soil. Somewhat larger changes in maximum dry unit weight occurred due to number of coverages in rolling a clayey sand (44), in which maximum dry unit weight up to about 5 pcf were attained by increasing the number of coverages from four to eight.

However, in a separate experimental study (47) of the compaction of sand, a 7,000-lb wheel load (45-psi tire inflation pressure) produced a maximum increase in dry unit weight of about only 2.5 percent of AASHO T 99 maximum. In other tests 25 coverages of a 15,000-lb wheel load, 6 coverages of a 35,000-lb wheel load, and 25 coverages of a 60,000-lb wheel load showed the greatest average dry unit weight for 6 passes of the 35,000-lb wheel load. All tires were inflated to 45 psi. This singular group of tests on a uniformly graded (one size) sand indicated that the number of coverages above six of lesser significance than the wheel load. Some significant data on the influence of coverages were obtained in another group of tests (53) but these are concerned with depth of compaction and are discussed later.

It has been shown in Figure 44 that the greatest rate of increase in dry unit weight usually occurs at coverages of four or less. This accounts for the rather small increases due to numbers of passes shown in Figure 41 for the lean clay compared to the effect of load and tire inflation pressure. Thus the reader must not be misled by the chart (Figure 41) because it does not show the effect of the first four coverages (8 passes) because the initial (uncompacted) unit weight is not given. The work of India (66), Townsend's cooperative work with Queens University and the Department of Highways of Ontario (120), as well as tests by the Swedish Road Institute (80), all confirm in greater or lesser degree the results that have been given in detail previously. Townsend's report (120) showed that the dry unit weight vs number of coverage relationships varies with the weight of the roller and the lift thickness–the heavier roller and the thinner lifts being productive of the highest state of compaction and also reaching that state with the least number of passes.

EFFECT OF NUMBER OF PASSES OF TRAFFIC COMPACTION

The increases in the unit weight of the subgrade (basement) soils and in the granular subbase of the WASHO Road Test (84) that occurred after the beginning of application of traffic on the completed pavement gives evidence of the potential compacting effect of traffic. Although the increase in unit weights has not been correlated with number of load applications, the data derived from the tests is of value. A summary of in-place unit weights is given for the single-axle sections for the subgrade soil in Table 17 to illustrate the increase attributable to traffic from the "as built" condition in 1952 to November 1953. A similar compilation in Table 18 indicates the compaction of the gravel subbase during the same period. Gains in dry unit weight of the basement soil from the time of construction in 1952 to the fall season of 1953 were of the order of 4½ to 5 pcf. Gains in dry unit weight of granular subbase material ranged from 1.5 to 2.2 pcf.

Compaction can also result from "accelerated traffic tests" of the type that might

TABLE 17

DRY UNIT WEIGHTS OF SUBGRADE (BASEMENT) SOILS OF WASHO ROAD TEST SECTIONS

(Single-Axle Sections)[a]

Section and Nominal Total and Surface Thickness (in.)	Nominal Depth of Testing (in.)	Percent of AASHO Maximum Dry Unit Weight[b]			
		As Built in 1952		November 1953	
		18,000-lb Sections	22,400-lb Sections	18,000-lb Sections	22,400-lb Sections
22 - 2 and 4	0 - 6	91.8	95.8	97.3	98.3
18 - 2 and 4	0 - 6	95.6	92.5	99.5	99.1
14 - 2 and 4	0 - 6	92.4	91.0	95.8	96.7
10 - 2 and 4	0 - 6	93.8	95.0	98.0	99.7
Average (unweighted)		93.4	93.6	97.8	98.5
Gain				+4.4	+4.9

[a] From Tables 4-f-7, 4-f-8, and 4-f-9, HRB Special Report 22 (1955).
[b] AASHO T 99 maximum dry unit weight 93.8 pcf.

TABLE 18

DRY UNIT WEIGHTS OF GRANULAR BASE AND SUBBASE OF WASHO ROAD TEST SECTIONS

(Single-Axle Sections)[a]

Section and Nominal Total and Surface Thickness (in.)	Nominal Depth of Testing (in.)	Percent of AASHO T 99 Maximum Dry Unit Weight[b]		
		As Built in 1952	November 1953	
		Average for 18,000-lb and 22,400-lb Sections	18,000-lb Sections	22,400-lb Sections
22 - 2 and 4	22	100.5	104.6	104.6
18 - 2 and 4	18	100.8	102.9	101.3
14 - 2 and 4	14	102.4	103.3	103.1
10 - 2 and 4	10	102.8	104.2	103.2
Average (unweighted)		101.6	103.8	103.1
Gain			+2.2	+1.5

[a] From Tables 4-f-11, 4-f-12, and 4-f-13, HRB Special Report 22, (1955).

[b] AASHO T 99 maximum dry unit weight 129.6 pcf, which is the average of three (130.4, 129.3, and 129.0 pcf).

be used in "proof rolling." An example is the application of 500 coverages of a heavy roller on a crushed limestone base (100). This test which has been described previously consisted of rolling, in 4-in. compacted lifts, a crushed limestone by 32 coverages of a 25,000-lb wheel load with 90-psi tire inflation pressure. This was followed by "traffic" compaction (airfield type) by 500 coverages of a 50,000-lb wheel load with a tire inflation pressure of 200 psi. The results (Fig. 42) also show the marked amount of drainage that occurred in this well-graded crushed rock base whose grain-size distribution is shown in Figure 10.

EFFECT OF MOISTURE CONTENT ON NUMBER OF PASSES REQUIRED

Moisture content has a similar type of effect on number of passes required regard-

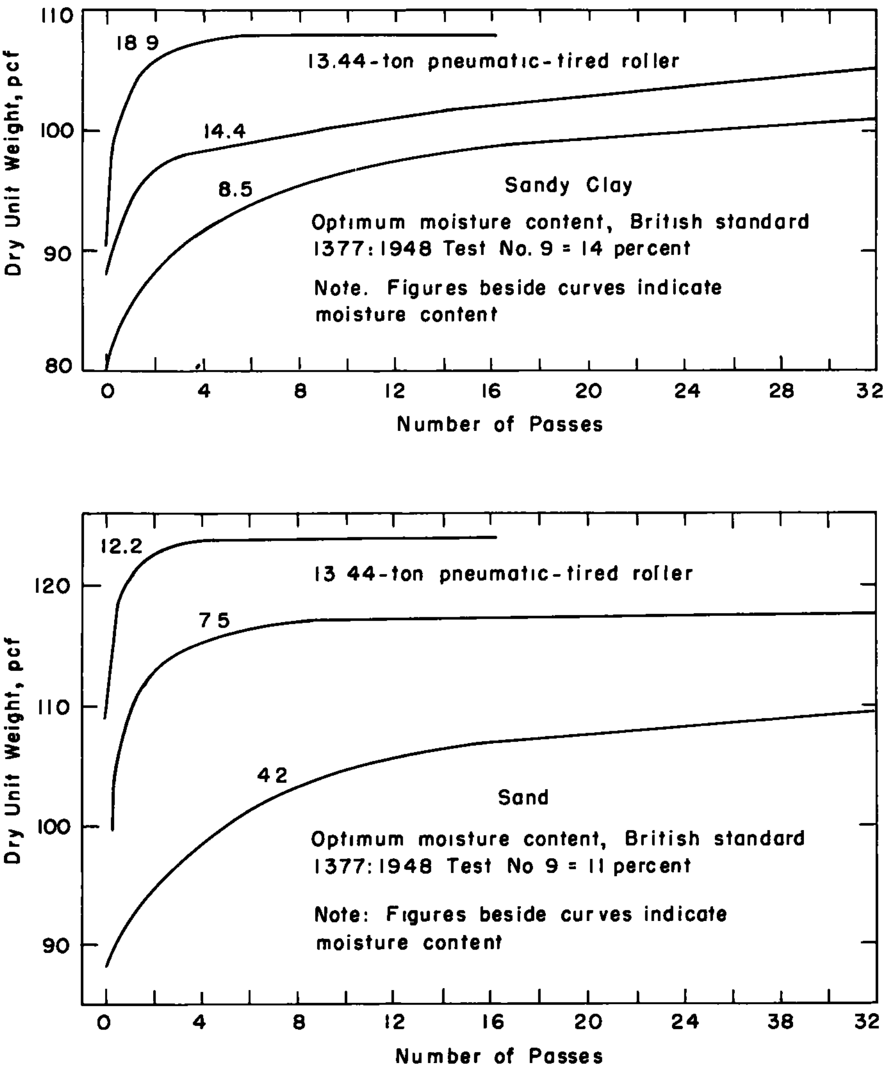


Figure 45. Influence of moisture content on number of passes needed to obtain maximum unit weight for a 13.44-ton, 9-wheel pneumatic-tired roller (11.00 x 12-in. tires, inflation pressure 36 psi, contact unit pressure 39 psi) on 9-in. loose lifts (56).

less of type of roller. An example of the influence of moisture content on the rate of increase in dry unit weight for a given number of passes is shown in Figure 45 for a relatively lightweight (13.44-ton, 9-wheel-2,987-lb wheel load, 36-psi inflation pressure) pneumatic-tired roller, on two types of soils, a sandy clay and a well-graded sand. Here it is shown that at water contents dry of optimum, a greater number of passes is required to attain full compaction for a given water content. The more nearly the moisture content approaches optimum the less the number of passes required to attain full compaction and the greater the dry unit weight.

EFFECT OF GROSS WEIGHT (WHEEL LOAD) AND CONTACT UNIT PRESSURE

Gross weight alone often expressed as wheel load, has its most significant influence on the depth of compaction. A number of tests have been performed to determine the relative effect of wheel load and contact pressure on the degree of compaction.

Similarly, computations have been made to determine the relative effects of wheel load and contact pressure on the total pressures existing at various depths below the surface. In the main, these are discussed later under "Depth of Compaction" and "Depth vs Pressure Relationships Under a Wheel Load." Here we are concerned more with the relative effects of wheel load and tire pressure at depths within normal lift thicknesses.

Tests were performed (46) on a Vicksburg silty clay (LL=37, PI = 14) employing wheel loads of 10,000, 20,000, and 40,000 lb and the nearly equal tire inflation pressures of 60, 55, and 57 psi, respectively. Another series (47) of experiments were performed to determine the influence of wheel load on the depth of compaction of a uniformly graded fine Florida non-plastic sand. The British Road Research Laboratory (127) performed a series of tests with different weights of rollers including wheel loads of 11,200 and 22,400 lb each with a tire inflation pressure of 90 psi. The results of these tests are summarized in Table 19. It should be kept in mind that the first of this series (46) involved compacted depths of only 6 in. The effect of doubling the wheel load from 10,000 to 20,000 lb was to increase the dry unit weight only about 0.6 pcf and the effect of increasing the wheel load from 10,000 to 40,000 lb was only about 1.3 pcf. The tests on the uniformly graded fine Florida sand (47) increased the dry unit weight about 4.7 pcf or 5 percentage units on increasing the wheel load from 15,000 to 60,000 lb at a constant tire inflation pressure of 45 psi. The results on the fine sand involved compacted depths of 24 in. and a greater number of coverages (25) than normal. The British tests (127) involving loads of 11,200 and 22,400 lb each at 90-psi tire pressure were performed on a 12-in. loose depth by 32 passes of the roller. Unit weight increases due to doubling the wheel load from 11,200 to 22,400 lb were 1.2 pcf for the heavy clay, 2.1 pcf for the sandy clay, 1.7 pcf for the sand and 1.5 pcf for the gravel-sand-clay. These data do show that increasing the wheel load does increase the dry unit weight. However, the increases are relatively small when considered in terms of the magnitude of the wheel loads and the very small depths involved.

On evidence that wheel load alone could not control the compaction of soil, experiments were conducted to determine the proportion of the compression factor that could be attributed to the contact unit pressure. When data on actual measured contact area and contact unit pressure were not available the value of tire inflation pressure was employed. Large amounts of data were collected by the Corps of Engineers (87) on compaction of a silty clay soil, data on dry unit weights being observed at tire inflation pressures of 50, 90, and 150 psi employing wheel loads of 15,875, 25,000, and 31,250 lb which wheel loads were well within the range previously tested under approximately constant tire inflation pressure. Similarly, data were obtained by the British Road Research Laboratory (127) on the effects of 36-, 80-, 90-, and 140-psi inflation pressures for wheel loads of 2,985, 4,978, 11,200, and 22,400 lb. Tests were conducted on four types of soils.

The significance of the effect of tire inflation pressure (87) as a factor influencing soil compaction can be appreciated by an inspection of Figure 46, in which three different tire inflation pressures and three different wheel loads were employed—each tire pressure being applied to the soil in 4, 8, and 16 coverages (8, 16, and 32 passes) of the roller. It should be noted that all data shown are for a compaction moisture content of 16.3 percent. If tire inflation pressures were plotted against roller maximum dry unit weight expressed as percentages of AASHO T 99 maximum dry unit weight at roller optimum moisture content the positions for the curves for the three different coverages tend to converge at the 90-psi tire pressure and to diverge at the 50-psi and 150-psi values.

The results of British tests (127) are shown in Figure 47. Here it is shown that the more compressible soils of the clayey types exhibit the greatest gain in dry unit weight when rolled with tires inflated to the higher tire pressures. The clays, rolled by the high pressure tires (140 psi) had unit weights 9 to 10 pcf greater than those rolled with the lowest pressure (36 psi) tires. The granular soils rolled by the 140-psi roller had unit weights 5 to 6 pcf greater than those rolled by the 36-psi roller. If plots were made of inflation pressure vs percent of standard maximum dry unit weight the curves for the clayey soils tend to fall closely together. This is also true for the granular soils.

TABLE 19

EFFECT OF WHEEL LOAD ON SOIL UNIT WEIGHT FOR EQUAL OR NEARLY EQUAL TIRE INFLATION PRESSURES

	Data on Roller and Its Operation				Lift Thickness		Average Roller Compacted Maximum Dry Unit Weight	
Soil Type	Reference No.	Wheel Load (lb)	Tire Inflation Pressure (psi)	No. of Coverages	Loose (in.)	Comp. (in.)	Percent of AASHO Max Dry Unit Weight^{a}	Percent of Modified AASHO Max Dry Unit Weight^{a}
Vicksburg silty clay	46	10,000	60	6	-	6	102.3^{b}	92.2
Vicksburg silty clay	46	20,000	55	6	-	6	102.9^{b}	92.7
Vicksburg silty clay	46	40,000	57	6	-	6	103.5^{b}	98.3
Florida fine sand	47	15,000	45	25	-	24	-	98.8
Florida fine sand	47	60,000	45	25	-	24	-	103.8
British heavy clay	127	11,200	90	32	12	-	107.3^{c}	90.5
British heavy clay	127	22,400	90	32	12	-	108.5^{c}	91.5
British sandy clay	127	11,200	90	32	12	-	107.0^{c}	94.0
British sandy clay	127	22,400	90	32	12	-	109.0^{c}	95.6
British well-graded sand	127	11,200	90	32	12	-	104.3^{c}	98.9
British well-graded sand	127	22,400	90	32	12	-	104.9^{c}	99.4
British gravel-sand-clay	127	11,200	90	32	12	-	103.5^{c}	97.8
British gravel-sand-clay	127	22,400	90	32	12	-	104.6^{c}	98.9

[a] In most instances values in pcf were scaled from roller compaction curves. Values for British soils are percent of B. S. 1377: 1948 Test No. 9 which is generally similar to AASHO T 99 Method C. [b] Percent of actual AASHO T 99 values. [c] Percent of British Standard 1377:1948.

The soil moisture content has a strong influence on the relationship between tire inflation pressure and number of coverages to attain a given dry unit weight just as moisture content has been shown to have a strong influence on the number of passes required of a given roller for a given soil type and condition. The lesser the moisture content dry of optimum the greater the effect of number of coverages on dry unit weight at all tire inflation pressures. At high moisture contents the effect of number of coverages tends to lessen particularly at the higher inflation pressures. This is illustrated in the three individual plots for the three moisture contents in Figure 48.

In summarizing, the effect of wheel load and tire inflation pressure, the following has been shown:

1. The contact area and contact pressure under the tires, both of which affect the state of compaction produced, are functions of the wheel load and the tire inflation pressure.
2. An increase in the wheel load or in the tire inflation pressure produces an increase in the roller maximum dry unit weight with a corresponding decrease in optimum moisture content.
3. The greater the wheel load and the tire inflation pressure, the greater the unit weight at any depth. However, increasing the tire inflation pressure without proportionately increasing wheel load, tends to produce greater compaction near the surface.
4. The marked effect of tire inflation pressure indicates the need for pneumatic-tired rollers equipped with tires permitting the range of inflation pressures desired (Tables 71 and 72) and provision for increasing or decreasing tire inflation pressures during operation. Rollers so equipped are currently available.

DEPTH OF COMPACTION

A substantial depth of increase in unit weight has always been sought in compaction primarily because of its direct effect in increasing production, and secondarily, because less spreading and compacting equipment are needed on the grade to interfere with hauling and dumping operations. However, there are other and equally real needs for seeking depth in compaction. One is to obtain deep compaction in natural subgrades at grade points and in cut sections as well as for foundations for shallow fills, or to compact refuse fills (59), or for purposes of proof rolling. These are some of

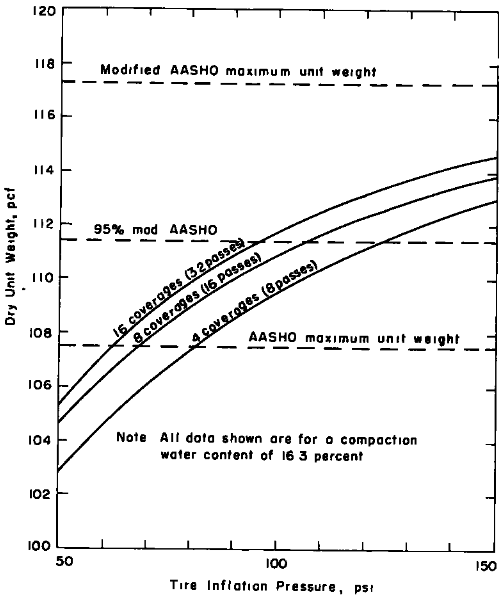


Figure 46. Relation between tire inflation pressure and unit weight of a Vicksburg lean clay (LL=36, PI=15) for 4, 8, and 16 coverages (8, 16 & 32 passes) of pneumatic-tired rollers on lifts of 6-in. compacted thickness when rolled at a moisture content of 16.3 percent (equivalent to laboratory optimum for a compaction effort resulting in a maximum unit weight of 95 percent of Modified AASHO maximum unit weight). (Laboratory compaction values are: Mod. AASHO max. unit wt.=117.3, O.M.C.=14.0, st'd AASHO max. unit wt.= 107.5, O.M.C.=17.7) (87).

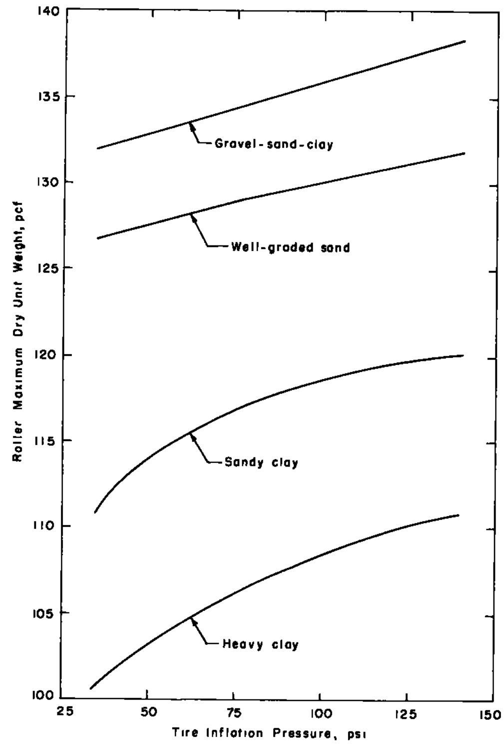


Figure 47. Relationship between tire inflation pressure and roller maximum unit weight for four soils after 32 passes of pneumatic-tired rollers in 9-in. loose lifts (36-psi roller) or 12-in. loose lifts (for heavier rollers). All unit weights are for top 6 in. of compacted soil (127).

the several conditions where deep compaction can serve a useful purpose. However, the principal reason for seeking equipment and methods for deep compaction is to lessen the cost of compaction and increase the output of compactors and to reduce the number of pieces of equipment on the grade. If knowledge is to be complete, it should bring out the effective depth of compaction of lightweight, medium weight as well as heavyweight equipment.

A single source (80) of information was found on the full depth of effectiveness of lightweight pneumatic-tired rollers. A 15.5-ton, 13-wheel roller with 2,381-lb wheel loads and 7.50 x 15-in. tires inflated to a pressure of 35 psi was employed in rolling three types of soils, each at about its optimum moisture content (Modified AASHO method). The three soils were placed in loose lifts of about 30 in. and rolled by 6 trips of the roller. Dry unit weight vs depth relationships for the three soils in which the dry unit weight is expressed in terms of percent of Modified AASHO maximum dry unit weight are shown in Figure 49. Here it may be seen that the roller produced about the same percent relative compaction (percent of Modified AASHO) at the surface for each of the three soils but that soil type had strong influence in determining the effective depth of compaction. The morainic soil, the heavier textured of the three, exhibited the least depth effect, the mo slightly more and the sand the greatest depth effect. In other words the sand showed the greatest depth (about 12 in.) in which there was small decrease in unit weight.

Special tests were conducted (95) on a lean (silty) clay (LL = 37, PI = 17) to determine the effective depth of compaction when compacted by two different rollers, one a 25,000-lb wheel load with a tire inflation pressure of 90 psi, the other a 31,250-lb wheel load with a tire pressure of 150 psi. Because of the behavior of the two rollers in this soil of rather low strength it is worthwhile reporting not only unit weight vs depth relations but also some of the behavior characteristics of the rollers and the soil.

The initial plan was to construct one test lane of six 6-in. thick lifts, another of four 12-in. thick lifts, and a third lane of three 18-in. lifts for each of the 90- and 150-psi tire-inflation pressure rollers. Separate test sections were constructed at different moisture contents to provide data on moisture content vs dry unit weight relationships for the various lift thicknesses. The plan worked out fairly well for the 90-psi roller, the 6-in. and the 12-in. lifts being built as planned but the three 18-in. lifts actually being 16-, 24- and 24-in. thickness commencing with the bottom lift. The three lanes for the 150-psi roller ended with compacted lifts, as follows:

Lane 1–7, 5½-, 7-, 3½-, 6½-, and 6½-in. lifts.

Lane 2–11½-, 8½-, 9½-, and 12-in. lifts.

Lane 3–16-, 16- and 19-in. lifts.

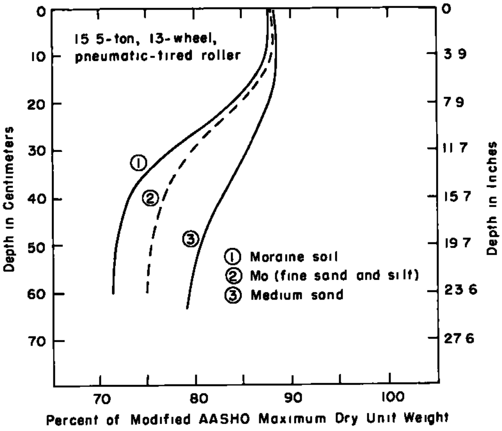


Figure 49. Relation between depth and percent Modified AASHO maximum dry unit weight for three soils when compacted by six trips of roller having tire inflation pressure of 35 psi (80).

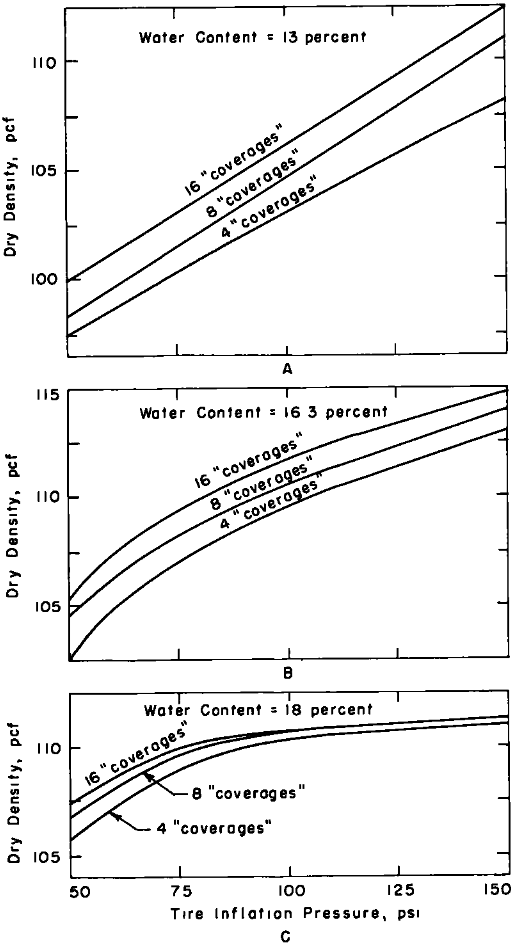


Figure 48. Effect of tire inflation pressure and coverages of pneumatic-tired rollers on unit weight (98).

Thus, only one lift for the 150-psi roller worked out as planned due to the behavior of the heavier roller.

Roller Behavior

90-Psi Roller.—The behavior of this roller on the lean clay soil was influenced by both soil water content and lift thickness. At about optimum water content on the 12- and 24-in. lift thickness sections an additional tractor was required for the first pass due to the roller pushing soil ahead of the wheels, causing rutting and excessive resistance to movement. This did not occur on the 6-in. lift thickness lane. The 12-in. section rolled out and had a good appearance after 8 coverages

(16 passes). The material wet of optimum showed increasing movement and rutting as the water content was increased. This was not so noticeable on the 6-in. lift thickness.

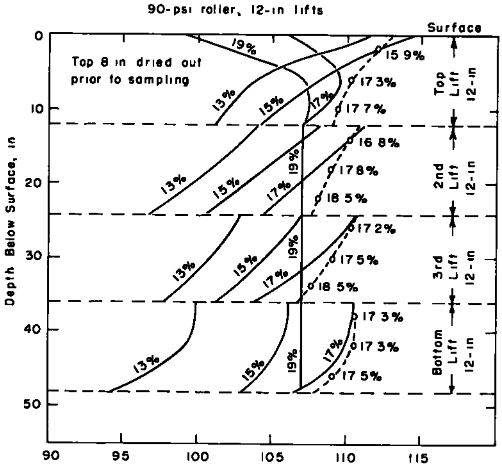
For the 24-in. lift thickness sections, rolling could not be continued after the first pass because of the excess lateral movement during the first pass. Therefore the fill was leveled by bulldozer and compacted by two coverages of the D-4 track-type tractor to a density sufficient to support the roller. At high moisture contents the material exhibited excess rutting caused by lateral movement.

150-Psi Roller. –The water content and lift thickness had greater effect on the 150-psi roller than on the 90-psi roller. Difficulty was not encountered on the 6-in. lifts but the roller had to be pushed by the tractor on the first pass on both the 12-in. and 18-in. lifts. The 16-in. and 19-in. lifts were precompacted by two coverages of the D-4 tractor. On the 6-in. lifts slight springing occurred at water contents of 20 to 22 percent but rutting did not occur. On the 12-in. lifts rutting increased as the water content increased. Springing and plastic movement occurred in the 17-19 and 20-22 percent sections. On the 18-in. lifts that were precompacted by the D-4 tractor, springing and plastic movement occurred as the water content increased, however, little rutting occurred even on the wet sections.

Crusting. –Often when smooth-wheel or pneumatic-tired rollers are used, some surface "crusting" of the compacted material takes place. This "crusting" causes "bridging" which reduces the compaction effort with depth. Crusting did not occur on the lean (silty) clay, which is not a material of high bearing capacity.

Dry Unit Weight Gradients for the 90-Psi Roller

Observations of unit weight and moisture content were made with sufficient regularity to permit the construction of families of roller compaction curves, each curve representing a given depth in a given lift and lane, the curves representing different compactive efforts for different depths below the surface (95). Although these individual roller compaction curves, each representing a given depth in a lift are of interest, the significant findings are the differences in dry unit weight from the top to the bottom of construction lifts of different thickness. The individual gradients of unit weight with depth for different moisture contents are shown in Figure 50 for the four separate compacted lifts of 12-in. thickness rolled by the 90-psi roller. Figure 50 illustrates the very marked decrease in dry unit weight with depth within each 12-in. compacted lift for soils existing at moisture contents considerably dry of optimum (AASHO T 99 values are 105 pcf and 17.9 percent O.M.C., Modified AASHO values are 116.8 pcf and 14.5 percent O.M.C.). For the second and third 12-in. lifts gradients were relatively "flat" even at moisture contents as high as 17 percent.



Note Figures beside curves are moisture contents Curves shown thus o---o are maximum unit weight with roller optimum moisture content alongside

Figure 50. Unit weight gradients at various moisture contents for a Vicksburg, Miss. lean clay (LL=39, PL=22, PI=17) after 8 coverages by a pneumatic-tired roller having wheel load of 25,000 lb and tire inflation pressure of 90 psi. Data are for 12-in. lifts (95).

It should be noted that only at 19 percent moisture content is the dry unit weight uniform throughout the full depth of each 12-in. lift for the 2nd, 3rd, and bottom lifts. Drying of the soil was believed to account for the abnormal nature of the 17 and 19 percent curves for the upper lift. Neither the laboratory optimum moisture contents nor the roller optimum moisture contents provide the most uniform vertical distribution of dry unit weight in the construction lifts. The roller optimums do provide the greatest average dry unit weight for the full depth of the lift. However the most uniform dry unit weight is provided by the 19 percent moisture content which is 1.6 percentage units greater than the average roller optimum and about one percentage unit greater than AASHO T 99 optimum moisture content.

Differences in unit weights at the top and bottom extremes of the 12-in. compacted lifts for the 13, 15, and 17 percent moisture contents for the 90-psi roller expressed in percent of AASHO T 99 maximum dry unit weight are given in Table 20. These data show that even with a 25,000-lb wheel load and a tire inflation pressure of 90 psi, and rolling to produce a 12-in. thick compacted lift having a dry unit weight of not less than 95 percent of AASHO T 99 maximum it is entirely possible that the upper portion of the lift may satisfy, but the lower portion fail to satisfy specification requirements. Further examination of Figure 50 shows that the differences in unit weights between top and bottom of lifts tend to become less for the deeper lifts. Whether this is due to the effect of the additional rolling of overlying lifts is not known. In any instance it has been found that moisture content-unit-weight relationship from construction lifts with sheepsfoot-type rollers (44) as well as with pneumatic-tired rollers (46) showed a ten-

TABLE 20

DRY UNIT WEIGHTS IN TOP AND BOTTOM OF 12-IN. LIFTS ROLLED BY 90-PSI ROLLER (95)

Lift From Top	Moisture Content (%)	Percent of AASHO T 99 Maximum Dry Unit Weight in Upper and Lower Extreme Portions of 12-in. Layers		Difference
		Bottom of Lift	Top of Lift	
2nd	13	92.4	99.2	6.8
2nd	15	95.0	103.0	8.0
2nd	17	99.4	105.9	6.5
3rd	13	93.2	97.1	3.9
3rd	15	96.5	101.9	5.4
3rd	17	99.0	105.5	6.5
Bottom	13	90.0	95.2	5.2
Bottom	15	98.2	101.0	2.8
Bottom	17	101.5	105.1	3.6

TABLE 21

DRY UNIT WEIGHTS IN TOP AND BOTTOM OF 24-IN. LIFTS ROLLED BY A 25,000-LB WHEEL LOAD WITH A 90-PSI TIRE INFLATION PRESSURE (95)

Lift	Moisture Content (%)	Percent of AASHO T 99 Maximum Dry Unit Weight in Upper and Lower Extreme Portions of a 24-in. Compacted Lift		Difference
		Bottom of Lift	Top of Lift	
Middle	13	86.2	99.1	12.9
Middle	15	88.5	101.7	13.2
Middle	17	92.4	104.3	11.9
Middle	19	95.0	103.0	8.0

tendency to produce higher unit weights in the upper three to four lifts but that they did not extend below the third or fourth lift.

Results with the 90-psi roller on the 16- and 24-in. lifts showed unit weight gradients similar to those shown in Figure 50 except that the vertical gradient for the 19 percent moisture content did not hold for the entire 24-in. depth. Differences in dry unit weights at the top and bottom extremes of the 24-in. compacted thickness middle lift are given in Table 21. Comparison of the differences in percent relative compaction shown in Table 20 for the 12-in. compacted lifts with those shown in Table 21 for the 24-in. compacted lift thickness shows that the differences in percent relative compaction between top and bottom of the 24-in. compacted lift are approximately twice the differences for the 12-in. compacted lift. Figure 51 illustrates actual values from the field construction lifts of 16- and 24-in. compacted thickness. It sets forth some of the problems that confront engineers and contractors who seek to increase production simply by increasing compacted lift thickness, without taking into account the nature of the soil (if it is strong enough to support the roller as it is or if it can be improved by precompaction) and the moisture content at which compaction can be accomplished. The foregoing summary and remarks have been limited to the 25,000-lb wheel load carrying a 90-psi tire inflation pressure.

Dry Unit Weight Gradients for the 150-Psi Roller

Dry unit weight gradients for the 150-psi roller were quite erratic for the shallow lifts, some exhibiting vertical gradients, some a gain in unit weight with depth, and others a reduction in unit weight with depth. Gradients for the 16- and 19-in. lift thicknesses are shown in Figure 52. Curves for the top and bottom lifts are not shown because of the scatter of basic data. These curves follow a pattern similar to that for the 90-psi roller, although it should be kept in mind that the wheel load was 31,250 lb compared to 25,000 lb for the 90-psi roller. Even with the increased wheel load, a significant decrease in unit weight occurs for the lifts having the lower moisture contents.

The proper lift thickness of 12 in. was obtained in only one lane with the 150-psi roller. The second and third lifts were 9.5 and 8.5 in., respectively. This discrepancy, no doubt, influenced test results. Examination of the family of moisture-unit weight curves for all depths showed them to be identical, hence the compactive efforts, especially at optimum must have been equal. On the first pass, tires sometimes sank to a depth of 6 to 8 in. in a 12-in. lift and 10 to 12 in. in a 16-in. lift. Thus the soil was being partially compacted in 8-in. lift thicknesses rather than the normal 12- or 16-in. thicknesses used in the analysis.

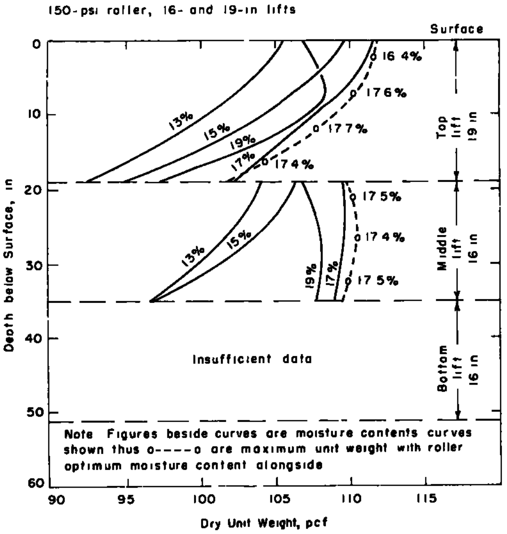
In summarizing the effect of lift thickness and tire inflation pressure on this rather weak lean clay soil (95) the following may be said:

1. The decrease in unit weight with depth of about the same proportion as the decrease in compaction effort (pressure intensity) with depth.
2. Field roller optimum increased with depth as the roller maximum dry unit weight decreased with depth within a lift.
3. As the compacted lift thickness increased, the difficulty of rolling increased. Compacted lifts greater than 12 in. should be precompacted by a lighter roller before rolling with a high tire pressure roller.
4. The unit weights in all lift thicknesses compacted by the 90-psi roller were more uniformly distributed at the higher moisture contents. Unit weight gradients, insofar as data were available, showed that the dry unit weight gradients for the 150-psi roller followed the trend developed by the 90-psi roller.

As a result of the experiments (95) it was concluded that the 90-psi roller can compact loose lift thicknesses up to 14 in. in depth at optimum moisture content. The 150-psi roller can compact loose lift thicknesses of 9 in. or less at optimum due to greater sinkage and rutting. The values are based on the supposition that the unit weight gradients produced under these conditions are satisfactory to the designer. Other values of maximum thickness may be more appropriate for other types of soils.

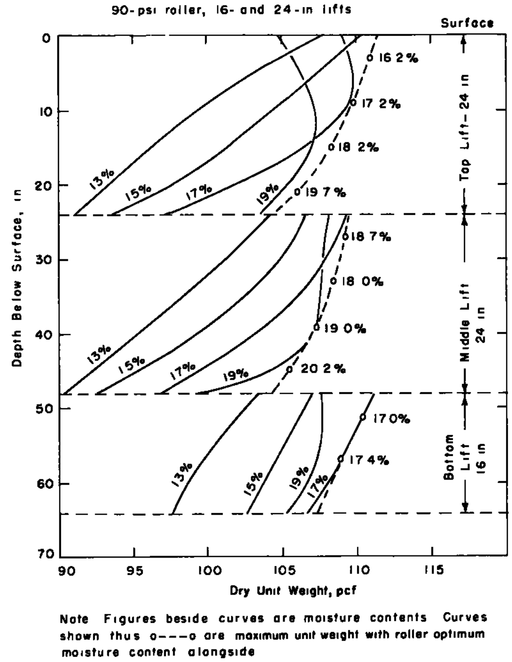
Recently completed British tests (127) were also aimed at determining the respective influences of wheel load and tire inflation pressure with relation to the depth below the surface. However, the tests also included determining the effect of soil type on dry unit weight at various depths. Some results of the tests are shown in Figure 53. The upper plot in Figure 53 shows the depth vs dry unit-weight relationship for two combinations of wheel load and tire inflation pressure for four types of soils. The heavy clay was compacted at a moisture content approximately midway between optimum for AASHO T 99 and Modified AASHO and likewise midway between roller optimums for the 22,400-lb wheel load, 140-psi roller and the 22,400-lb wheel load, 90-psi roller.

The unit weight gradients for the clayey soils occur as expected from computations. That is, the greater the tire inflation pressure, for either load, the smaller the difference between dry unit weight for any two depths below the surface, including the maximum depth for which measurements were observed. The gravel-sand-clay shows slight reverse tendencies whereas the sand shows little change in the over-all gradient for the full 12-in. depth. It should be noted that the sand exhibited reduced dry unit weights near the surface, possibly due to overstressing by the high inflation pressure tires.



Note Figures beside curves are moisture contents curves shown thus o----o are maximum unit weight with roller optimum moisture content alongside

Figure 52. Unit weight gradients at various moisture contents for a Vicksburg, Miss. lean clay (LL=39, PL=22, PI=17) after eight coverages (16 passes) by a pneumatic-tired roller having a wheel load of 31,250 lb and a tire inflation pressure of 150 psi. Data are for 16- and 19-in. lifts (95).



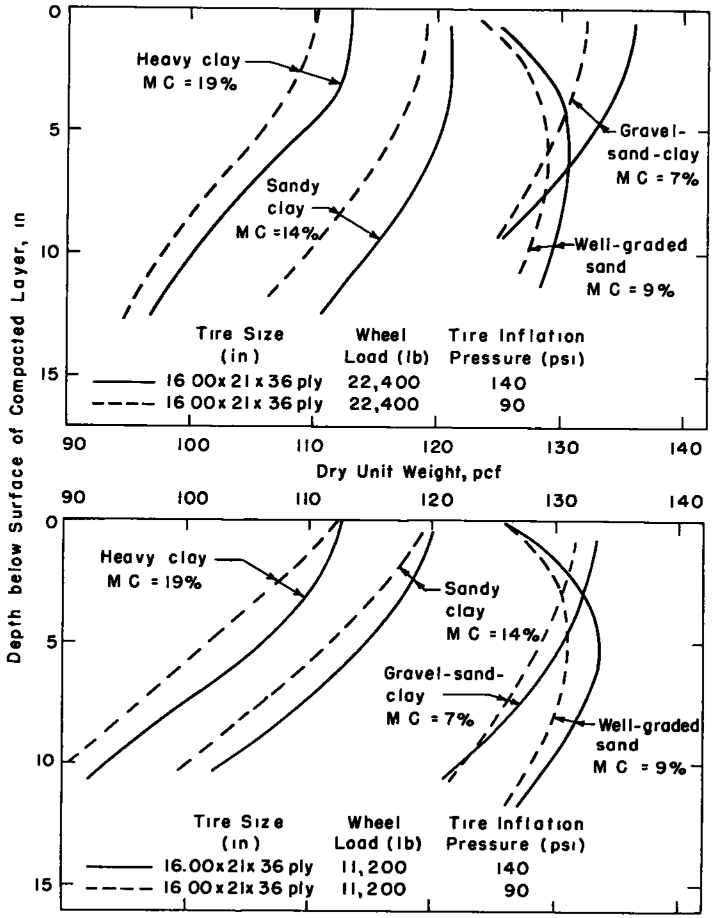
Note Figures beside curves are moisture contents Curves shown thus o---o are maximum unit weight with roller optimum moisture content alongside

Figure 51. Unit weight gradients at various moisture contents for a Vicksburg, Miss. lean clay (LL=39, PL=22, PI=17) after 8 coverages (16 passes) by a pneumatic-tired roller having a wheel load of 25,000 lb and a tire inflation pressure of 90 psi. Data are for 16- and 24-in. lifts (95).

Altogether, the data presented furnish the practicing engineer with a good concept of what he might expect in reduction in unit weight with depth for pneumatic-tired rollers of different wheel loads, tire inflation pressures and thickness of lift.

DEPTH VS PRESSURE RELATIONSHIPS UNDER A WHEEL LOAD

Inasmuch as stress (pressure) has been measured under loaded areas and reasonably close correlation has been found between measured stresses and computed stresses, it should be possible to predict with reasonable accuracy the effect of total load, contact area and contact pressure on the distribution of stresses with depth. The weight of a pneumatic-tired roller is the product of contact area and contact pressure. For example three rollers of 10,000-, 20,000-, and 40,000-lb wheel load, having a contact unit pressure of 65 psi had contact areas as indicated in Figure 54. If there is an increase in the wheel load from 10,000 lb and the tire pressure is constant, the contact area increases but the intensity of the loading is constant. Because the intensity of the pressure is constant, it is apparent that the unit weight may not be affected by an increase in the total weight of the roller. (Cohesionless soils are an exception to this as the confining effect of a



Soil	Laboratory Compaction				Roller Compaction[b]					
	Standard[a]		Mod AASHO		22400-140		22400-90		11200-90	
	Un. Wt. (pcf)	OMC(%)	Un.Wt.(pcf)	OMC(%)	Un Wt.(pcf)	OMC(%)	Un.Wt.(pcf)	OMC(%)	Un.Wt.(pcf)	OMC(%)
Heavy clay	99.8	22.8	118.3	14.7	110.7	18.5	108.3	19.7	107.1	20.7
Sandy clay	109.4	16.5	125.7	11.7	119.8	13.8	119.2	14.4	117.1	14.7
Well-graded sand	124.4	10.2	131.2	8.4	131.9	9.0	130.5	9.0	129.8	9.0
Gravel-sand-clay	129.5	9.2	137.0	6.3	138.5	6.4	135.5	6.9	134.0	7.1

[a] British Standard similar to AASHO T99.

[b] For top 6 in of compacted soil.

Figure 53. Effect of soil type on relation between dry unit weight and depth below surface of compacted soil after 32 passes of pneumatic-tired rollers compacting loose lifts approximately 20 in. thick (127).

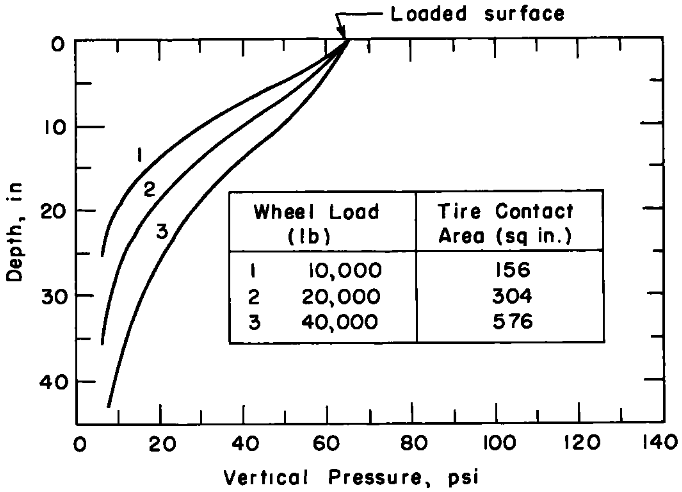


Figure 54. Pressure distribution beneath wheel loads. (Actual tire contact area replaced by equivalent circle. Stresses shown are beneath tire. Contact pressure is 65 psi.) (51)

larger area becomes a factor in giving better compaction.) Generally, with lifts as thin as 6 in., any area of soil will be affected principally by the contact pressure and is little affected by the areal extent of the load. This is illustrated in Figure 54 which shows pressure distribution based on Boussinesq's equation (51) for various sizes of tire loads indicating that for relatively shallow depths in ordinary lift construction (6 to 9 in.) the pressure imposed on the soil being compacted is practically independent on the area of the load. (Actual test results in which wheel loads of the magnitude previously given and nearly uniform tire pressures have resulted in little or no change in dry unit weight of the compacted soil (44, 46).)

The significance of contact pressure is further emphasized in the series of tests (95) with 50-, 90-, and 150-psi pneumatic-tire rollers on various thicknesses of lifts on a lean clay soil. In these tests the results of the 50- and 90-psi rollers were directly comparable in that their contact areas were 305 sq in. and their differences in compaction could be attributable to contact pressure. Different size tires were employed in the tests with the 150-psi roller. Computations were performed to determine the relative differences in pressures at the surface and at various depths for the three tires and contact areas used and also for the case of the 150-psi tire if it would have had a similar contact area (305 sq in.).

The results are illustrated in Figure 55. Although actual pressures may have been slightly different from those computed, they do indicate relative differences in pressure. The solid line curves show the computed pressure intensities beneath the tires used. The dashed line indicates pressure intensities resulting from a 150-psi roller acting over a tire contact area of 305 sq in. As the pressure intensities beneath the 260-sq in. area are less than those under the 305-sq-in. area it may be expected that slightly higher densities may have been attained had a 305-sq

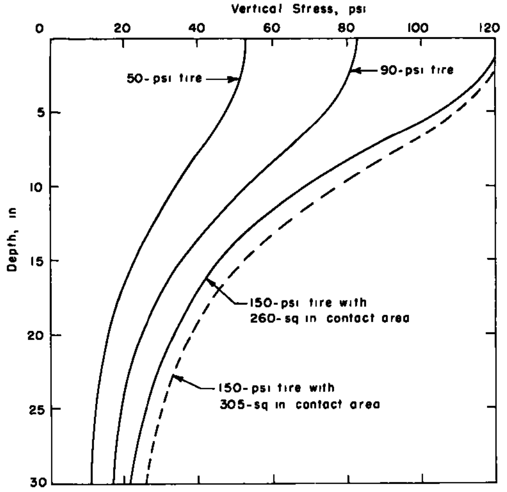


Figure 55. Stress increase with depth for 50-, 90- and 150-psi rollers (95).

TABLE 22

INTERRELATIONSHIPS BETWEEN LOAD, CONTACT AREA AND TIRE PRESSURE (87)

Wheel Load (lb)	Contact Area (sq in.)	Tire Inflation Pressure (psi)	Measured Contact Pressure (psi)
15,875	305	50	52
25,000	305	90	82
31,250	260	150	120

in. area been available for the 150-psi tire pressure loading. Interrelationships for the aforementioned tire inflation pressures are as given in Table 22.

EFFECT OF SPEED OF TRAVEL ON DRY UNIT WEIGHT

Although data are limited, it has been established that the speed of travel of pneumatic-tired rollers has some small but measurable effect on the compacted dry unit weight. Rolling tests at 3, 6, and 10 mph on loose lifts of crushed rock (57) resulted in small reductions estimated from interpolations of data to be of the order of 2 to 3 pcf. Agronomists, although working with loose soils (mulches) but proportionately small contact pressures (108), also reported reductions when speed of travel ranged from 1 to 7 mph. Further tests by agronomists (109) at speeds of 1 to 12 mph showed reductions in dry unit weight of the order of 2 pcf but this was on a soil considered to be of low unit weight (87 to 94 pcf) for a fine sandy loam.

More recent experiments with a 50-ton roller (127) in compacting four types of soils were made at speeds of 1.5 and 3.4 mph. Although the higher speed can hardly be considered rapid travel in the light of speeds two to three times as great by some compactors, the 3.4-mph speed did have a small effect, the least effect being on the heavy clay and the most on the well-graded sand and gravel-sand-clay. For purpose of illustration Figure 56 shows the effect of speed for the heavy clay and for the well-graded sand. It may be seen that the reduction in dry unit weight is hardly commensurate with the increased production that would be gained on increasing the speed between the limits indicated. Speed appears to have no effect at pass numbers greater than 16.

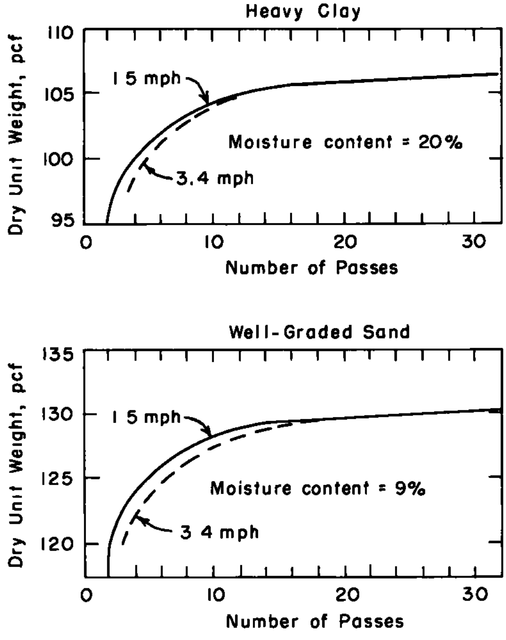


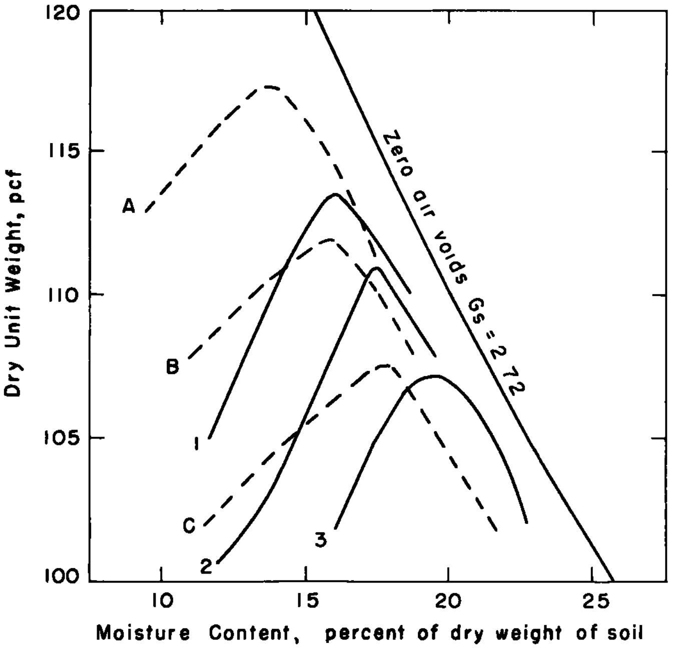
Figure 56. Effect of speed of travel on relation between dry unit weight of top 6 in. of compacted soil and number of passes of a pneumatic-tired roller having a wheel load of 11,200 lb and a tire inflation pressure of 90 psi (127).

COMPARISONS BETWEEN PNEUMATIC-TIRE ROLLER AND LABORATORY COMPACTION

Comparisons between the results of laboratory compaction tests and pneumatic-tire roller compaction have been made repeatedly throughout this summarization of information on pneumatic-tire rolling. These comparisons have been made of roller-produced dry unit weights, and maximum dry unit weights, optimum moisture contents, the comparative shapes of the laboratory and roller moisture- unit weight curves and the relative ease or difficulty of attaining roller unit weights equivalent to laboratory maximum unit weights. No attempt has been made to compare field dry unit weights or lines of optimum moisture contents with those obtained from other than standard laboratory impact compactors (for example, kneading compactors or vibratory compactors).

The range of roller compacted unit weights range from a low of 82 percent of AASHO T 99 maximum in some of the depth vs compaction studies to of the order of 111 to 112 percent of British Standard (generally similar to AASHO T 99 Method C) on a 12-in. loose lift by 32 passes of a 22,400-lb wheel load roller having a tire-inflation pressure of 140 psi. It may be argued by some engineers that these percentages are perhaps beyond the applicable limits of AASHO Method T 99 that should be used. However, the results of the full-scale tests do show that 100 percent of AASHO T 99 maximum dry unit weight can be attained by compacting 5- to 12-in. loose lifts by a nominal number of coverages (4 to 8) with a wide range in wheel loads and tire-inflation pressures.

One of the best comparisons between roller and laboratory results are from tests made using three different weights of rollers with tire inflation pressures of 50, 90, and 150 psi. The shape of the roller compaction curves was somewhat steeper on the dry side of optimum than were those produced by laboratory compaction (Fig. 57). The roller curves on the wet side of optimum are approximately similar to the laboratory curves but lie nearer to the line of zero air voids. Inasmuch as the roller curve has a sharper peak (steeper slopes on the dry side of optimum) it indicates the soil is more sensitive to moisture changes under rolling than in compaction in the mold.



Compaction Effort

A– Modified AASHO,[a] 5 layers, 55 blows per layer, 10-lb hammer, 18-in. drop, 56,022 ft lb/cu ft
B– Intermediate,[a] 5 layers, 26 blows per layer, 10-lb hammer, 18-in. drop, 26,483 ft lb/cu ft
C– Equal to AASHO,[a] 5 layers, 12 blows per layer, 10-lb hammer, 18-in drop, 12,223 ft lb/cu ft
1– Four coverages,[b] 31,250-lb wheel load, 16.00 x 21-in tire, inflation pressure 150 psi
2– Four coverages,[b] 25,000-lb wheel load, 18 00 x 24-in tire, inflation pressure 90 psi
3– Four coverages,[b] 15,875-lb wheel load, 18.00 x 24-in. tire, inflation pressure 50 psi

[a] 6-in diam. x 4.5-in high mold. [b] Four coverages require 8 passes of roller.

Figure 57. Comparison of laboratory compaction curves (dashed lines) and pneumatic-tired roller compaction curves (solid lines) for a lean clay soil (LL=36, PI=15) (87).

The roller curves in Figure 57 represent only those for four coverages (8 passes). The effect of increasing the number of coverages is shown in Figure 41, which shows the roller compaction curves for three tire-inflation pressures and three sets of coverages. These results are plotted on a much larger scale in Figure 58 to illustrate the difference in the lines of optimum for roller and laboratory compaction. Figure 58 shows that by control of roller compactive effort by varying wheel load, tire-inflation pressure and number of coverages, roller dry unit weights from 99.6 to 108.5 percent of AASHO T 99 maximum unit weight (91.3 to 99.4 percent of Modified AASHO) maximum unit weight was attained.

The roller compaction curves developed their peak dry unit weights nearer saturation than did those compacted in the laboratory (Fig. 58). The difference between field and laboratory optimum is greatest for the lowest compactive efforts used.

Another comparison (127) between roller and laboratory compaction has been shown in Figure 43 for other illustrative purposes. Here, it may be seen that for three types of soils in all instances the roller optimum moisture contents exceeded those determined from laboratory tests. In both laboratory and field compaction, the optimum moisture content decreased with increase in compactive effort.

In Figure 43 the points of the individual maximum densities and optimum moisture contents are indicated by the figures beside the field curves. It may be noted that the value 90 appears twice adjacent to each field curve. The two values of 90 indicate two wheel loads, 11,200 and 22,400 lb each at 90-psi tire-inflation pressure. It may be seen that for these three soils, the maximum difference between the smallest and greatest roller densities were 10 pcf for the heavy clay, 8.3 pcf for the sandy clay and 3.3 pcf for the well-graded sand. The differences between extreme values in the two laboratory tests were 18.5, 16.3, and 6.8 pcf, respectively.

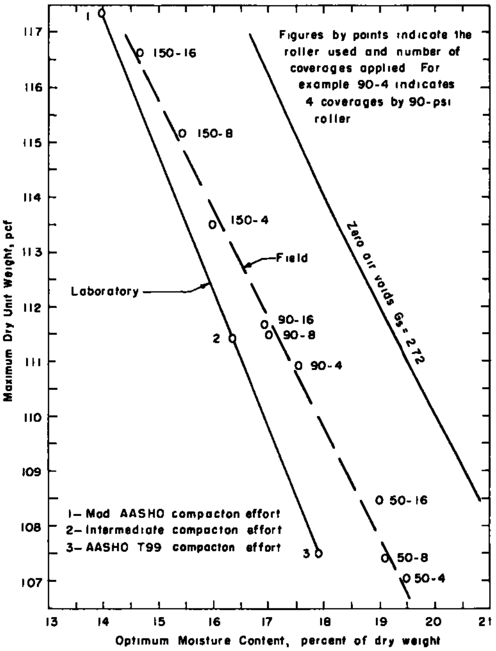


Figure 58. Influence of field and laboratory compaction effort on optimum moisture content for a lean clay soil (LL=36, PI=15). Field compaction effort by pneumatic-tired rollers having 50-, 90-, & 150-psi inflation pressures each applying 4, 8, & 16 coverages in constructing fills in lifts of 6-in. compacted thickness. Laboratory compaction effort from 12, 26, & 55 blows of 10-lb rammer, 18-in. drop, 5 layers in mold 4.5-in. high x 6-in. diameter, yielding efforts of 12,223, 26,483 & 56,022 ft lb per cu ft, respectively. (Note: Two passes required for one coverage.) (87)

FACTORS INFLUENCING PRODUCTIVE CAPACITY (OUTPUT) OF PNEUMATIC-TIRED ROLLERS

The output of pneumatic-tired rollers is influenced by the same factors that affect other types of rollers. They involve the compaction characteristics of the roller; that is, the wheel load and the tire pressure and the lift thickness that can be successfully compacted to the degree of compaction required with a nominal number of passes. They also include those operating characteristics of the roller which overlap somewhat with the compaction characteristics; namely, lift thickness and the manner in which it influences the number of passes required and whether or not these items permit

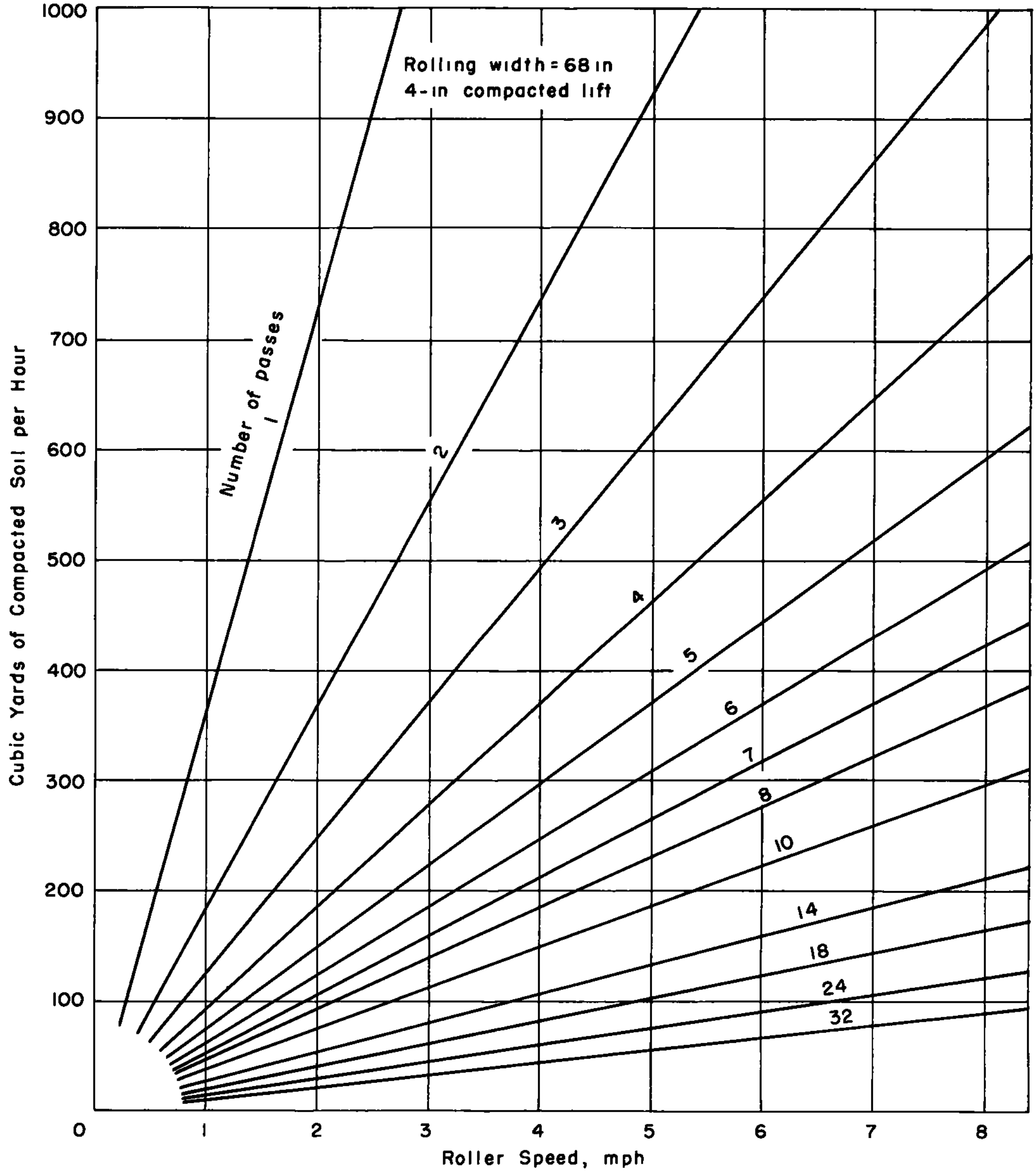


Figure 59. Maximum output in cubic yards of compacted soil per hour for lightweight pneumatic-tired rollers (having wheel loads of approximately 1,500-1,700 lb and inflation pressures of 35-50 psi). Based on continuous operation, a 68-in. rolling width, and a 4-in. compacted lift thickness.

compacting to satisfy specification requirements both as to uniformity and average dry unit weight. Other operating characteristics include rolling width and speed of travel. Operating conditions (including the moisture content of the soil) are also significant in determining output.

Data on actual output of rollers on construction projects are not available for some of the newer models of towed-type heavy-duty rollers, nor on some of the self-propelled models that have come into use recently. However, many lightweight two-axle, multiple-wheel rollers are in common use and actual records for them continue to be useful. Actual cubic yards output for rollers of 60-in. rolling width, 1,500-lb wheel load, and 35-psi tire-inflation pressure on sample construction projects are given in Table 23.

TABLE 23

OUTPUT OF 9-WHEEL, 1,500-LB WHEEL LOAD, 35-PSI TIRE-INFLATION PRESSURE ROLLERS OF 60-IN. ROLLING WIDTH ON SILTY CLAY AND SANDY, SILTY CLAY SOILS (29)

State	Loose Lift Thickness (in.)	Speed of Roller		Average No. of Trips Required to Obtain Specified Unit Weight	Average AASHO T 99 OMC (%)	Average Fill Moisture Content (%)	Volume[a] Compacted in Cu Yd per Hour
		fpm	mph				
Indiana	6	250	2.8	2.9	18.4	20.4	361
Indiana	9	175	2.0	3.9	21.6	22.9	438
Indiana	12	220	2.5	2.7	21.6	27.1	557
Ohio	6	280	3.2	4.8	17.6	15.6	220
Ohio	9	280	3.2	6.0	18.7	18.2	277

[a] Not stated whether measurement was based on excavation or compacted fill volume.

The specification requirement has marked effect on the output of a roller. In Table 23 the specifications in Indiana required compaction equivalent to 95 percent of AASHO T 99-38 maximum wet unit weight. Specifications for the Ohio project required compaction to not less than 100 percent of AASHO T 99 maximum dry unit weight.

In comparing outputs of a somewhat similar 13.44-ton, two-axle, 9-wheel pneumatic-tired roller with a 2,987-lb wheel load with a tire-inflation pressure of 36 psi (56) it was found that the roller would compact 2,000, 670, and 200 cu yd per hour on a silty clay to 90, 95, and 100 percent, respectively, of standard maximum dry unit weight, while for a gravel-sand-clay, 100 percent relative compaction was unobtainable at any number of passes (on a 9-in. loose lift).

Another listing of some interest is one given for Great Britain after a comprehensive study of the operation of various sizes and weights of pneumatic-tired rollers (127). The output is based not on optimum moisture content for either the laboratory test or the roller but rather on rolling the high moisture content soils normally existing in Great Britain to an air content of not less than 10 percent. The rollers are of three general weight classes and are not unlike some rollers used in the United States. In all instances the natural ("in-situ") moisture contents are approximately similar to the optimum moisture contents for the British Standard 1377:1948 Test No. 9 (generally similar to AASHO T 99 Method C). Compaction to a minimum of 10 percent air voids at British Standard optimum would range from about 91 to 95 percent of maximum dry unit weight for the standard test. Thus compaction would be approximately equal to 95 percent compaction, which is equivalent to minimum requirements for embankments by a number of states, some of which are in the cooler, wetter climes. The data on roller output for compaction to a minimum of 10 percent air voids at their existing moisture contents are given in Table 24.

The proper adjustment between wheel load and tire-inflation pressure; the beneficial influence of operating at the proper moisture content; the adjustment of number of passes to weight of equipment and soil moisture content; the use of the best combination of wheel load, tire-inflation pressure and lift thickness; as well as rolling at the most efficient speed have all been considered in the preceding text.

Because the productivity of a roller is so greatly dependent on speed and the number of passes, it is convenient to prepare charts for the purpose of estimating output of rollers under known operating conditions. Figures 59, 60 and 61 are examples of

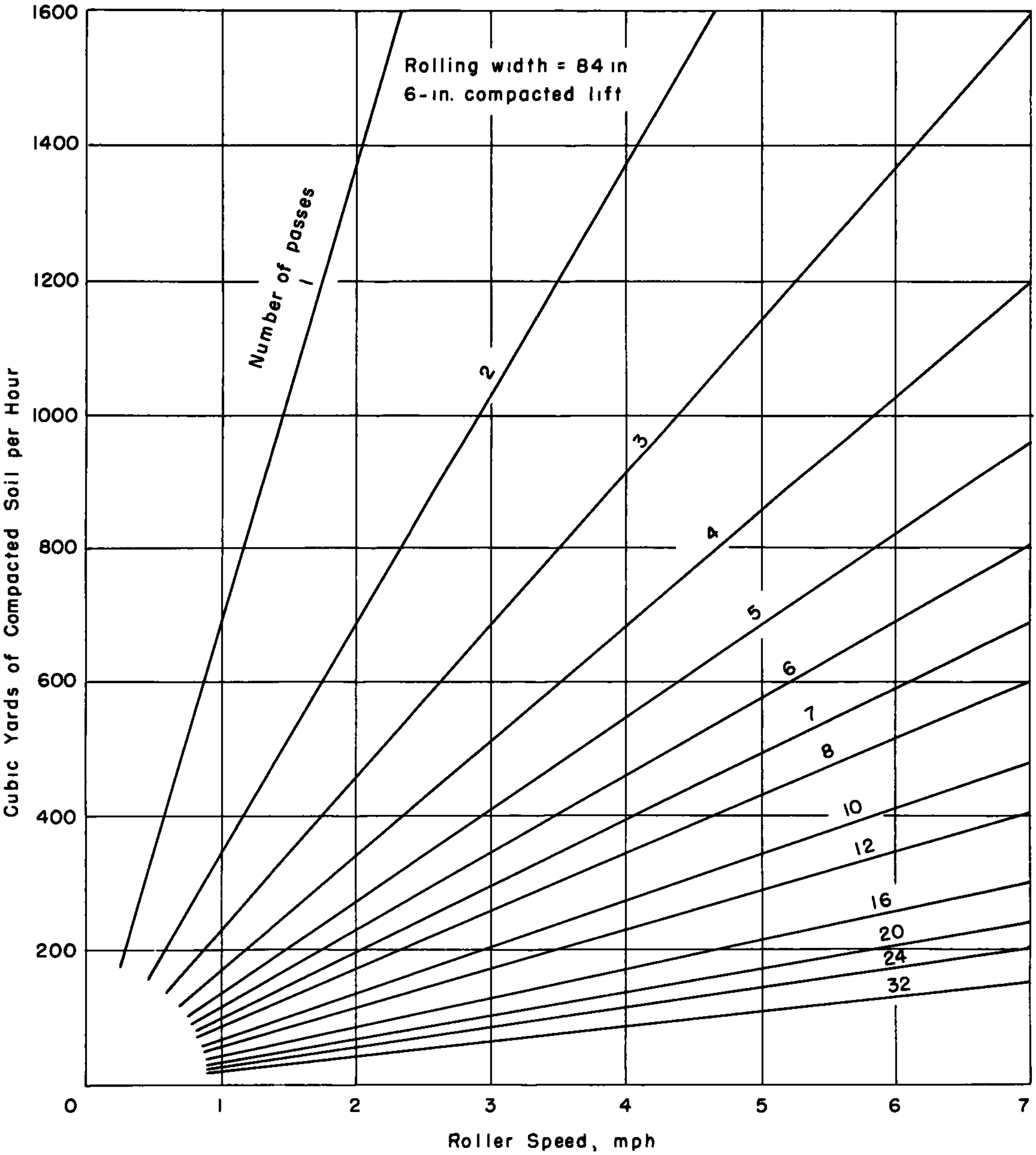


Figure 60. Maximum output in cubic yards of compacted soil per hour for medium-weight pneumatic-tired rollers (having wheel loads of approximately 2,000-5,000 lb and inflation pressures of 50-75 psi). Based on continuous operation, an 84-in. rolling width, and a 6-in. compacted lift thickness.

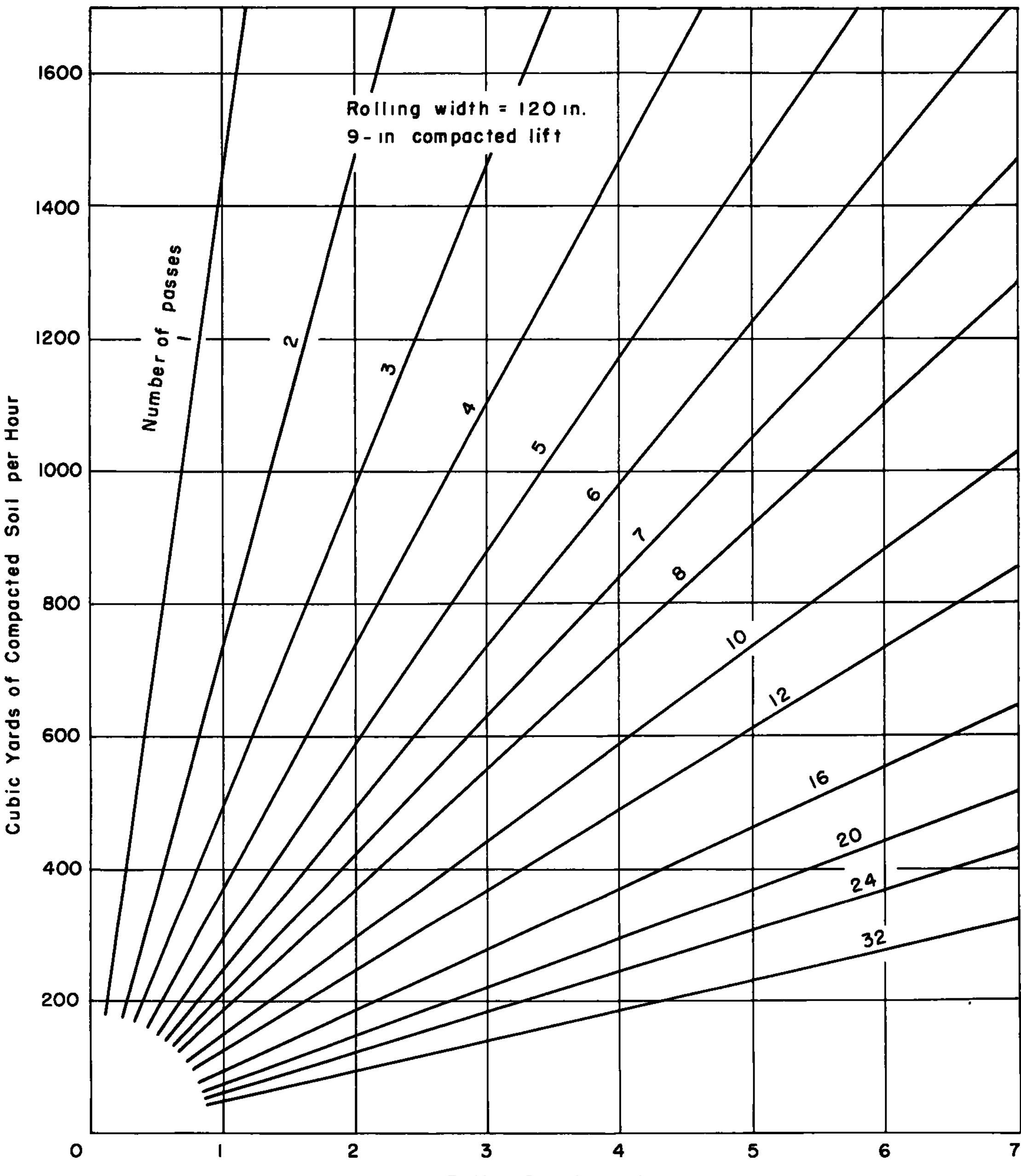


Figure 61. Maximum output in cubic yards of compacted soil per hour for heavy-weight pneumatic-tired rollers (having wheel loads up to 25,000 lb and inflation pressures up to 150 psi). Based on continuous operation, a 120-in. rolling width, and a 9-in. compacted lift thickness.

TABLE 24

AVERAGE POSSIBLE OUTPUTS OF PNEUMATIC-TIRED ROLLERS USED IN BRITISH FULL-SCALE TESTS WHEN COMPACTING TO 10 PERCENT AIR VOIDS (127)

Nominal Rating of Roller (tons)	Wheel Load (lb)	Tire Inflation Pressure (psi)	Width of Compacted Strip (in.)	Speed of Roller (fpm)	Speed of Roller (mph)	Number of Passes	Thickness of Compacted Layer (in.)	Output of Compacted Soil per Hour (cu yd/hr)
13.44	2,985	36	82	200	2.27	4	5	260
22.4	4,978	80	84	200	2.27	4	6	320
50.4	11,200	90	93	200	2.27	4	7	420
50.4	11,200	140	93	200	2.27	4	8	480
50.4	22,400	90	93	200	2.27	4	9	720
50.4	22,400	140	93	200	2.27	4	10	800

charts prepared for given sizes and weights of rollers and nominal compacted thicknesses of lift with which each may be associated. It should be kept in mind that the charts on output do not recognize soil type. Yet it has been shown repeatedly that soil type, when coupled with moisture content has strong influence on the productivity of pneumatic-tired rollers.

Full-Scale Field Tests With Vibratory Compactors

WHEN A HEAVY OBJECT (for example, a metal ball) is dropped and strikes the ground, the earth absorbs the energy developed in the fall by a compression of the soil. A part of that compression remains in the form of a permanent depression due either to compaction or displacement of the soil, or both. Another part of the compression is an elastic deformation. Because of its elastic property, the soil seeks to restore its position in keeping with the new set of conditions. In doing this, it pushes the weight up some small distance and thus starts an oscillating movement that is termed vibration. Because there is no sustaining force, the vibrations cease quickly due to the damping action of the soil. In vibratory compaction a mechanical oscillator is employed to set up the vibrations in the soil mass. Here the oscillator furnishes a sustained dynamic force that causes some of the underlying soil to respond by moving with the vibrator. The restoring force is the elasticity of the soil.

Vibration is a complex phenomenon, in that a number of factors individually and collectively influence its nature. Some of these factors that determine the nature of vibratory compactors are, as follows:

1. The frequency—that is, the number of revolutions per minute (usually referred to as cycles per minute (cpm) or cycles per second (cps)) of the oscillator.

The amplitude (displacement) which is the distance through which the machine moves in one oscillation (usually refers to the vertical distance).

3. The dynamic force, F, which is the energy from each impulse created by the centrifugal force of the oscillator (this force increases as the square of the frequency).
4. The dead (static) weight, W, of the portion of the machine that vibrates.
5. The relationship between the dynamic force, F, and the dead weight, W, expressed as the force weight ratio F/W.
6. The shape and size of the area of the vibrator contacting the soil.
7. The stability of the machine.

The foregoing items are inherent in the design of the vibratory compactor and determine the nature of the vibrations imparted to the soil. In addition, the operation of the machine in terms of speed of travel and thickness of lift, and the type of soil and its initial unit weight and moisture content have large influence on the results obtained by vibratory compaction.

Limited data on interrelationships between some of the foregoing factors insofar as they influence soil densification have been developed for experimental vibratory compactors for the soils used in the experiments (61, 60, 72, 78, 82, 106) and by theoretical studies (71). The reports on these researches should be consulted for details of the relationships established.

Of the characteristics of compactors stated previously perhaps none has received more study and discussion by researchers and engineers than frequency. Every mass system, such as a vibrator-soil system, when allowed to vibrate freely has a tendency to do so at a certain definite frequency known as the "natural" frequency. When the frequency of forced vibrations (by the vibrator) approximately coincides with the "natural" frequency of the system, the phenomenon known as "resonance" occurs (for practical purposes the "natural" and "resonant" frequencies are synonymous). Inasmuch as the maximum dynamic displacements (amplitudes) occur at resonant frequency, some investigators (60, 78, 91) have anticipated that operation at resonant frequency would produce optimum compaction of the soil. (Some of the old automobiles that bounced severely on rough roads would bounce violently at certain speeds. This violent bouncing occurred at the resonant frequency of the spring-car system. When the bouncing was damped by adding shock absorbers the bouncing reduced markedly but the resonant frequency remained relatively unchanged.) This does not infer that compaction cannot be accomplished at frequencies other than at resonance, because there are in current use commercially produced vibratory compactors of different types that operate at frequencies other than at resonance and yet produce a high degree of densification in the types of soils they were designed to compact. This is attested to by full-scale tests, the results of which are presented later.

All soils, regardless of type, respond to vibrations induced by mechanical oscillators. However, there are marked differences in the manner in which they respond and in the effect of their response in increasing soil unit weight. Cohesionless sands and sand-gravels respond differently both in manner and degree than do soils whose shear strengths are dependent mainly on cohesion.

Loose granular soils that owe their strengths principally to interparticle friction, do not have equal contact pressures between particles. Hence when they are loaded they cannot develop equal friction between particles throughout the mass. Thus, when a load is applied, some particles adjoining pore spaces move into those spaces. This movement of the particles requires a sufficient force acting through the required distance, and a sufficient time for movement to take place. If the load is suddenly released there results a further readjustment of the positions of some of the soil grains. This "release" effect explains in part why repeated loadings result in increased unit weight. Vibration consists of alternate loading and releasing the load. Simply stated, adequate vibration meets those requirements of having sufficient force (dead weight plus dynamic force) acting through the required distance (amplitude) and giving sufficient time for movement of soil grains (frequency) to take place.

In fine-grain cohesive soils it is necessary to break the bond holding the particles together before they can be moved into a more dense state. This requires a compressive force of sufficient magnitude to cause shearing displacement and plastic flow under compression. The use of resonant frequency may be significant for certain cohesive soils. Resonant frequency may be markedly lower for cohesive soils when heavy equipment is used (60, 78). This is discussed later.

After development of theory for compacting cohesive soils by vibration and evaluating the theory by constructing and testing a large vibrating base-plate-type compactor (13,200 lb in weight and having a 3- by 5-ft base plate), Converse (106) gave the following basic rules for compacting cohesive soils by vibration:

1. The dead weight unit soil pressure should be adequate for the type of soil being compacted. Values of 6 to 12 psi appeared adequate for the sandy loam (LL = 25, PI = 4) and clay loam (LL = 39, PI = 21) soils tested.
2. The frequency of the applied dynamic force should be such that the oscillator-soil mass is in resonance.
3. The dynamic force should be approximately equal to the dead weight of the oscillator.
4. The moisture content should be on the wet side of optimum as determined by the Modified AASHO laboratory compaction test. Specific recommendations were not made for vibrating rollers. Data given later indicate characteristics of rollers that influence the degree of compaction in cohesive soils.

The preceding discussion is intended to state some of the characteristics of vibratory compaction. In doing so, it shows that there is no simple definition for vibration either in terms of its characteristics or how it effects compaction of different types of soils. In other words, there is no range of frequency, or amplitude or combinations of the two that define the limits of what constitutes vibratory compaction. Researchers have used frequencies ranging from over 5,000 to 300 cpm (83 to 5 cps), and amplitudes from a few thousandths to ¼-in. or more. Dead weights used in successful vibratory compaction have ranged from about 3 psi for cohesionless soils to 12 psi or more for cohesive soils on plate-type compactors. The exact unit dead weights for vibratory rollers is not known but in studies reported here, unit weights have been up to 119 lb per inch of width of roll.

Thus, frequencies have ranged from relatively high values for machines of the weight used to values so low that they approximate the frequency of some types of tampers. Some amplitudes have been sufficiently great to constitute a tamping action.

(Amplitudes bear some relation to the firmness of the soil as it compacts causing relatively high frequency vibrators to impart impact forces under certain conditions of compaction.)

From the limited data available, and the limited studies of vibratory and impact compaction it is seen that simple definitions for the two phenomena cannot be given because the action within the soil ranges from rearrangement of sand particles by vertical and lateral movements under high frequency vibration to compression under a tamping action on cohesive soils. It should be borne in mind that as the falling metal ball produced vibrations in the soil, a tamping action will also produce oscillating movements in the soil as it is being tamped. Thus there is a tamping action in vibration at the lower frequencies and higher amplitudes, and a vibrating action associated with tamping—even in a single tamp.

EARLY HISTORY OF VIBRATORY COMPACTION

Vibration first became of concern to engineers in Europe in the design of foundations for engines and other heavy machinery usually of the type having reciprocating parts whose oscillating movements were transmitted by the foundations to the underlying soil resulting in excessively large settlements. The first studies aimed toward solution of these problems were conducted in Europe (30) and were based largely on wave propagation velocities. Special machines were built to create continuous forced vibrations and transmit them to the soil. The results of these European investigations were published in 1933 and 1934.

Among the first efforts in the United States in the use of vibration was in the development of vibratory equipment for the tamping of ballast (soil) under railroad ties (Fig. 62). The earliest patent known to be issued for use as a soil compaction device was the Jackson patent No. 1,329,049 issued January 27, 1920 on an application filed May 23, 1919 (9, 12). A second patent No. 2,015,899 issued October 12, 1935 (12) was entitled "Tamping Machine." Modification of the original patents for various uses is disclosed in other Jackson patents, including Jackson's patent No. 1, 988,315 issued January 15, 1935 for compacting surfaces by high frequency vibration. Certainly the 1920 patent was the forerunner of vibratory compactors and patent No. 2,015,899 did revolutionize the placement of mass material by vibration.

In 1936 (16) limited data were presented comparing the effectiveness of the various methods then known for the compaction of cohesionless soils. These included (a) ponding; (b) washing (sluicing); (c) compaction by impact of heavy steel plates; (d) the Delmag "bull-frog" explosion-type tampers (500 and 1,000 kg (1,102 and 2,205 lb) sizes); (e) large mechanical-type tamping machine with four 1½-ton hammers; (f) a 25-ton vibration machine; (g) rollers; (h) the FRANKI pile; and, (i) Rutteldruck, a

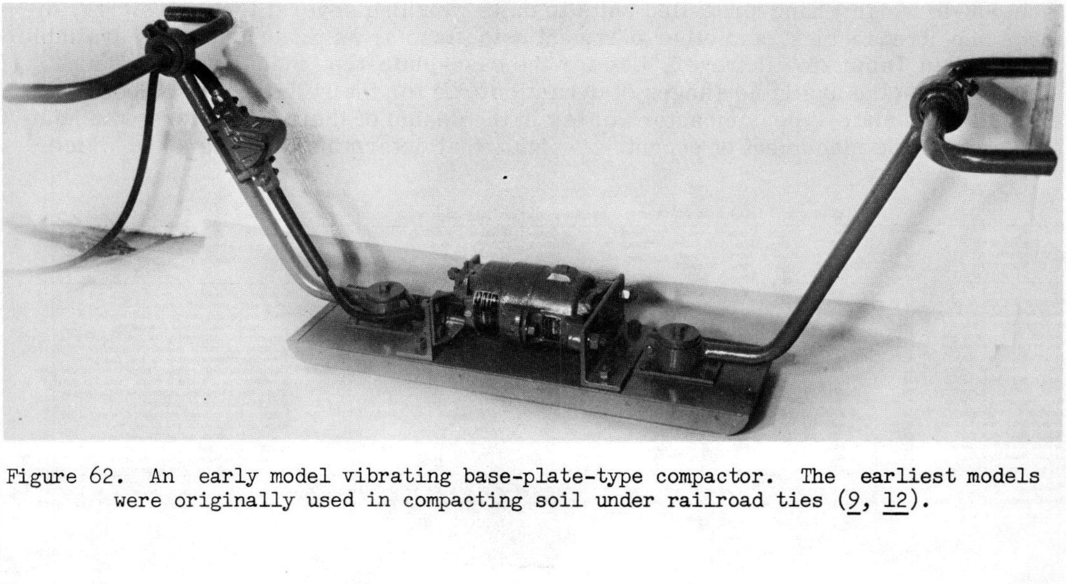


Figure 62. An early model vibrating base-plate-type compactor. The earliest models were originally used in compacting soil under railroad ties (9, 12).

deep vibration process. (See Vibroflotation for a presently used method of deep vibration of previous granular soils.) Degree of compaction was determined on the basis of relative density (RD) (see "Definitions"). Impact of heavy steel plates produced relative densities up to 50 percent, the Delmag frog up to 50 percent, and vibration up to 90 percent relative density.

In the late 1930's and early 1940's engineers faced the problem of designing pavements that would adequately support heavy airplane wheel loads in the presence of vibrations imposed by the aircraft. Thus the early technological studies concerned the bearing properties of soils under sustained vibrations by loads. Some of the early tests (30) reported in 1944 were of the form of "penetration" tests with vibrators attached to plungers up to 5 in. in diameter imposing loads on soils compacted into molds up to 15.5 in. in diameter. The tests showed that penetrations of vibrating plungers in sands were up to a maximum of 140 times greater than deformations produced by an equivalent static force (33).

These early studies in the laboratory were followed by development of laboratory vibratory compactors and the use of and testing of vibratory compactors on field projects, as well as by the extensive studies of vibration by Bernhard of Rutgers (61) and by Converse at the California Institute of Technology (60, 78).

RANGE OF SOIL TYPES INCLUDED IN FULL-SCALE TESTS

Although in the main, the vibrators were tested on granular soils non-plastic in nature, the tests did include a sufficient number of plastic soils to indicate the behavior of the compactors and the unit weights attained on soils of a plastic nature. The range of soils tested by vibratory compactors is indicated in Table 1.

TYPES AND RATINGS OF VIBRATORY COMPACTORS USED IN TESTS

Equipment employed in the tests included both the vibrating base plate (sometimes called "pan"-type compactors because of the characteristic shape of the base plate) and the vibrating roller types. Good representation was obtained in sizes among the base-plate-type compactors. The sizes ranged from small single-unit hand-operated machines weighing about 150 lb to the large tractor-mounted multiple-unit compactors weighing several tons. Although each unit was not tested under the wide range of soil types and conditions desirable, data were obtained in some instances that were indicative of their potentials and limitations as compactors. The weights, dimensions, frequencies and other characteristics of base plate compactors insofar as those data were available are given in Table 25.

The rollers tested represented a moderately wide range in sizes, types and ratings of machines, like the plate-type compactors, ranging from small, lightweight (less than 500-lb weight) hand-propelled units to units weighing several tons. Weights, dimensions, frequencies, and other pertinent data, insofar as those data were available are given in Table 26. However, like for the base-plate-type machines, few data were given on the available ranges of dynamic force for the rollers. Also, both rollers and base-plate-type compactors differ in the design of their oscillators, the number, weight and placement of eccentric weights that determine the axes about which

TABLE 25

CHARACTERISTICS OF BASE-PLATE-TYPE VIBRATORY COMPACTORS USED IN FULL-SCALE COMPACTION TESTS

Personnel or Organization Reporting Tests	Reference Number	Gross Weight of Compactor (lb)	Weight of Each Vibrating Unit (lb)	Contact Area of Base Plate (sq in.)	Unit Contact Pressure (Dead Wt) (psi)	Frequency or Range of Frequency (cps)	Frequency or Range of Frequency (cpm)	Amplitude of Vibration (in.)	Dynamic Force (psi)	Width of Compacted Strip (in.)	Speed of Travel (fpm)	Speed of Travel (mph)	Description of Unit
Allen and Linzell	37	6,400	180	306	0.59	46	2,800	0.08	-	150	10-140	0.1-1.6	Multiple-unit tractor-mounted Compactor
Washington Dept. of Hwys	55	-	-	-	-	Max[a]	-	-	-	-	2-6[b]	.02-.07	Small single-unit self-propelled Compactor
Civil Aeronautics Adminis	61A	150-370[c]	-	-	-	-	-	-	-	-	-	-	Small single-unit self-propelled Compactor
Rutgers Univ.—Bernhard	61	1,500	-	1,024	1.5	25	1,500	-	-	-	60	0.7	Single-unit experimental Compactor
Rutgers Univ.—Bernhard	61	3,300	-	1,440	2.3	26	1,500	-	-	-	18	0.2	Large single-unit, self-propelled Compactor "A" in tests
Rutgers Univ.—Bernhard	61	8,000	290	306	0.94	46	2,760	-	-	-	30	0.34	Multiple-unit tractor-mounted Compactor "B" in tests
British Road Res. Lab	62	-	-	-	-	-	-	-	-	-	-	-	Traveling vibratory concrete road finisher
British Road Res. Lab	62	-	-	-	-	-	-	-	-	-	-	-	Vibrator attached to single "large" rectangular plate
British Road Res. Lab	62	-	-	-	-	-	-	-	-	-	-	-	Same vibrator attached to single "small" circular plate
Calif. Inst. of Technology	60	13,200	-	2,160	6.1	7-27	420-1,620	0.025-0.5	6	36	36-75	0.41-0.8	Single-unit towed-type experimental Compactor
Kentucky Dept. of Hwys	75	-	450	240	1.9	37	2,200	0.25	-	-	20	0.22	Multiple-unit tractor-mounted
Swedish Road Institute	80	2,204[d]	-	1,554	1.4	12-13	700-800	-	-	32.3	15-132	0.17-1.5	Large single-unit self-propelled Compactor
British Road Res. Lab	81	4,480	-	1,700	2.6	17.5	1,050	-	-	34	-	-	Single-unit self-propelled Compactor
British Road Res. Lab	81	3,350	-	970	3.45	18.3	1,100	-	-	30	-	-	Single-unit self-propelled Compactor
British Road Res. Lab	81	530	-	280	1.9	30	1,800	-	-	15	-	-	Single-unit Compactor
British Road Res. Lab	81	1,480	-	660	2.2	20	1,200	-	-	24	-	-	Single-unit self-propelled Compactor
British Road Res. Lab	81	1,570	-	570	2.75	25	1,500	-	-	24	-	-	Single-unit self-propelled Compactor

[a] Operated at full speed [b] Operated at 2 and 6 ft per minute [c] Four different sizes of compactors used. They were of 150-, 210-, 315- and 370-lb weights [d] Listed as a one-ton compactor. Two makes were used. One was Swedish-made Model MRJ from A. B. Vibroverken. The other was of German manufacture Model AT ,000 Losenhausenwerk. They were said to be so nearly similar that the same specification holds for both vibratory compactors

TABLE 26

CHARACTERISTICS OF VIBRATORY ROLLERS USED IN FULL-SCALE COMPACTION TESTS

Personnel or Organization Reporting Tests	Reference Number	Diameter of Rolls Front (in)	Diameter of Rolls Center (in)	Diameter of Rolls Rear (in)	Width of Rolls Front (in)	Width of Rolls Center (in)	Width of Rolls Rear (in)	Roller Weights Gross (lb)	Roller Weights Load in lb Front Roll	Roller Weights Load in lb Center Roll	Roller Weights Load in lb Rear Roll	Rolling Width (in)	Speed of Travel (fpm)	Speed of Travel (mph)	Frequency or Range of Frequency (cps)	Frequency or Range of Frequency (cpm)	Ampl of Vibra (in)	Description
Allen and Linzell	37	39 4	32 3	39 4	39 4	39 4	39 4	17,650	151[a]	151[a]	151[a]	39 4	43- 350	0 49- 3 98	60	3,600	-	3-wheel tandem with center vibratory roll
Country Rds Bd (Australia)	57	-	-	-	-	-	-		-	-	-	-	88- 176	1-2	-	-	-	Not given
Rutgers Univ —Bernhard	61	44[b]	-	-	-	-	-	27,760	75[c]	-	-	-		-	17 5	1,050[d]	-	4-wheel pneumatic-tired compactor "C" in tests
British Rd Res Lab	62	-	-	-	-	-	-	450	-	-	-	-	-	-	-	-	-	Hand-propelled single-drum vibrating roller
Swedish Rd Inst	80	39 4	32 3	39 4	39 4	39 4	39 4	15,432[f]	131[a]	131[a]	131[a]	39 4	42	0 48	55	3,300	0 039[e]	3-wheel tandem with center vibratory roll
Swedish Rd Inst	80	39 4	-	-	39 4	-	-	6,614	168	-	-	39 4	-	-	29	1,750	0 039[e]	Single-drum towed-type
British Rd Res Lab	81	30	-	30	32	-	32	5,400	68	-	100	32	-	-	83	5,000	-	2-wheel tandem with front vibratory roll
British Rd Res Lab	81	21	-	-	24	-	-	480	20	-	-	24	-	-	75	4,500	-	Single-drum, hand-propelled
Central Rd Res Inst (India)	104	29 5	-	-	35 5	-	-	3,584[g]	101	-	-	35 5	50- 100	0 57- 1 14	40- 57	2,400- 3,400	-	Single-drum, self-propelled
Central Rd Res Inst (India)	104	21	-	-	24	-	-	476	20	-	-	24	-	-	75	4,500	-	Single-drum, hand-propelled
British Rd Res Lab	129	22 5	-	-	28	-	-	760	27	-	-	28	-	-	-	-	-	Single-drum, self-propelled
British Rd Res Lab	129	48	-	-	72	-	-	8,620	119	-	-	72	26- 311	0 3- 2 4	30- 38	1,800- 2,320	-	Single-drum, towed-type

[a] Weight per inch of width with vibrating roll locked tangent to rear roll [b] Tire size. [c] Tire inflation pressure. [d] Maximum frequency [e] Amplitude given as one mm [f] Listed as 7 tons (Swedish) One metric ton = 2,205 lb. [g] Listed as 1 6 tons (India). It is assumed one Indian ton is equal to 1 12 U S tons

oscillation occurs, and the degree of movement that occurs if power is adequate.

An examination of Table 25 shows that with few exceptions, there is a general uniformity of frequency and contact pressure (dead weight). However, reports did not include data on amplitude and dynamic force. An examination of Table 26 shows wide differences in frequency and very few data on the dynamic force, amplitude and depth of lift best suited for each soil type.

In designing a vibratory compactor, the oscillator may be designed to produce vibrations that are essentially in the vertical direction. However, the numbers of weights employed and their positions on the eccentrics can be arranged to produce vibrations in several directions. It is the direction of these, their frequency and their amplitude that account for differences in degree to which certain vibratory compactors compact cohesionless soils, or soils that are low in cohesion. Data given in Tables 25 and 26 do not include information on designs that may explain differences in the behavior of the compactor and in the results obtained.

COMPACTION CHARACTERISTICS OF VIBRATORY COMPACTORS

Data that are available concern pressures generated in the soil by vibratory compactors, dry unit weight and moisture content relationships, dry unit weight and number of pass relationships, the effective depth of compaction, the influence of frequency, dead weight as an influencing factor, the effect of speed of travel, the application of vibration in the construction of macadam bases, pipe bedding and backfill, the productive capacity of vibratory compactors and comparison with laboratory impact test results. In addition, a brief explanation of a commercial method of deep compaction (vibroflotation) is included.

PRESSURES GENERATED BY VIBRATING ROLLERS

Bernhard (61), Whiffin (74) and Lewis (81) reported the results of tests to measure vibration pressures generated in the soil by vibratory rollers. Bernhard made pressure measurements at various depths in a well-graded cohesive gravelly sand (about 75 percent between No's. 10 and 200 sieves) under a 4-wheel pneumatic-tired compactor weighing 27,760 lb with an additional dynamic force of 20,000 lb at a frequency of 17.5 cps (1,050 cpm). The soil had an AASHO T 99 maximum unit weight of 120 pcf at an optimum moisture content of 7 percent. Measurements of pressure were made separately at a moisture content of 7 percent under both static and dynamic compaction, at depths of 1, 2, and 3 ft. These data, taken from Figures 31, 32 and 35 of Bernhard's report (61) are given in Table 27. The ratio of peak pressures with vibration to peak pressures with no vibration for the three depths given in Table 27 are 1.22, 1.08, and 1.25.

The reports of Whiffin (74) and Lewis (81) showed measured pressures in a silty clay (LL = 40, PI = 20 with 17, 49, and 34 percent sand, silt and clay, respectively) having a moisture content of 16 percent and placed in a loose condition 20 in. in depth. The roller weighed 5,400 lb, had two rolls each 30 in. in diameter and 32 in. wide.

TABLE 27

SOIL PRESSURES DEVELOPED WITH AND WITHOUT VIBRATION BY A TWO-WHEEL PNEUMATIC-TIRED ROLLER WITH 6,940-LB WHEEL LOAD, 75-PSI TIRE-INFLATION PRESSURE AND AN ADDITIONAL DYNAMIC FORCE OF 20,000 LB AT 25 CPS (61)

Depth of Pressure Gauge (ft)	Without Vibration		With Vibration	
	Peak Pressure in Soil (psi)	Maximum Dry Unit Weight of Soil (pcf)	Peak Pressure in Soil (psi)	Maximum Dry Unit Weight of Soil (pcf)
1	5.65	116.6	6.9	122.9
2	3.70	111.7	4.0	116.6
3	1.00	108.0	1.25	110.0

Static pressures on front (vibrating) roll and rear roll were 68 and 100 lb per inch of width. The vibrator had a peak acceleration of 14 G (14 times as great as the acceleration due to gravity) and a frequency range of 80-91 cps (4,800 to 5,500 cpm).

Tests to measure pressures developed were made with the roller traveling forward as well as backward and with and without vibration of the front roll. A typical pressure record is shown in Figure 63. The rear non-vibrating roll produced a pressure diagram similar to that produced by the front roll of an 8½-ton roller. There are two pressure curves for the vibrating roll representing the upper and lower limits between which the pressure oscillated while vibrating, also there is a third curve produced by the front roll when not vibrating. The relative pressures of the two rolls are those generated by the static pressures of 68 and 100 lb per inch width of front and rear rolls, respectively. Vibration approximately doubled the maximum pressure of the front roll giving a peak pressure of 136/100 of that generated by the rear roll. The unit weights resulting are discussed later.

DRY UNIT WEIGHT VS MOISTURE CONTENT

Base-Plate-Type Compactors

Inspection of Table 25 shows that except for the tests on macadam-type roads in Ohio (37) and Kentucky (75) experimental data on the large multiple-unit base-plate-type compactors of the type normally employed in construction are limited to those given by Bernhard (61). Nevertheless, the data do include results from a wide range in dimensions of base plates, their contact unit pressures and their frequencies.

A well-documented series of tests are those performed by the Civil Aeronautics Administration (61A) in the construction of experimental base courses. Many of these were constructed by placing the material in 6-in. loose lifts and compacting them by the use of small single-unit vibratory compactors having gross weights of 150 to 370 lb. However, some construction lifts were placed in 12-in loose depths. Three types of materials were employed, a crushed rock, a gravel, and a sand. The gravel, for which most of the data are available, had about 90 percent passing the ¾-in., 70 percent passing the No. 4, 55 percent passing the No. 10, about 20 percent passing the No. 40 and about 7 percent passing the No. 200 sieves. The greatest dry unit weight attained was 142 pcf at an optimum moisture content of 6.2 percent for the Modified AASHO test and 135 pcf and 8.0 percent, respectively, for AASHO T 99. The greatest vibrated unit weight was 142 pcf at 6 to 8 percent moisture content—which

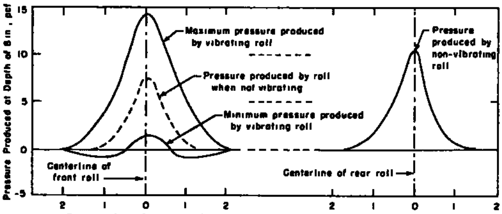


Figure 63. Pressures produced at a depth of 8 in. in a silty clay soil by a 5,400-lb vibrating roller (81).

was attained after two passes. Unit weights in the bottom half of 12-in. loose lifts were less than in the upper half. A rather complete account of the capability of a 370-lb single-unit vibrating base-plate compactor in compacting 135 4-in. lifts is given in the average values shown in the charts in Figure 64. It may be seen that in actual compaction with a limited number of passes the dry unit weight equalled or exceeded AASHO T 99 in most of the tests and in the remaining stayed within a 2-pcf limit. Moisture contents, percent passing the No. 200, and fineness modulus attest to the lack of complete uniformity of the material.

Tests were performed by British engineers (62) employing a single size vibrator, first on one size base plate and then on another size to determine the effect of size of base plate. Although details regarding the sizes of plates and types and lift thicknesses of soil were not given, the data shown in Figure 65 illustrate generally the marked effect of the dimensions of the base plate (and therefore also its contact unit pressure) in this type of compactor. The vibrator resulted in a maximum unit weight that far exceeded the value for the standard compaction test.

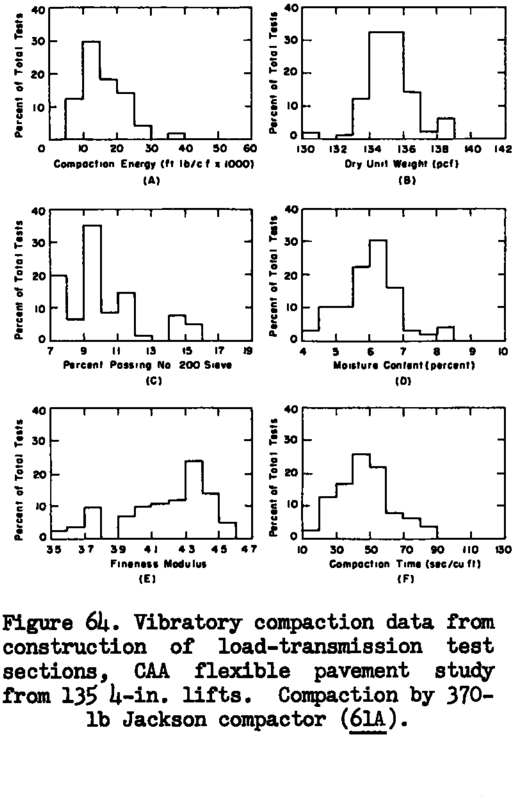


Figure 64. Vibratory compaction data from construction of load-transmission test sections, CAA flexible pavement study from 135 4-in. lifts. Compaction by 370-lb Jackson compactor (61A).

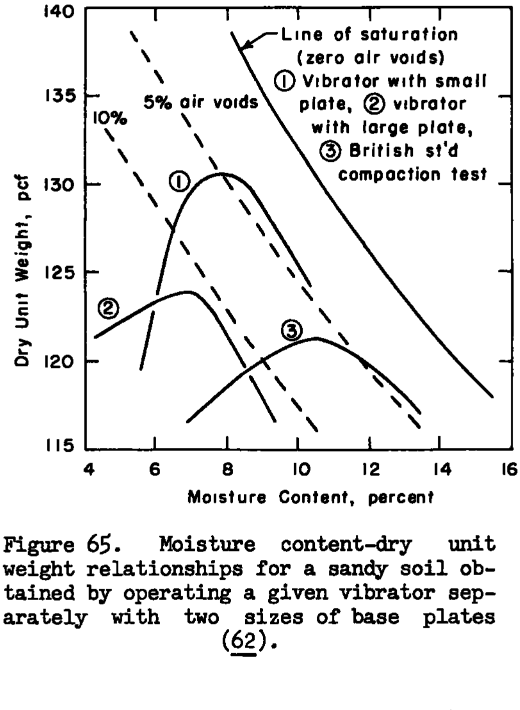


Figure 65. Moisture content-dry unit weight relationships for a sandy soil obtained by operating a given vibrator separately with two sizes of base plates (62).

The Road Research Laboratory of Great Britain tested a total of five (5) sizes of base-plate vibratory compactors (81, 129) (Table 25) (see Table 1 for Index Properties of Soils and Figure 11 for grain size distributions of soils) on four types of soils that differed widely in characteristics. For simplicity in evaluating the results on the British tests the principal data are given in Table 28. Data on laboratory tests are also given in Table 28 for later comparison with field results.

Examination of the data in Table 28 shows that two of the compactors were able to attain unit weights in excess of 100 percent of standard maximum dry unit weight for the heavy clay soil. Field optimum moisture contents were 3 to 9 percentage units dry of laboratory optimum for the standard test. Tests on a second cohesive soil, a sandy-clay yielded unit weights ranging from 101.7 to 106.4 percent of British standard maximum unit weight and 90.5 to 92.1 percent of Modified AASHO maximum unit weight. (Sandy clays described in two separate reports differed in their

TABLE 28

MAXIMUM DRY UNIT WEIGHTS AND OPTIMUM MOISTURE CONTENTS FROM LABORATORY COMPACTION TESTS COMPARED WITH VALUES OBTAINED IN TESTS WITH SINGLE-UNIT VIBRATING BASE-PLATE-TYPE COMPACTORS (81, 129)

	Laboratory Compaction					Data on Compactor and its Operation							Field Compaction			
	Brit. Std.			Mod. AASHO									Dry Unit Weight			
									Frequency							
Soil Type	Reference Number	Max. Dry Unit Wt (pcf)	OMC (%)	Max. Dry Unit Wt (pcf)	OMC (%)	Gross Weight (lb)	Contact Area (sq in.)	Static Pressure (psi)	(cps)	(cpm)	Number of Coverages	Loose Lift Thickness	Max. (pcf)	% of Brit.[a] Std Max.	% of Mod AASHO Max	OMC (%)
Heavy clay	129	99	24	116	16	1,480	660	2 2	20	1,200	16	9 or 12	103	104.0	88 8	21
Heavy clay	129	99	24	116	16	1,570	570	2.75	25	1,500	16	9 or 12	87	87.9	75.0	20
Heavy clay	81	97	26	113	17	4,480	1,700	2.6	17.5	1,050	16	9	98	101.0	86 7	17
Sandy clay	81	115	14	128	11	4,480	1,700	2.6	17.5	1,050	16	9	117	101 7	91.4	15
Sandy clay	129	109	16	126	12	1,480	660	2.2	20	1,200	16	9 or 12	116	106.4	92.1	15
Sandy clay	129	109	16	126	12	1,570	570	2.75	25	1,500	16	9 or 12	114	104.6	90 5	16
Well-graded sand	81	121	11	130	9	530	280	1 9	30	1,800	10	9	128	105.8	98.5	10
Well-graded sand	129	121	11	130	9	1,480	660	2.2	20	1,200	16	9 or 12	135	111 6	103 8	8
Well-graded sand	129	121	11	130	9	1,570	570	2.75	25	1,500	16	9 or 12	130	107 4	100.0	9
Well-graded sand	81	121	11	130	9	3,350	970	3.45	18.3	1,100	16	9 or 12	129	106 6	99.2	9
Well-graded sand	81	121	11	130	9	4,480	1,700	2.6	17 5	1,050	16	9	128	105.8	98.5	9
Gravel-sand-clay	81	129	9	138	7	530	280	1.9	30.0	1,800	10	9	127	98 4	91.2	9
Gravel-sand-clay	129	129	9	138	7	1,480	660	2.2	20.0	1,200	16	9 or 12	141	109 3	102.2	6
Gravel-sand-clay	129	129	9	138	7	1,570	570	2.75	25.0	1,500	16	9 or 12	137	106.2	99.2	7
Gravel-sand-clay	81	129	9	138	7	3,350	970	3.45	18.3	1,100	16	9 or 12	135	104.7	97.8	8
Gravel-sand-clay	81	129	9	138	7	4,480	1,700	2 6	17.5	1,050	16	9 or 12	137	106.2	99.2	7

[a] British Standard 1377:1948 Compaction Test is similar to AASHO T99-57 Method C.

index properties. The soil (81) had a LL = 27, PI = 8, while the sandy clay (129) had a LL = 40 and a PI = 20.) Field optimum moisture contents were equal to one percent less than optimum for the standard test. These values are somewhat surprising in view of the popularly held opinion that vibrators of this type cannot produce unit weights of the order shown, even after a large number of coverages.

The field results on the well-graded sand and gravel-sand-clay (81, 129) were well in excess of the values from the standard test, the sand ranging from 105.8 to 111.6 percent of standard maximum dry unit weight and 98.5 to 103.8 percent of Modified AASHO maximum dry unit weight. Field optimums were on the average, identical with optimums from the modified test. Maximum dry unit weights for the gravel-sand-clay ranged from 98.4 to 109.3 percent of standard unit weight. Field optimums were approximately equal to optimum for the modified test. Additional data on the characteristics of soils compacted by base-plate compactors follow under appropriate paragraphs.

Vibrating Rollers

The results of three types of rolling tests using vibratory rollers are reported here. These three types of tests consist of (1) compacting macadams as reported by Allen and Linzell (37); or of (2) rolling soils dry or at a moisture content that may or may not be near their laboratory optimum moisture contents (57, 61, 62, 80); or (3) rolling soils at a number of moisture contents to develop sufficient data on moisture content-unit weight relationships that the maximum roller unit weights can be determined from the roller-compaction curve in a manner similar to that employed in obtaining AASHO T 99 maximum dry unit weight from the laboratory compaction curve (81, 104, 129).

Data from each group of tests are useful but data from group (3) is most useful because it establishes the limits attainable by the roller within the limits of the test. Data from group (1) are given later under "Effectiveness of Vibration in Constructing Macadam Bases." Data from group (2) are limited. Tests from Australia (57) showed that a vibratory roller (data on roller not given) could, in 16 passes, compact a sand to 111 percent of Modified AASHO maximum dry unit weight, and, in 64 passes could compact a well-graded crushed rock to approximately 99 percent of Modified AASHO maximum unit weight. A four-wheel heavy (27,760-lb) pneumatic-tired roller (61) in two passes produced a dry unit weight in excess of 102 percent of AASHO T 99 maximum, to a depth in excess of 36 in. Tire pressure was 75 psi and frequency 1,050 cpm. A small (450-lb) self-propelled vibrating roller produced a unit weight of 108.9 percent of British standard maximum (62). (Details on the soils and roller are not given.) Swedish tests with two types of rollers (80) yielded less than 100 percent relative compaction in 6 trips on an 8-in. depth of compacted soil (loose lift initially was about 30 in. deep).

The results of type (3) tests in Great Britain (81, 129) and India (104) are summar-

TABLE 29

MAXIMUM DRY UNIT WEIGHTS AND OPTIMUM MOISTURE CONTENTS FROM LABORATORY COMPACTION TESTS COMPARED WITH VALUES OBTAINED IN FIELD COMPACTION EXPERIMENTS WITH VIBRATING ROLLERS OF VARIOUS TYPES AND RATINGS (81, 104, 129)

		Laboratory Compaction				Data on Compactor and Its Operation									Field Compaction				
		AASHO T99 or[a] Equiv		Mod AASHO				Frequency		Speed of Travel			Lift Thickness		Dry Unit Weight				
Soil Type	Reference Number	Max Dry Unit Wt (pcf)	OMC (%)	Max Dry Unit Wt (pcf)	OMC (%)	Gross Weight (lb)	Lb/In of Width (lb)	(cps)	(cpm)	(fpm)	(mph)	Coverages	Loose (in.)	Comp (in.)	Max (pcf)	% of AASHO T99[a] Max	% of Mod AASHO Max	Opt (%) Roller Moist	Remarks
Heavy clay	129	99	24	116	16	760	27	75	4,500	-	-	32	9	-	92	92.9	79.3	28	Single-drum self-propelled
Heavy clay	81	97	26	113	17	5,400	68	83	5,000	-	-	32	9	-	96	99.0	85.0	21	Two-wheel tandem, vibrating front roll
Heavy clay	129	99	24	116	16	8,620	119	38.7	2,320	-	-	32	13	-	106	107.1	91.4	21	Single-drum towed type
Silty clay	81	104	21	120	14	5,400	68	83	5,000	-	-	32	9	-	110	105.8	91.7	17	Two-wheel tandem, vibrating front roll
Sandy clay	129	109	16	126	12	760	27	75	4,500	-	-	32	9	-	100	91.7	79.4	16	Single-drum, self-propelled
Sandy clay	129	109	16	126	12	8,620	119	38.7	2,320	-	-	32	13	-	119	109.2	94.4	14	Single-drum, towed type
Well-graded sand	81	121	11	130	9	480	21	75	4,500	-	-	32	9	-	124	102.5	95.4	11	Single-drum, hand-propelled
Well-graded sand	129	121	11	130	9	760	27	75	4,500	-	-	32	9	-	127	105.0	97.7	9	Single-drum, self-propelled
Well-graded sand	81	121	11	130	9	5,400	68	83	5,000	-	-	32	9	-	133	109.9	102.3	7	Two-wheel tandem, vibrating front roll
Well-graded sand	129	121	11	130	9	8,620	119	38.7	2,320	-	-	32	13	-	137	113.2	105.4	7	Single-drum, towed type
Gravel-sand-clay	81	129	9	138	7	480	21	75	4,500	-	-	32	9	-	123	95.3	89.6	8	Single-drum, hand-propelled
Gravel-sand-clay	129	129	9	138	7	760	27	75	4,500	-	-	32	9	-	132	102.3	95.7	8	Single-drum self-propelled
Gravel-sand-clay	81	129	9	138	7	5,400	68	83	5,000	-	-	32	9	-	139	107.7	100.7	6	Two-wheel tandem, vibrating front roll
Gravel-sand-clay	129	129	9	138	7	8,620	119	38.7	2,320	-	-	32	13	-	145	112.4	105.1	6	Single-drum, towed type
Clayey soil	104	116	13	-	-	3,584	101	50	3,000	50-100	0.57-1.14	64	9	-	114	98.4	-	11.5	Single-drum, self-propelled
Silty soil	104	117	12	-	-	3,584	101	50	3,000	50-100	0.57-1.14	64	9	-	112	95.7	-	10.5	Single-drum, self-propelled
Sandy soil	104	116	10	-	-	3,584	101	50	3,000	50-100	0.57-1.14	64	9	-	112	96.7	-	11.0	Single-drum, self-propelled

[a] British Standard 1377 test is approximately similar to AASHO T 99 Method. The Central Road Research Institute of India employ the British Standard Test. Note: The above values are only for those tests that developed a moisture content-dry unit weight for the roller for each soil tested.

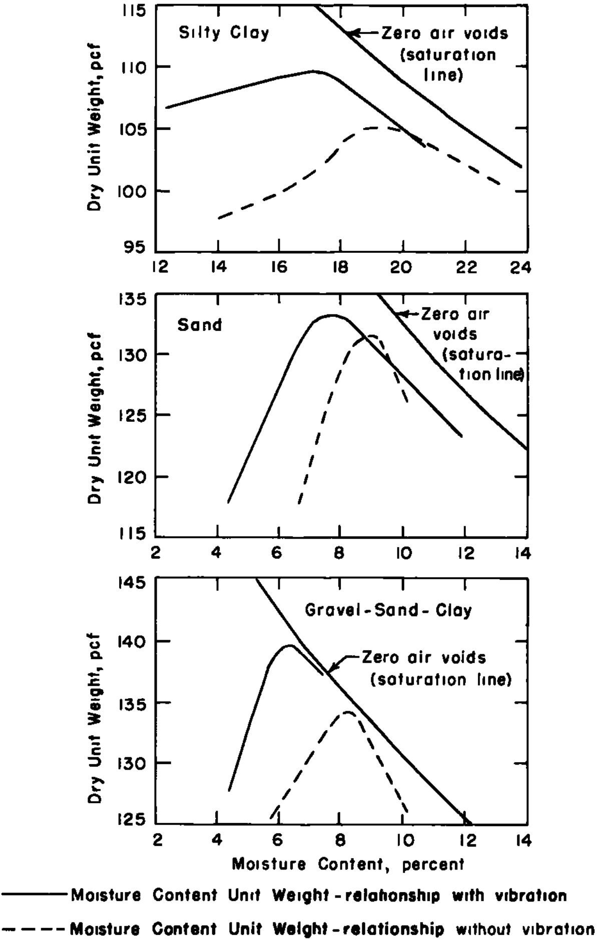


Figure 66. Roller compaction curves for three soils when compacted in 9-in. loose lifts by 32 passes of a two-wheel tandem roller with vibrating front roll. Roll pressures were 68 lb per in. on front roll and 100 lb per in. on rear roll. Total roller weight was 5,400 lb (81).

ized in Table 29. The data show that even a 480-lb hand-propelled roller can attain unit weights in excess of 100 percent of the equivalent of AASHO T 99 maximum unit weight on a sandy soil. The 760-lb roller further increased the unit weight on either the sand or the gravel-sand-clay, but could produce values of relative compaction no greater than 92.9 and 91.7 percent on the heavy clay and sandy clay soils. The 5,400-lb roller can best be appraised in terms of the compression on the vibratory roll inasmuch as it is a two-wheel tandem type. It produced dry unit weights equivalent to 110 percent relative compaction (102 percent of Modified AASHO maximum). The results of rolling by the 5,400-lb roller with and without benefit of vibration are shown in Figure 66. Differences in dry unit weight with and without vibration are greater for a 4.3-ton single-drum towed-type roller, however, those data are not available for reproduction. (The results of all tests on the heavy (8,620-lb) roller are available for inspection (110) but are not available for reproduction until publication. Only the maximum dry unit weights and optimum moisture contents presented in a paper at the 1960 meeting of the Highway Research Board (129) are available for reproduction.)

The results of vibration studies in India (104) with a single-drum self-propelled vibrating roller having a dead weight of 101 lb per inch width of roll ranged between 95 and 100 percent relative compaction (British standard test). It is rather unique to find this one set of data uniformly lower than values found in other tests employing similar lift thicknesses. The results are given in Table 29. No explanation is offered for these lesser unit weights on alluvial soils other than that in some previous tests with rollers some evaporation occurred.

DRY UNIT WEIGHT VS NUMBER OF PASSES

For no other type of compactor is the number of passes (and speed of travel) more significant than for the vibratory compactor, for collectively they determine the number of dynamic load applications available for a given point. This is true for vibrating base-plate-type compactors as well as rollers although the relative degree of significance for the two types of rollers for different types of soils and depths is unknown. Therefore, any data presented herein by this committee that indicates a comparison of the degree of densification by the two types, regardless of number of passes, are given simply as data for the rollers concerned on the soils tested.

The effect of number of passes differs markedly depending on the size and rating of the compactor, and the soil type and its moisture content as has been shown for the other types of compactors (rollers). Therefore these are given here only as examples of data to illustrate the manner in which the number of passes influence the dry unit weight.

Base-Plate-Type Compactors

Tests have been made on a non-cohesive "plaster" sand (55) with 99 percent passing a No. 10, 35 percent passing a No. 40, and 1 percent passing a No. 200 mesh sieve. The "plaster" sand exhibited the following laboratory dry unit weights in pcf: loose dry 93.6, saturated 98.2, AASHO T 99 maximum 99.6, vibrated dry (syntron vibratory table) 106.3, and vibrated saturated 106.3 pcf. Data on the effect of increasing the number of passes from one to five are given in Table 30.

A difference in moisture contents for tests numbers 1 and 2 compared to those for tests 3 and 4 may have accounted for some differences in dry unit weights. However, because the laboratory vibrated unit weights for dry and saturated conditions were identical it is believed the results indicate the effect of numbers of passes.

For a given lift thickness, the soil type, its water content and the nature of the compactor influence the number of passes required to compact to a given percent relative compaction. The Swedish Road Institute (80) performed tests on soils from two airfields (Barkåkra and Halmsjö) to determine the influence of the number of passes on the dry unit weight of the soils. Three granular soils from the Barkåkra Airfield were tested. They consisted of a uniformly graded sand, a gravel and a crushed gravel (grain size distribution curves 4, 5, and 6 in Figure 12). Values of maximum dry unit weight and optimum moisture content were for the sand 106.7 pcf at 13.5 percent; for the gravel 129.8 pcf at 8.5 percent; and for the crushed gravel 135.4 pcf at 7.5 percent, respectively. The results of tests to determine the effect of number of trips are shown in Figure 67. Here, it may be seen that with one exception, all soils were

TABLE 30

EFFECT OF NUMBER OF PASSES ON DRY UNIT WEIGHT OF A FINE COHESIONLESS SAND WHEN COMPACTED BY A SINGLE-UNIT, SELF-PROPELLED VIBRATING BASE-PLATE COMPACTOR (55)

		Dry Unit Weight			
Test No.	Moisture Content (%)	Compacted by Vibrator (pcf)	% of AASHO T 99 Max (pcf)	% of Lab Vibrated (pcf)	Number of Passes
1	4.6	104.1	107.8	97.9	1 pass, upper half of 11-in. layer
2	7.0	109.0	112.8	102.5	5 passes, upper half of 11-in. layer
3	6.6	106.5	110.2	100.2	1 pass, lower half of 11-in. layer
4	15.3	110.0	113.9	103.5	5 passes, lower half of 11-in. layer

Note: Tests performed at normal speed for vibrator.

compacted to 100 percent relative compaction or more after five trips, the sandy soil attaining full compaction after two trips. Coarse gravels require a grater number of passes than do fine gravelly sands and sands. The vibrating base-plate compactor employed in these tests had a gross weight of 2,204 lb, a contact area of 1,554 sq in. and a frequency of 700 to 800 cpm. Speed of travel range was from 15 to 132 fpm (0.17 to 1.5 mph). Comparison of moisture content data in Figure 67 shows that except for the sand and one test on the gravel, the moisture contents at which compaction occurred were of the order of laboratory optimum.

A separate experiment was performed using a similar compactor to determine the most suitable lift thickness for the base-plate compactor in the compaction of a sand. Inasmuch as the unit weight observations were made after various numbers of passes and the moisture content was near optimum, these data are of especial interest in that they indicate the effect of lift thickness on unit weight when lift thickness is a variable. The results are shown in Figure 68. The sand is identified by line number 3 in the grain-size distribution chart in Figure 12.

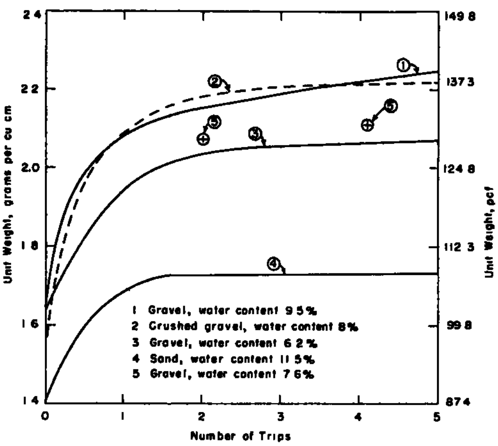


Figure 67. Relationship between unit weight and number of trips of a single-unit heavy pan-type vibratory compactor for three types of soil (Swedish Barkåkra Airfield) (80).

Tests by the British Road Research Laboratory (81, 129) included measurements of the effect of number of passes on dry unit weight of soil by single-unit base-plate compactors ranging in gross weight from 530 to 4,480 lb, and in contact area from 280 to 1,700 sq in. Descriptions of these base-plate compactors are given in Table 25. Results giving maximum field unit weights and optimum moisture contents (for the compactor) are compared with laboratory values in Table 28. Tests by the single-unit compactors when compacting the well-graded sand showed that dry unit weights were attained in 3 to 4 passes that were not increased substantially by increasing the number of passes to ten or more. Early tests by the Michigan State Highway Department (38A) showed that maximum densities in excess of AASHO T 99 or the Michigan cone method were obtained by the most effective of the small vibratory compactors tested. Thus, in summarizing, it may be said that insofar as data are available, base-plate vibratory compactors attain their maximum unit weights in a relatively small number of passes, depending on the thickness of lift being compacted.

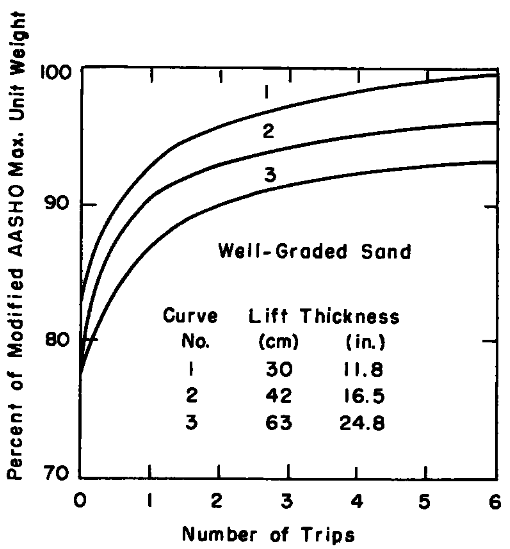


Figure 68. Relation between lift thickness, unit weight and number of trips of a single-unit pan-type vibratory compactor (80).

Vibrating Rollers

Vibrating rollers have shown an ability in the attainment of high values of dry unit weight that insofar as can be detected from data available from full-scale field tests does not differ from that of the vibrating base-plate-type compactor. Data on the relative number of passes necessary to attain a given percent relative compaction are, however, insufficient from which to form conclusions. Some comparison is possible from tests performed in Sweden (80) and in Great Britain. In most instances in these tests the base-plate-type compactor required a slightly lesser number of trips to attain a given percent relative compaction. This is illustrated later under "Comparison of Results from Different Types of Vibratory Equipment."

UNIT WEIGHT VS DEPTH

For no other compactors are such extravagant claims made concerning the depth to which they will compact soil as they are for vibratory compactors. Some of these claims made by manufacturers concern the compaction of cohesionless sands to meet certain requirements of percent relative compaction, sometimes to depths of 4 ft or more. They include both the base-plate and roller types of compactors. Somewhat similar claims have been made by engineers who have constructed full-scale experimental models of field compactors (61, 60, 78, 82).

Adequate evidence that vibratory compactors will compact certain non-cohesive soils to greater depths than other types of compactors is found in reports on vibratory compaction. Moderately well-graded medium to fine cohesionless sands respond to compaction to depths up to 5 ft or more, depending on compaction requirements, type and rating of compactor, etc. Compaction to lesser depths but depths that are in excess of those attained by static rolling can be done with relatively lightweight base-plate-type or roller-type compactors.

Tests were made on a non-cohesive "building" sand (55) by a small single-unit base-plate compactor. The sand contained the following percents passing the given sieve numbers: No. 4-97, No. 10-85, No. 100-26 and No. 200-1 percent. Values of percent relative compaction of 112 for the 0-5-in. depth, 109 for the 8½-13-in. depth, and 100.8 percent of AASHO T 99 maximum for the 14- to 20- in. depth attest to the ability of the lightweight compactor to compact to average high unit weights to substantial depths. The foregoing values are for moisture contents ranging from 5.0 to 6.8. It should be recalled that for fine-grained soils the effect of moisture content can mask the effect of depth as was shown in Table 30 which presented data for a "plaster" sand compacted by the identical vibrator producing the results described here.

TABLE 31

DATA ON COMPACTORS USED IN TESTS BY BERNHARD (61)

Type of Compactor	Travel Speed (fps)	Contact Area (sq in.)	Gross Weight (lb)	Dynamic Force at a Given Speed (lb at cps)
Compactor A, single-unit base-plate type	0.3	1,440	3,300	4,000 at 25
Compactor B, multiple-unit base-plate type	0.5	306[a]	8,000	5,700 at 40
Compactor C, 4-wheel pneumatic	-	-	27,760[b]	20,000 at 17.5
(12:00 x 20 x 14-ply tires at 75 psi)			12,500[c]	

[a] Area of each individual "shoe" or "pad."
[b] Fully loaded.
[c] Empty.

Bernhard (61) performed tests on a cohesive (cohesion = 6 psi) silty sand having about 10 percent gravel (¾-in. max size) and about 10 percent fines (passing the No. 200 sieve). The nature of the vibrators are indicated in Tables 25 and 26. However, the data are assembled for greater convenience in Table 31. The results of the tests at a stated number of runs are shown in Figure 69 in plots of dry unit weight and percent relative compaction vs depth. It may be seen that even for this slightly cohesive soil both the base-plate type and the heavy pneumatic-tired roller produced values of relative compaction at 2-ft depths equal to approximately 100 percent of AASHO T 99 maximum unit weight or greater. Values at the 1-ft depth were substantially greater than AASHO T 99 maximum.

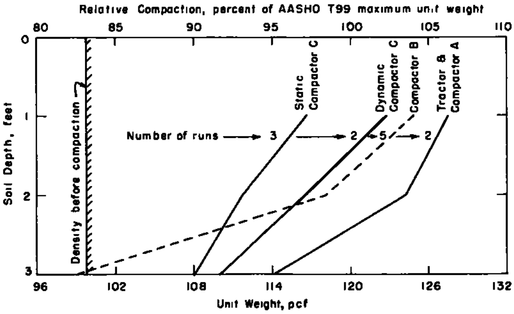


Figure 69. Static and vibratory compaction of a cohesive silt-gravel sand vs depth for various compactors at a soil moisture content of 7 percent (61).

Converse (60) employing a towed-type experimental base-plate-type compactor with a contact area of 2,160 sq in.; dead loads of 9,200 and 13,200 lb; and operating frequencies of 13.8 to 18 cps; an average speed of 0.6 to 1.25 fps produced values of relative compaction of at least 95 percent of Modified AASHO for depths of 1 to 1.5 ft and values of 93 to 96 percent for depths of 2 to 5 ft. Effective depth of compaction in granular soils was two to three times the width of the plate but for cohesive soils was limited to the width of the plate.

The Swedish Road Institute (80) observed the depth of compaction by three types of vibratory compactors on three types of soil: morainic soil containing a high proportion of fines, a mo soil consisting essentially of sand and silt, and a well-graded sand. The depth vs dry unit weight for these three soils compacted by a 3.3-ton towed-type vibratory roller, and when compacted by a 2,204-lb single-unit base-plate vibratory compactor (Table 25), are shown in Figure 70 except that for the moraine soil data are shown only for the roller. (Note the base-plate type yielded the greatest dry unit weights. Weights for the towed-type and 3-wheel tandem roller with center vibrating roll yielded almost similar results.) Figure 70B shows dry unit weight expressed in percent of Modified AASHO maximum dry unit weight vs depth expressed in centimeters (on left-hand scale) and inches (on right-hand scale). Both the moraine and mo soils failed to attain 90 percent relative compaction in the few trips over the very thick (initially up to 30-in. loose depth) lifts employed in these tests. However, the sand compacted by the vibrating roller averages approximately 90 percent of Modified AASHO maximum dry unit weight for almost the 5-ft depth shown. The average value for the 5-ft depth for the base-plate compactor is well in excess of the 90 percent value sometimes employed in embankment specifications. The aforementioned data establish the fact that for granular soils having little or no cohesion, a vibratory compactor of adequate weight

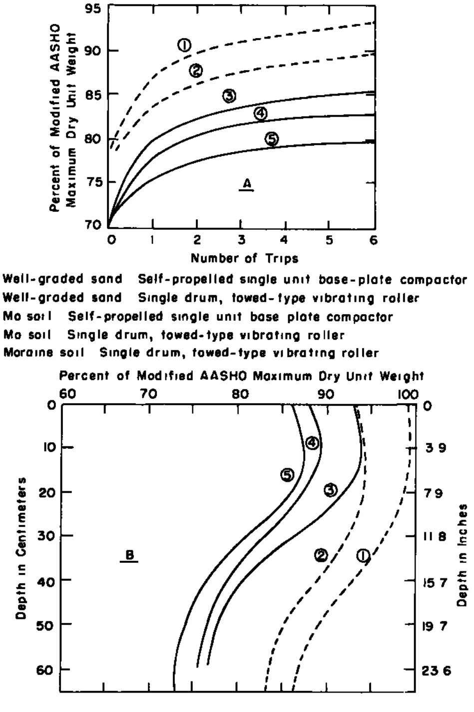


Figure 70. Relationships between unit weight and number of trips and depth of compaction for two types of compactors on two types of soil (80).

and having the proper design characteristics can attain high average dry unit weights to depths far greater than formerly attainable.

It may be noted from Figure 70B that the less cohesive the soil, the more nearly vertical is the unit weight gradient. The more clayey the soil the flatter the gradient. Vibration compaction data in the process of being published will show very flat unit weight vs depth gradients for highly cohesive soils. In other words, they will not differ materially from those shown for other types of compaction equipment.

LATERAL COMPACTION

Large size (3- by 4-ft+) base-plate-type compactors influenced the unit weight of sands laterally as well as vertically. In an experiment (60) where the vibrator did not move laterally for 20 sec, between depths of 2 and 4 ft and at a distance 3 ft from the vibrator centerline, dry unit weights increased 2 to 5 percentage units in one test and 2 percentage units in another test.

DRY UNIT WEIGHT VS FREQUENCY

The natural frequency at which a given material vibrates freely is dependent on its composition, structure, and dry unit weight. When vibrations are impressed on different materials, the natural frequency becomes one characteristic of the vibrator-soil system and differs with differences in the vibrator as well as the characteristics of the soil. Few data are available to illustrate the direct effect of unit weight. A German source (30) showed that a certain vibrator weighing 5,950 lb on a loaded area of 9.3 sq ft (1,339 sq in.) was used in a special study. The natural frequencies of this vibrator plus soil was found to range from 760 cpm for peat to 2,040 cpm for sandstone. Some of the values obtained are given in Table 32.

TABLE 32

NATURAL FREQUENCIES OF VIBRATOR-SOIL SYSTEMS WHEN VIBRATED BY AN EARLY GERMAN-TYPE VIBRATOR (30)

Nature of Soil or Rock	Natural Frequency	
	cps	cpm
Six feet of peat overlying sand	12.5	750
Six feet old fill of sand with remnants of peat	19.1	1,145
Gravelly sand with clay lenses	19.4	1,165
Old traffic compacted slag fill	21.3	1,280
Lias clay, moist	23.8	1,430
Very uniform medium sand	24.1	1,445
Uniform coarse sand	26.2	1,570
Quite dry tertiary clay	27.5	1,650
Limestone, undisturbed rock	30.0	1,800
Sandstone, undisturbed rock	34.0	2,040

Tests with a 1.8-ton single-drum self-propelled vibrating roller (104) showed a small but consistent relationship between dry unit weight and frequency that is illustrated for a sandy soil and a clayey soil by the two plots in Figure 71. The maximum dry unit weight of the sandy soil (LL = 26, PI = 6) occurred at a frequency of 3,000 cpm, while the clayey soil (LL = 31, PI = 13) exhibited a minimum unit weight at about 2,600 cpm and increased with increase in frequency within the range of the test. In an unpublished report (110) all soil types showed some relationship with frequency but the effect ranged from about 1 pcf for a heavy clay to about 7 pcf for a gravel-sand-clay.

The California Institute of Technology in their reports of compaction studies of sands (60) and of cohesive soils (78, 82) placed emphasis on the fact that "Since the maximum dynamic displacements occur at resonant frequency it was anticipated that operations at this frequency would produce optimum compaction of the soil" (60).

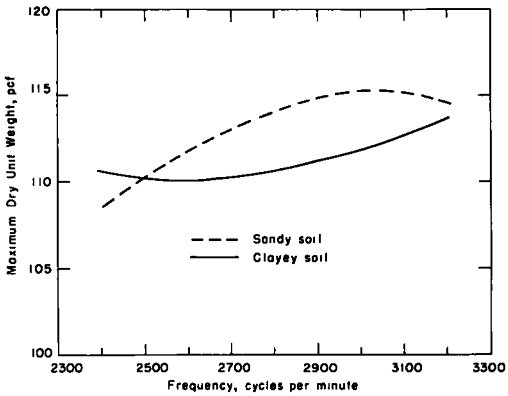


Figure 71. Relation between unit weight and frequency of a 1.8-ton single drum self-propelled vibrating roller after 64 passes on 9-in. loose lifts for a sandy soil (LL = 26, PI = 6) and a clayey soil (LL = 31, PI = 13) (104).

In summarizing the influence of frequency on dry unit weight, the limited data available indicate that both the amplitude and frequency strongly influence the degree of compaction and that the magnitude of each individual value is related to soil type (shape and size of the particles to be moved) as well as to moisture content. For a single compactor, the frequency may have a marked influence on the number of passes necessary to produce a given percent relative compaction. Dry unit weight often increases with increase in frequency to a maximum that may or may not be the resonant frequency. It depends on the nature of the vibrator and the type and state of the soil.

Even though the influence of frequency may be small for some vibrator-soil combinations, it is of sufficient magnitude for some vibrator-soil combinations to make it worthwhile adjusting the frequency where practicable, provided the soil has sufficient uniformity. The authors see no reason why vibratory compactors, powered for variable speed, cannot come equipped with indicators to indicate frequency.

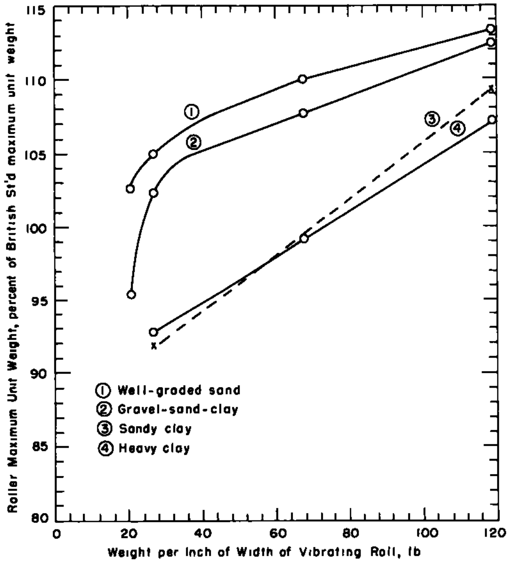


Figure 72. Relationship between roller maximum unit weight and weight per inch width of vibrating roll for four vibratory rollers compacting different types of soil in 9-in. loose lifts, except for heaviest roller which compacted soils in 13-in. loose lifts (81, 129.)

DRY UNIT WEIGHT VS DYNAMIC FORCE, DEAD WEIGHT AND FORCE/ WEIGHT RATIO

Even in experimental studies designed to evaluate these separate effects (60, 78, 82) these parameters were so interrelated that it was not possible to evaluate their separate influences completely. Although some manufacturers provide data on dynamic force, the reports of full-scale tests on commercially manufactured vibrators did not provide data on dynamic forces, hence it was not possible to determine the effectiveness of these forces in producing unit weight. Some reports produced compaction data on rollers with and without benefit of operating the vibrating mechanism. These data have been shown in Figures 66 and 69. Earth pressure data due to dynamic forces have been shown in Figure 63.

Dry Unit Weight Vs Dead Weight

Although the dynamic force of most of the vibrators employed in the tests was not known, the dead weights of the vibrat-

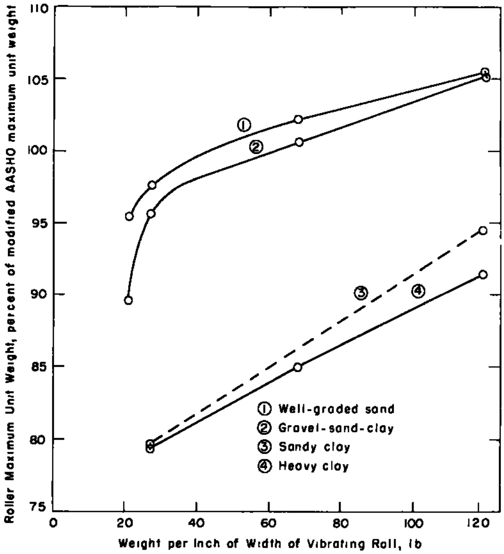


Figure 73. Relationship between roller maximum unit weight and weight per inch width of vibrating roll for four vibratory rollers compacting different types of soil in 9-in. loose lifts, except for heaviest roller which compacted soils in 13-in. loose lifts (81, 129).

ing rollers (in terms of lb per inch width of roll) that were vibrated (81, 129) bore a distinct relationship to the roller-produced maximum dry unit weight. This is shown in Figure 72 in which the roller maximum unit weight is expressed in terms of percent of British Standard maximum dry unit weight. It should be noted that there is a distinct grouping of the data from the clayey soils compared to that from the granular soils. This grouping becomes even more apparent and further separates the two general types of soils when data are expressed in terms of percent of Modified AASHO maximum as shown on Figure 73. It is of interest to note that the vibratory roller maximum dry unit weight vs weight per inch width of roll displayed no tendency to "level off" at the higher values of static weight.

Plots of static weight per square inch vs maximum compactor dry unit weight expressed as percent relative compaction for four base-plate-type compactors operating on two types of soils are shown in Figure 74. The significance of the relationships indicated in these plots in Figure 74 are not fully understood because of known differences in sizes of contact area, and frequency and unknown differences in magnitude of displacement (amplitude).

DRY UNIT WEIGHT VS SPEED OF TRAVEL OF VIBRATORY COMPACTORS

For no other compactor is speed of travel as significant as for a vibratory compactor because its number of vibrations per minute are not tied to its forward speed. Thus the forward speed determines the number of applications of dynamic force to a given point yet the literature contains few data to indicate the effect of speed. Examples can serve to indicate the effect. For a small single-unit base-plate compactor, one leveling pass plus one pass at 2 fpm produced a dry unit weight of 103.8 pcf (107.5 percent relative compaction) while one leveling pass plus one pass at 12 fpm produced a dry unit weight of 101.1 pcf (104.7 percent relative compaction). In another similar test one pass at 2 fpm gave a dry unit weight of 106.2 pcf while one pass at 6 fpm gave 100.1 pcf. On another project where a vibratory roller was employed tests were made to determine dry unit weights obtained at speeds of about 25 and about 200 fpm. After 8 passes, the greater speed resulted in a dry unit weight of about 126 pcf while the 25 fpm speed resulted in a unit weight of 135 pcf. Additional passes at each speed increased the unit weights obtained. However, after 16 passes the difference between the unit weights for the two speeds was considerably less. Generally, the slower the speed of travel, the more vibrations at a given point, and the lesser the number of passes required to attain a given

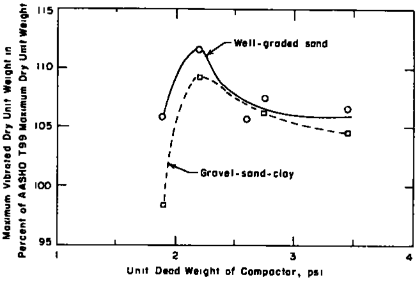


Figure 74. Relationship between unit dead weight and maximum dry unit weight for four single-unit pan-type vibratory compactors in compacting two non-plastic granular soils by 16 passes in 9-in. or 12-in. loose lifts (81, 129).

dry unit weight and the greater the unit weight for a given number of passes.

EFFECTIVENESS OF VIBRATION IN CONSTRUCTING MACADAM BASES

Several tests have been made to determine the effectiveness of vibratory compactors in the construction of macadam bases. One report (37) describes the performance of both a base-plate-type compactor and a vibrating roller. Aggregates consisted of 3½- to 1½-in. coarse material and ⅜ in. to No. 100 screenings.

Tests With the Vibrating Roller

The roller, then an experimental model being tested by a manufacturer consisted of a three-wheel tandem type, the intermediate roll being a vibrating roller. Gross weight was 15,430 lb. Ballasted weight was 17,650 lb. The weight of the center vibrating roll assembly was 2,000 lb, the roll being 32.3 in. in diameter and 39.4 in. wide. Frequency was 3,000 cpm. The report states that the weight of the vibrating roll, when locked in place, was 129 lb per inch of width.

Crushed limestone coarse aggregate was spread in lifts of 4 to 6 in. (one 8-in. lift was used) to total depths of 10 in. Dry screenings at 15 lb per sq yd (psy) vanished after one pass of the roller. Up to 1½-in. depth of screenings could be vibrated into a 4-in. lift of coarse aggregate in two passes. Three passes were required to vibrate screenings into a 10-in. depth of coarse aggregate. There was some question if the vibrator was as effective in keying the coarse aggregate as was a 3-wheel-type roller having a compression of at least 350 lb per in. of width of drive roll.

Tests With Multiple-Unit Vibrating Base-Plate-Type Compactor

Tests similar to the aforementioned (37) were made on slag coarse aggregate in an 8-in. macadam laid in two courses. Keying was with a 10-ton 3-wheel roller. The multiple-unit vibratory compactor weighed 6,400 lb and had 6 "shoes," each 20 x 25 in., each weighing 180 lb. Frequency was 2,800 cpm and amplitude 0.08 in.

After placing the layer of coarse aggregate, one-third of the screenings required were spread and vibrated into place with one pass of the vibrator. The remaining screenings were applied in two increments. The base was then wetted, followed by additional rolling and vibration.

The ratio of aggregates used may be computed from the weights used. They were: for project (a) an 8-in. course on 31,772 sq yd, CA = 7,642 lb, and screenings = 3,278 lb; for project (b) a 9-in. course on 19,653 sq yd, CA = 6,702 lb, and screenings = 2,299 lb; and, for project (c) an 8-in. course on 8,488 sq yd, CA = 2,555 lb, and screenings = 876 lb. These weights result in ratios of weights of coarse aggregate to screenings of 2.3, 2.9, and 3.3, respectively.

Another project (75) also employed the multiple-unit base-plate compactor. Coarse aggregate passed a 4-in. sieve with not more than 10 percent passing a 1½-in. sieve. Screenings were of ½-in. maximum size. One pass of the vibrator at its lowest speed (20 fpm) was used in keying the coarse stone. Screenings were placed in three applications consisting of 50, 25 and 25 percent with the compactor operating at a speed of 20 fpm. The final 25 percent was placed by dry brooming and rolling followed by wetting, brooming and rolling until a slurry filled all surface voids. The base was 8 in. thick. High unit weights were attained. The unit weights ranged from a low of 135.4 pcf with 27.8 percent screenings to a high of 142.9 pcf with 30.6 percent screenings. The data are summarized in Table 33.

VIBRATORY COMPACTION OF PIPE BEDDING AND BACKFILL

A special research project (105) by the Bureau of Reclamation was initiated to compare results of various methods of placing pipe bedding and backfill. The researches were performed by using 24- and 48-in. pipes. The methods of placing the bedding and the backfill, the equipment used, and some of the average unit weights attained are given in Table 34.

The test results and observations showed that an excellent backfill of high unit

TABLE 33

TEST DATA PERTAINING TO A VIBRATED MACADAM BASE (75)

Location (Station)	Dry Unit Weight (pcf)	Screenings (%)	Percent of Solid Dry Unit Weight
60 + 00	139.7	33.6	82.7
80 + 14	135.4	27.8	80.3
105 + 21	138.6	29.0	82.1
120 + 50	137.4	34.3	81.4
120 + 00	140.3	33.9	83.2
124 + 00	142.9	30.6	84.7

weight can be obtained at the sides and under the pipe by saturating and vibrating sands and sandy gravels. The vibrator must have the dimensions and power to provide strong vibrations in the area being compacted. Large size, flexible shaft concrete vibrators

TABLE 34

PARTIAL RESULTS OF CONDUIT BACKFILL TESTS[a] OVER 48-IN. DIAMETER PIPE (105)

Placement Condition	Equipment	Average Dry Unit Wt Below 80-Deg Line (% Bureau of Reclamation Max)[b]
Dumped dry, 1 ft over pipe		66
Vibrated dry, 1 ft over pipe	Small flexible shaft vibrator[c]	73
Tamped dry in 6-in. layers	Air tamper[d]	87
Tamped in 6-in. layers at OMC to 80-deg line	Air tamper	94
Vibrated at OMC to 80-deg line	Small flexible shaft vibrator	91
Jetted to 80-deg line	½-in. pipe jet	92
Jetted to 1 ft over pipe	½-in. pipe jet	86
Saturated and vibrated to 80-deg line	Small flexible shaft vibrator	91
Saturated and vibrated to 1 ft over pipe	Small flexible shaft vibrator	91
Saturated and vibrated to 80-deg line	Large flexible shaft vibrator[e]	100
Saturated and vibrated to 1 ft over pipe	Large flexible shaft vibrator	99

[a] Three backfill materials were placed by the methods shown in Table 34. The bottom of the pit was filled with 2 ft of clean sand. Free-draining sands and sandy gravels were used as backfill materials.

[b] Bur. of Recl. method employs ⅟₂₀-cu ft mold but uses same compactive effort as AASHO T 99 (12,375 ft lb per cu ft).

[c] 1½- by 18-in. head, ½-hp electric motor, 4,500 rpm.

[d] Pneumatic tamper, 34 lb, 100-psi air pressure.

[e] 2⅛-by 10¾-in. head, ¾-hp electric, 9,500 rpm.

were adequate in that they permitted penetration to the underside of the pipe. The superimposed load of the backfill aided in the compaction of the underlying material.

Backfill Materials

Inasmuch as the limits of fines (percent passing No. 200 sieve) were not known for available sands and gravels, a general laboratory research program was initiated for the purpose of observing the effect of fines on dry unit weight and on the permeability rate (105), the latter determining whether or not the materials would densify properly under vibration. The results on four types of materials are shown in Figure 75. (The four basic types of materials are described under the four plots in Figure 75. The "fines" used to vary the percent passing the No. 200 sieve were a loess soil.)

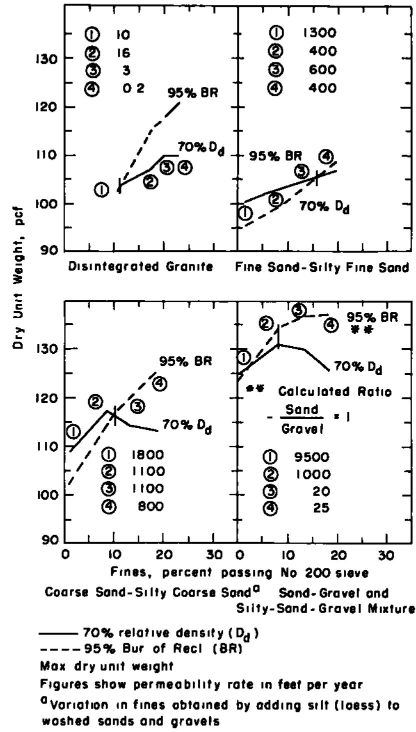


Figure 75. Effect of fines on unit weight (105).

The relative density criteria were considered (105) to be applicable only to relatively free-draining materials. Therefore as the fines were increased a point is reached where the Bureau of Reclamation impact compaction test for maximum dry unit weight must be used. The problem of construction control is then to determine which method is applicable. The field control adopted was based on the criterion that produced the highest density. Thus, for a borderline soil the density requirement was based on 70 percent relative density or the specified percent of the Bureau of Reclamation impact test maximum dry density, whichever produced the greater density.

For all materials tested, the fines content ranged from 8 to 16 percent. The unified soil classification system is used as an aid in selecting soils for use in bedding and backfill. The coarse-grained soils can be catalogued as to suitability, as follows:

1. GW, GP, SW and SP soils are suitable. (Fines are limited to 5 percent by definition.)
2. Borderline GW-GN, GW-GC, GP-GM and GP-GC soils containing less than 8 percent fines are usually suitable.
3. Borderline SW-SM, SP-SM and SP-SC soils are suitable. (Fines in these soils are limited to 12 percent by definition.)
4. SM and SC soils require special consideration. They may or may not be suitable.

COMPARISON OF RESULTS FROM DIFFERENT TYPES AND RATINGS OF VIBRATORY COMPACTORS

The tests performed by the British (81, 129) and Swedish (80) organizations offer some opportunity for comparing the effectiveness of the base-plate-type vibratory compactor with that of the vibratory roller, although the comparison is based on a very few sizes and ratings of machines. No multiple-unit base-plate-type compactor was employed, hence all data on vibrating base-plate compactors were for single-unit devices.

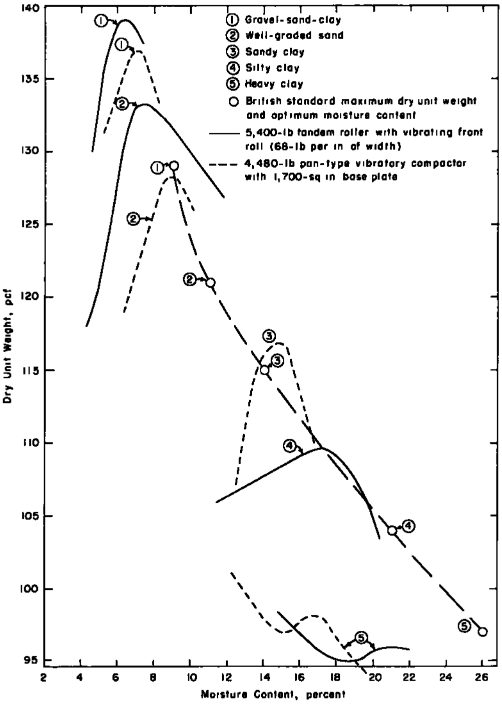


Figure 76. Roller compaction curves for 5,400-lb tandem roller with vibrating front roll (81).

Examples of field vibratory compaction curves for four types of soils for a base-plate-type compactor and a vibrating roller are shown in Figure 76. Here the plate type produced the higher values of dry unit weight on two soils and the roller did the same on the two other soils. This situation could well have been reversed had the unit dead weights and dynamic forces been substantially different. Another type of comparison is made in Figure 77 which illustrates, in terms of percent relative compaction for both AASHO T 99 and Modified AASHO, the greatest maximum dry unit weights that were obtained in the field in the full-scale tests. This comparison shows no significant difference between maximum dry unit weights that can be produced by the two types of equipment. Comparisons on the basis of numbers of passes have in some instances showed a lower number of trips required for one type over the other, whereas other tests have shown opposite results.

The effect of frequency and unit dead weight have been discussed and data presented to show their effects. Least evaluated in the tests was the item of dynamic force, because it was not available for all of the test equipment. There can be little doubt about the effect of dead weight of vibratory rollers. This is illustrated by Figures 72, 73 and 74 showing relationships between roller dead weight and compacted soil unit weights.

The marked effect of dead weight of the vibrating roll of a vibratory roller on the vibrated soil dry unit weights for three types of soil is illustrated in Figure 77A. Here also are shown the roller maximum dry unit weights for the same soil obtained by conventional three-wheel rollers of much greater weight per inch width of roll. For a well-graded sand (soil No. 1) and a gravel-sand-clay (soil No. 2) the maximum vibrated dry unit weights for a vibrating roller having a dead weight of 119 lb per inch width of roll were 112.3 and 113.2 percent of British standard maximum dry unit weight, while corresponding values for a

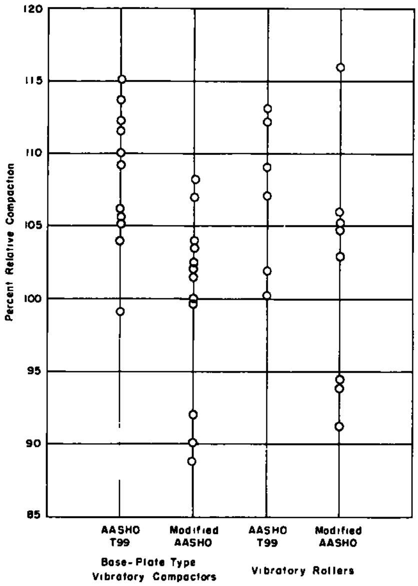


Figure 77. Some of the greatest percentages of relative compaction attained in tests on base-plate-type vibratory compactors and vibratory rollers on soils ranging from heavy clays to non-plastic granular types. The lesser percentages of relative compaction are for the plastic soils.

3-wheel roller having a weight of 310 lb per in. of width of roll were 109.1 and 107.0 percent, respectively. The combinations of dead weight, dynamic force, frequency, etc., that combine to make a vibrator that produces the greatest unit weights are not evident from data available.

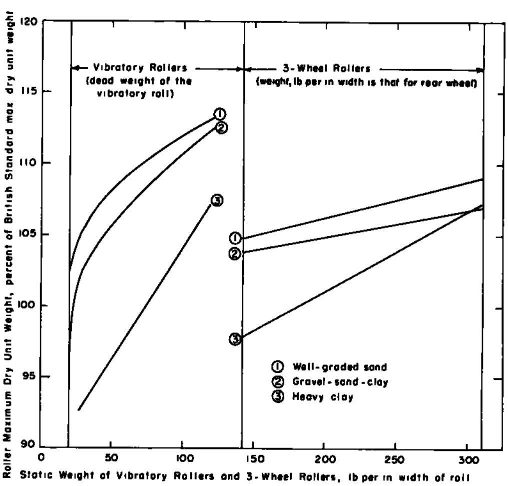


Figure 77A. Relationship between roller maximum unit weight and static weight for vibrating rollers and non-vibrating 3-wheel-type rollers on three types of soils (56, 81, 129).

COMPARISON OF FIELD VIBRATORY COMPACTION WITH LABORATORY IMPACT COMPACTION

The maximum field vibrated dry unit weight and maximum dry unit weight from the laboratory impact test bear no direct relationship to each other. It is not difficult to compute the energy applied to the soil in the laboratory impact test but it is in many instances for cohesionless soils difficult to determine the proportion of that energy converted into increase in unit weight. Thus, there is now no acceptable valid basis for comparing the unit weights determined by the two methods. Although work has been done toward the development of a standard laboratory vibration test, that work remains incomplete and the necessity for specifying a standard test calls for the use of AASHO T 99 or AASHO T 180.

Actual comparisons of field and laboratory results are made throughout the entire section on compaction by vibration. Figure 64 shows the distribution of dry unit weight in percent of total tests on one project to indicate range of and frequency of distribution of various percentages of unit weight. Figure 66 relates dry unit weight to moisture content with and without vibration, Figures 67 and 68 illustrate the effect of number of trips on unit weight or on percent relative compaction, Figure 69 shows field compaction in terms of percent relative compaction, Figure 71 illustrates a relationship between frequency and unit weight, and Figure 76 shows typical field vibratory compaction curves compared with points of laboratory maximum dry unit weight and optimum moisture content for the same soils. Figure 77 shows maximum dry unit weights from full-scale field tests expressed in terms of percent compaction. It is believed that data shown here will indicate well what can be expected of vibratory compactors operating on actual construction projects.

PRODUCTIVE CAPACITY OF VIBRATORY COMPACTORS

Vibratory compactors, especially when they include those improperly used in compacting soils for which they were not designed, may exhibit more extreme ranges in output than any other type of compactor. For example, and although vibratory compactors are seldom recommended by their manufacturers for the compaction of heavy clays, suppose a 6-ft wide vibrating roller traveling at a rate of 1.4 mph is used to construct a 6-in. compacted layer of heavy clay to 95 percent of AASHO T 99 maximum dry unit weight, and that 7 passes of the roller were required. Thus, the roller would be compacting soil in 1 hr, as follows:

$$\frac{0.5 \times 6 \times 1.4 \times 5{,}280}{7 \times 27} = 117 \text{ cu yd per hour}$$

Suppose the compactor is employed to compact a sandy loam subgrade to 100 percent AASHO T 99 maximum, but because of the sandy nature of the soil the machine is capable of compacting a 9-in. thick (compacted thickness) strip in 5 passes, the quan-

TABLE 35

APPROXIMATE POSSIBLE OUTPUTS OF COMPACTORS TESTED BY THE BRITISH ROAD RESEARCH LABORATORY IN COMPACTING SOIL TO A STATE OF COMPACTION CORRESPONDING TO 10 PERCENT AIR VOIDS (129)

Type of Compactor	Average Output of Compactor: Width of Strip Compacted (in.)	Speed of Travel (fpm)	Speed of Travel (mph)	Number of Passes Required	Area Compacted Per Hour (sq yd)	Depth of Compacted Layer (in.)	Output of Compacted Soil per Hour (cu yd)
480-lb vibrating roller (hand-propelled)	24	30	0.34	8	42	3	3.5
760-lb vibrating roller	28	60	0.68	16	49	6	8.2
8,620-lb vibrating roller	72	120	1.36	6	670	6	110
530-lb base-plate-type compactor	15	28	0.32	3	65	5	9
1,480-lb base-plate-type compactor	24	60	0.68	4	170	8	37
1,570-lb base-plate-type compactor	24	42	0.48	2	230	6	39
3,350-lb base-plate-type compactor	30	25	0.28	2	170	12	57
4,480-lb base-plate-type compactor	34	27	0.31	2	210	12	70

tity, even when it is required to compact to 100 percent relative compaction, becomes

$$\frac{0.75 \times 6 \times 1.4 \times 5{,}280}{5 \times 27} = 246 \text{ cu yd per hour}$$

In making a third supposition, the compactor is used in densifying a cohesionless sand into an embankment at 95 percent relative compaction. Suppose the vibrator is capable of developing an average satisfactory degree of compaction to a depth of 3 ft in two passes. Here the output becomes

$$\frac{3 \times 6 \times 1.4 \times 5{,}280}{2 \times 27} = 616 \text{ cu yd per hour}$$

These and even greater differences in values have occurred with vibratory compactors.

The values computed are for continuous operation at the stated speed. Adjustments can be made for time required for turning, and other delays, and plots can be made to indicate the ranges of output for compactors of different dimensions and compacting ability. In some instances two or more rows of vibrating base plates are constructed into a single compactor to increase capacity. In others two or more towed-type vibrating rollers are towed by a single tractor to increase capacity without increasing manpower requirements.

Bernhard (61) compared the productive capacities of vibratory compactors (see

TABLE 36

COMPARISON OF VALUES FROM LABORATORY COMPACTION TESTS WITH VALUES OF DRY UNIT WEIGHT EQUIVALENT TO COMPACTION TO 10 PERCENT AIR VOIDS AT IN-PLACE MOISTURE CONTENTS OCCURRING IN THE BRITISH ISLES

Type of Soil	AASHO T 99 or Its Near Equivalent: Max Dry Unit Wt (pcf)	AASHO T 99 or Its Near Equivalent: OMC (%)	Mod. AASHO or Its Near Equivalent: Max Dry Unit Wt (pcf)	Mod. AASHO or Its Near Equivalent: OMC (%)	Limiting Values of In-Place Moisture Content in the British Isles[a]: Min (%)	Limiting Values of In-Place Moisture Content in the British Isles[a]: Max (%)	Limiting Values of Dry Unit Weight Determined by 10% Air Voids and "In-Place" Moisture Contents — Range in Unit Weights with Limiting Moisture Content: Max (pcf and %)	Range in Unit Weights with Limiting Moisture Content: Min (pcf and %)	Range in Relative Compaction with Limiting Moisture Contents: Max (% and %)	Range in Relative Compaction with Limiting Moisture Contents: Min (% and %)
Heavy clay	99	24	116	16	24	28	95.0 at 24	88.0 at 28	96.0 at 24	88.8 at 28
Sandy clay	109	16	126	12	16	21	106.3 at 16	97.0 at 21	97.5 at 16	89.0 at 21
Well-graded sand	121	11	130	9	7	11	127.5 at 7	117.0 at 11	105.4 at 7	96.7 at 11
Gravel-sand-clay	129	9	138	7	5	9	132.5 at 5	121.5 at 9[b]	102.7 at 5	94.2 at 9

[a] Average moisture content range (81).

[b] Extrapolated.

Tables 25 and 26 for descriptions of vibrators) used in compacting the cohesive silty sand gravel to 95 percent of AASHO T 99 relative compaction. The greatest output was attained by compactor C, a 14-ton, 4-wheel pneumatic-tired roller (tire pressure 75 psi) operating as a vibratory roller (over 1,300 cu yd per hour). Compactor A, a large commercial single-unit base-plate-type vibrator compacted 600 cu yd per hour. The rather large outputs were due to the effective depth of compaction by these vibrators.

The British Road Research Laboratory (129) after testing several sizes and ratings of vibratory rollers and base-plate-type compactors prepared a table showing the estimated output in cu yd per hour for each of the compactors. These estimates are summarized in Table 35. The values of output in cu yd per hour (given in Table 35) are for operation of the compactor 50 min out of each hour. The values of output given in cu yd per hour are for compacting the soil to a unit dry weight equivalent to that at 10 percent air voids for the average natural moisture content at which that soil exists in Great Britain. This is of especial interest because in large areas of the United States the fine-grained clayey soils have a similar tendency to exist at moisture contents ranging from optimum to the plastic limit, while in other areas, clayey soils become dry during the summer and wet during the fall, winter and spring seasons. Thus, here, as in Great Britain, there are areas where the soil exists within a range of moisture contents that is broad for clayey soils and quite narrow for sandy and gravelly soils.

In other words, there are areas where a type of specification based on "in-place" moisture content could be a practicable approach to compaction of embankments. Examples of the maximum dry unit weights and optimum moisture contents from the laboratory tests are given in Table 36; also given are the limiting values of in-place moistures contents that would be encountered during construction (81). The limiting values of dry unit weights and percent ages of relative compaction have been determined for compaction to a condition of 10 percent air voids and are also given in Table 36.

Deep Compaction by Vibration (Vibroflotation)

A FORUM of very deep vibration known by the trade name of Vibroflotation has been used to increase the unit weight of deep loose sands to improve their bearing capacities, as foundations for structures. Since this report is devoted to surface compaction, details regarding Vibroflotation are not given here. Those interested may consult the following (20, 40, 43, 45, 73, 83, 86, and 123).

Compaction with Track-Type Tractors

PRIOR TO THE DEVELOPMENT of vibratory compactors, track-type tractors were often used in the compaction of sands. The opinion has been held that there is a marked vibratory movement associated with the track movement, and therefore the older and more worn the tractor the better it serves as a compactor. The maneuverability of the tractor has also made it a useful tool in compacting areas difficult of access.

Full-scale tests have been performed on five sizes and models of track-type tractors. They include the model RD-8 34,500-lb tractor tested at gross weights of 34,500 and 80,000 lb (44, 46, 47) by the Corps of Engineers; two models (40-HP and 80-HP) weighing 12,840 and 24,160 lb tested by the British Road Research laboratory (81); and a model D-7 weighing 24,250 lb tested by the Swedish Road Institute (80). Altogether, these tractors were tested on a clayey sand (44), a silty clay (46), a fine sand (47), a heavy clay, a silty clay, a sand, and a gravel-sand-clay (81) and a stony gravel (80). Data on the soils are given in Table 1 and in Figures 10, 11, and 12.

DRY UNIT WEIGHT VS MOISTURE CONTENT

The track-type tractor produced compaction curves that have moisture content-dry unit weight relationships quite similar to those characteristic of other types of rollers, hence examples need not be shown here. Average data concerning moisture content-dry unit weight relationships for all the tests are given in Table 37 under "Tractor Compaction." Average values of optimum for the tractor ranged from one to two percentage units greater than AASHO T 99 laboratory values for the clayey sand and silty clay (44, 46) tested by the Corps of Engineers. Maximum tractor compacted unit weights after only 2 or 3 passes were approximately 97 percent of AASHO T 99 maximum unit weight. Results of the Swedish test yielded 100 percent of Modified AASHO value on a stony gravel after six coverages. The British Compaction was more intensive, requiring 32 passes. All values of tractor optimum moisture content were less than laboratory optimum for the British standard test, the differences ranging from two to four percentage units for the clayey soils but only one percentage unit for the coarse-grained soils. With three exceptions (the 40-HP tractor on the heavy clay and both tractors on the gravel-sand-clay) all tractor compacted unit weights exceeded 100 percent relative compaction for the standard test. These tests show conclusively that although they have low average unit pressures, track-type tractors can be depended on for compaction to about 100 percent relative compaction (based on the standard test) for all types of soils, and that in some instances as for the Florida sands (47) and Swedish stony gravels (80) they may attain dry unit weights equal to Modified AASHO maximum unit weight. Lift thicknesses for these tests are given in Table 37.

DRY UNIT WEIGHT VS NUMBER OF PASSES

A limited number of tests were performed (81) to determine the relationship between unit weight and number of passes for track-type tractors for three types of soils, a heavy clay, a well-graded sand and a gravel-sand-clay. The heavy clay soil when compacted with either tractor (40- or 80-HP) developed nearly the maximum unit soil weight each tractor was capable of in six to ten passes. The gravelly soil responded almost as well by attaining near maximum after about 10 passes but the well-graded sand required 15 to 20 passes to attain near the maximum unit weight attainable by tractor compaction. The sand reached 95 percent relative compaction in two passes; the heavy clay in 3 to 4 passes (3 passes for the 40-HP tractor) but the gravel-sand-clay required 14 passes of the 80-HP tractor. These values illustrate the difference in response of different types of soils to compaction by a track-type tractor.

TABLE 37

COMPARISONS OF MAXIMUM DRY UNIT WEIGHTS AND OPTIMUM MOISTURE CONTENTS OBTAINED IN LABORATORY COMPACTION TESTS WITH VALUES OBTAINED IN FULL-SCALE FIELD TESTS WITH TRACK-TYPE TRACTORS

		Laboratory Compaction Data				Data on the Tractor and Its Operation									Tractor Compaction			
		AASHO T 99 or Its Near Equivalent		Mod AASHO or Its Near Equivalent						Speed of Travel			Lift Thickness					
Soil Type	Reference Number	Max. Dry Unit Wt (pcf)	O M C (%)	Max. Dry Unit Wt (pcf)	O M C (%)	Type or Model of Tractor	Gross Weight (lb)	Width of Track (in)	Average Unit Contact Pressure (psi)	(fpm)	(mph)	No of Coverages	Loose (in)	Comp (in.)	Max Tractor Comp. Dry Unit Weight (pcf)	Percent of AASHO T 99 Max.	Percent of Modified AASHO Max.	O. M. C for Tractor Comp. (%)
Clinton, Miss clayey sand	44	116.2	11 5	122 2	10 0	D-8	34,500	-	8	-	-	3	-	6	113.0^{a}	97.3	92.4	13.5^{a}
Vicksburg, Miss. silty clay	46	105 3	17 9	116 8	14 8	D-8	34,500	-	8	-	-	2	-	6	102.9^{b}	97 7	88.1	18.7^{b}
Florida non-plastic sand	47	-	-	103-111	-	RD-8	34,000	-	-	97	1 1	6-18	-	-	105 0^{c} 109.5	-	95-101	6 0^{c} 8 4
Florida non-plastic sand	47	-	-	103-111	-	RD-8	80,000	-	-	132	1.7	12	-	-^{d}	112^{c}	-	102	4.8^{c}
Swedish stony gravel	80	-	-	121.7	-	D-7	24,250	19 7	7 97	126	1 43	6	39 4	-	121 7	-	100	-
British heavy clay	81	97 0	26 0	113 0	17 0	40-HP	12,840	15	7 3	-	-	32	9	-	96.0	99 0	85 0	22.0
British heavy clay	81	97 0	26 0	113 0	17 0	80-HP	24,160	20	7 2	-	-	32	9	-	99 0	102.1	87.6	24 0
British silty clay	81	104.0	21 0	120 0	14 0	40-HP	12,840	15	7.3	-	-	-	9	-	106 0	101.9	88.3	17.0
British well-graded sand	81	121 0	11 0	130.0	9 0	40-HP	12,840	15	7 3	-	-	32	9	-	128 0	105 8	98.5	10 0
British gravel-sand-clay	81	129 0	9 0	138 0	7 0	40-HP	12,840	15	7.3	-	-	-	9	-	128.0	99 2	92 8	8.0
British gravel-sand-clay	81	129 0	9 0	138.0	7.0	80-HP	24,160	20	7 2	-	-	32	9	-	126.0	97 7	91.3	8.0

[a] Drive tube samples O. M C from Table 1 of 91A [b] Average values for 0-9 and 12-21 in. depths. [c] Actual moisture content and density. Not a maximum density or O M C. [d] Densities were observed to depths of 12 ft value given is for upper 2 ft

COMPARISON BETWEEN TRACTOR COMPACTION AND LABORATORY IMPACT COMPACTION

Tractor compaction (that is, maximum dry unit weight and optimum moisture content obtained with track-type tractors) bore no constant relationship to values obtained from laboratory impact compaction. However, as was given in Table 37, the tractor-compacted maximum dry unit weight bore no consistent relationship to tractor gross weight either in the United States or in Great Britain. Although there appeared to be no consistent relationships, it appears that there is better general agreement between laboratory values and tractor values for the wide range of soil types tested than has occurred for other types of compactors. The addition of sands tested in Florida (47) and data from the British heavy tractor (80 HP, 24,160 lb) does not materially change the validity of this state-

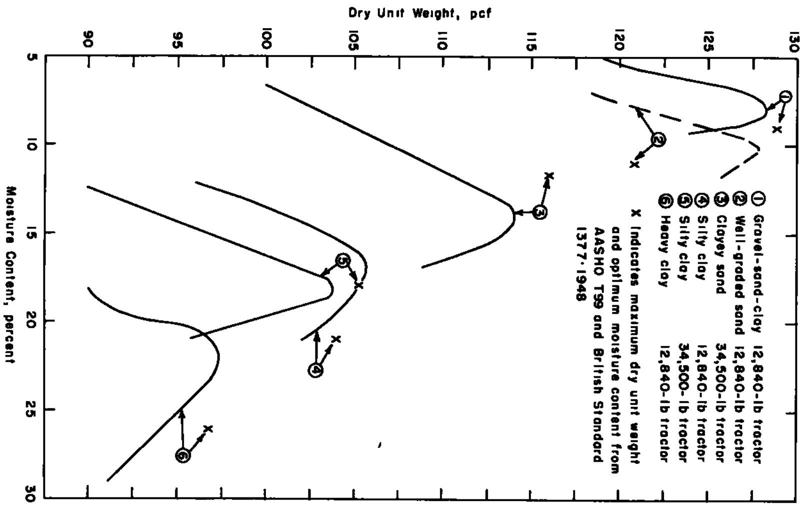


Figure 78. Field compaction curves for six soils compacted by track-type tractors (91A, 92A, 184A).

ment. Comparisons of tractor-compaction curves with points of laboratory maximum dry unit weight and optimum moisture content for six soils are indicated in Figure 78. This figure shows higher values of laboratory optimum for two of the fine-grained soils. The roller optimums for the remaining soils do not differ significantly from the laboratory optimums.

Compaction by Tamping

SOME OF THE EARLIEST TESTS to determine the degree of compaction attained by tamping were done by the Corps of Engineers prior to the construction of the Franklin Falls Dam (21). The tests were made on a drop weight tamper, an air-hammer tamper and a hand-operated pneumatic tamper. The tests showed that a fine silty sand containing up to 12 percent of material passing a No. 250 sieve could be compacted to average relative densities up to 85 percent.

Two types of tampers, each of them being of the explosion type have been tested by the British Road Research Laboratory (56, 81). The first tests were performed with a frog rammer weighing 1,350 lb and having a base diameter of 29 in. and an approximate height of jump of 12 in. This tamper has been known here as the "Leaping Lena." The more recent tests were with four makes of explosion-type tampers having a weight of about 250 lb, a base-plate diameter of about 9.5 in. and an approximate height of jump of 12 in. Additional tests were performed to determine the effect of employing base plates having different diameters on the compacted unit weights.

DRY UNIT WEIGHT VS MOISTURE CONTENT

The relationships between dry unit weight and moisture content attained in field compaction with the 1,350-lb frog rammer are shown in Figure 79 where the peaks of the field curves may be compared with points of maximum dry unit weight and optimum moisture content attained by the British standard test. The field results represent compaction to refusal or by compaction by about 48 passes of the tamper in which about six passes represent one coverage. Figure 80 shows five moisture content-dry unit weight curves for five soils compacted by 250-lb explosion-type rammers of the type that has had wide usage in the United States. Here again, points of laboratory maximum dry unit weight and optimum moisture content are also shown except for the heavy clay which would plot off the graph (dry unit weight = 97 pcf, OMC = 26 percent). Here the plot for the heavy clay shows two peaks for the rammer compaction curve just as it showed two peaks for the 6,160-lb and 19,010-lb smooth-wheel rollers, the 26,880-lb pneumatic-tired roller, the 4,480-lb base-plate-type vibratory compactor, and the 5,400-lb vibrating smooth-wheeled roller. However, as may be seen in Figure 80 the unit weights attained by the explosion-type rammers were markedly greater than maximum values from the standard laboratory test for all except the sandy clay soil. Field values of unit weight exceeded laboratory values by 6 to 10 pcf. Field optimum was dry of laboratory optimum.

In the moisture content vs dry unit weight tests the tampers having smaller base diameter and lesser weight (81) produced greater unit weights than did the frog tamper (56).

For the heavy clay the 250-lb rammer produced a weight increase of 4 pcf at one percentage unit increase in OMC; for the sandy clay a weight increase of 6 pcf at 3 percentage units decrease in OMC; for the sand, a weight increase of 1 pcf at two percentage units decrease in optimum; and for the gravel-sand-clay a gain in 1 pcf in weight and a reduction of one percentage unit in optimum. Thus, field optimums departed from laboratory values even more widely than they did for the frog tamper. This departure, like that for the frog, resulted from differences in compactive effort. Lines drawn through points of maximum unit weight and optimum moisture content for field and laboratory peak dry unit weights resulted in approximately parallel lines spaced rather closely together.

Increasing the size of the base plate decreased the maximum unit weight and increased the corresponding optimum moisture content. The effect of size of base plate on depth of compaction was not studied. Increasing the size of the base plate increased output but made the tamper more difficult to control, there being a tendency for the soil to adhere to the base plate. Field compaction curves for the 250-lb explosion-type rammer for four sizes of base plates for the heavy clay and sandy clay soils are shown in Figure 81.

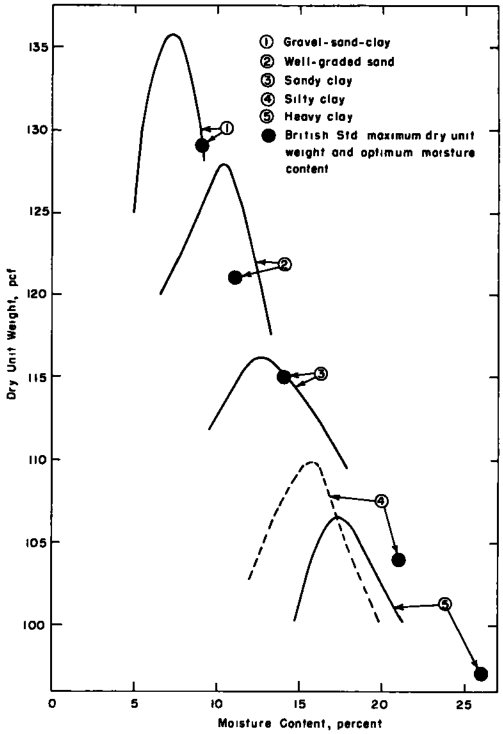


Figure 79. Unit weight vs moisture content for five soils compacted in 9-in. loose lifts by frog rammer (56).

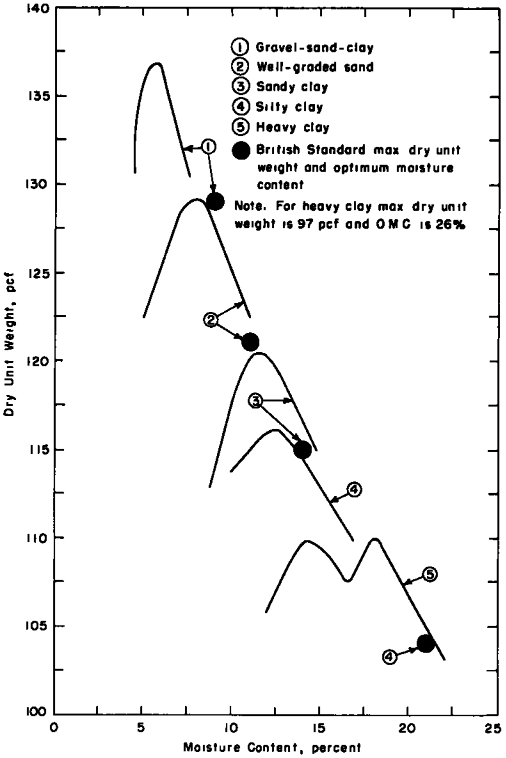


Figure 80. Moisture content-unit weight relationships for five soils when compacted in 9-in. loose lifts by 250-lb explosion-type tampers having a 9.5-in. diameter base and 12-in. high "jump." Data are mean results obtained with four makes and/or models of rammers (81).

DRY UNIT WEIGHT VS NUMBER OF PASSES

Relationships between unit weight of the compacted soil and number of passes were determined for five soils for the 1,350-lb frog rammer and for three soils for the 250-lb tamper. As was shown by the unit weight vs moisture content studies, the study to determine the relation between number of passes and dry unit weight also indicated a slightly greater compaction by the 250-lb units but on only two of the three soils on which both types of machines were tested–the well-graded sand and the heavy clay. The relationships between number of passes and soil unit weight for the two machines are shown in Figure 82. It should be kept in mind in the study of this chart that for the frog rammer, one coverage has been plotted as six passes and for the 250-lb weight tamper, one coverage has been plotted as two passes. Values of 95 and 90 percent relative compaction are shown in Figure 82 for the 1,350-lb rammer showing that 95 percent relative compaction was attained in all but one instance in about 10 or less passes or in other words in two or less coverages.

DRY UNIT WEIGHT VS DEPTH

In tests to determine the relationship between unit weight and depth for compaction

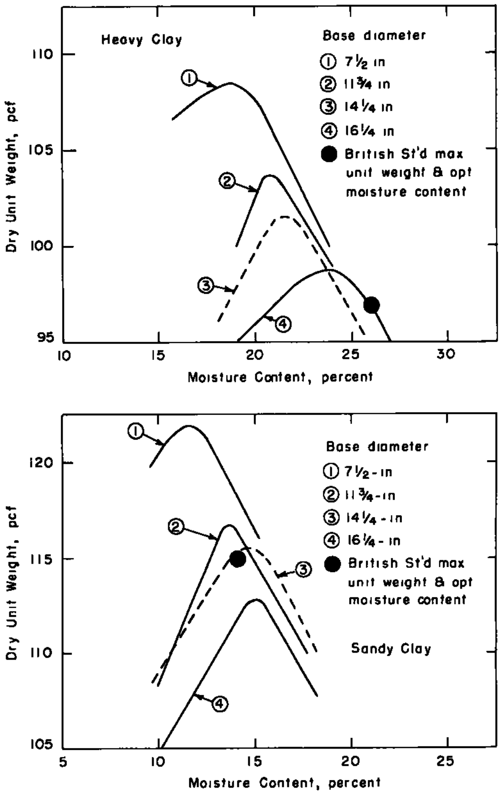


Figure 81. Dry unit weight vs moisture content for two soils when compacted in 9-in. loose lifts by ten passes of a 250-lb explosion-type power tampers using base plates of different diameters (81).

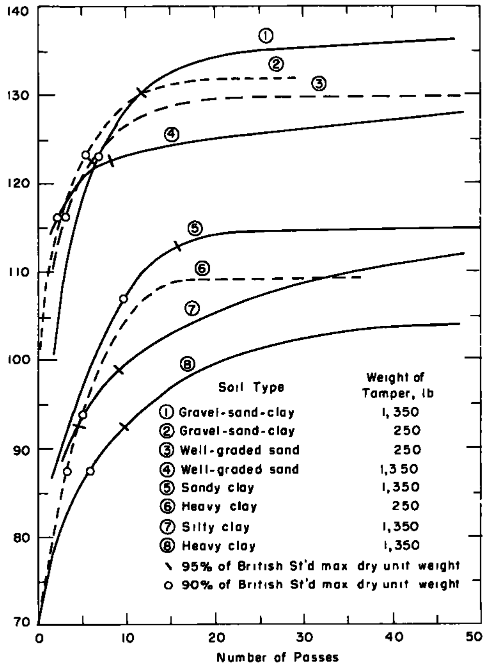


Figure 82. Dry unit weight vs number of passes of a 1,350-lb explosion-type frog rammer (solid lines) with 29-in. base diameter; and for 250-lb explosion-type tamper with 9.5-in. base diameter and 12-in. height of jump. For the frog rammer six passes equals one coverage. For the 250-lb tamper two passes is equivalent to one coverage (56, 81).

by the frog rammer (56) a 30-in. loose lift was prepared for each of three of the soils at the optimum moisture content previously determined and shown in Figure 79. After compaction the thickness of each lift was about 20 in. The dry unit weight of each successive 4-in. depth was determined. Table 38 gives values of unit weight and provides data on the effect of depth on unit weight for each of the three types of soils compacted by 6 coverages of the frog tamper.

The tests with the four diameters of base plates on the 250-lb tampers also included measurement of soil unit weight at various depths throughout the compacted lift. The results of these tests exhibited marked decrease in unit weight with increase in depth. This decrease in unit weight is of the order of four to ten times that found for the heavier and larger diameter frog. The magnitude of the decrease in unit weight with depth is given in Table 39.

PRODUCTIVE CAPACITY (OUTPUT) OF TAMPERS

The output of a 1,350-lb frog tamper (56) like any other compaction device depends on lift thickness, unit weight required, soil type and other pertinent variables. A 9-in. loose lift thickness was used in testing tampers. For a requirement of 90 percent of the British Standard, the output was about 70 cu yd per hour. For a 95 percent

TABLE 38

UNIT WEIGHT GRADIENTS THROUGH LAYERS OF SOIL COMPACTED IN 30-IN. LOOSE LAYERS BY SIX COVERAGES OF THE FROG RAMMER (56)

			Dry Unit Weights at Various Depths Below Compacted Surface							
Soil Type	Moisture Content (%)	Dry Unit Wt as Placed (pcf)	0 to 4 in. (pcf)	4 in. to 8 in. (pcf)	8 in. to 12 in. (pcf)	12 in. to 16 in. (pcf)	16 in. to 20 in. (pcf)	Average Dry Unit Wt Gradient (pcf/in.)	Av Dry Unit Wt in Compacted Layer (pcf)	Av Rel Compaction (% of British Std.)
Silty clay	16.5	70	110	106	102	97	93	1.0	102	98
Well-graded sand	10.5	88	129	126	125	124	122	0.5	125	102
Gravel-sand-clay	8.5	85	135	130	130	127	124	0.6	129	100

TABLE 39

AVERAGE DECREASE IN DRY UNIT WEIGHT OBTAINED WITH 250-LB POWER TAMPERS WITH VARIOUS DIAMETERS OF BASE PLATE (81)

	Average Decrease in Dry Unit Weight with Depth (pcf per in.)	
Diameter of Tamper Base (in.)	Sandy Clay	Heavy Clay
7.5	5.1	4.1
11.75	4.5	3.7
14.25	5.1	4.4
16.25	4.9	4.3

requirement, the compactor was a little more sensitive to soil type, compacting about 70 cu yd per hour on the sand, but only 35 cu yd per hour on the heavy clay, silty clay, sandy clay and gravel-sand-clay. For the 100 percent requirement, capacities were 23, 23, 17, and 35 cu yd per hour, respectively, for the four soils.

Increasing the diameter of the base plates on the 250-lb tampers influences output as is indicated in Table 40. The relative effect of base diameter on possible output may be determined from the number of blows per sq ft required to give the equivalent of one coverage listed in Table 40.

TABLE 40

NUMBER OF BLOWS PER SQUARE FOOT OF A 250-LB TAMPER REQUIRED TO GIVE THE EQUIVALENT OF ONE COVERAGE (81)

Diameter of Tamper Base (in.)	Area of Tamper Base (sq ft)	Number of Blows per Sq Ft Equivalent to One Coverage
7.5	0.31	3.3
11.75	0.75	1.3
14.25	1.1	0.9
16.25	1.4	0.7

Comparative Effectiveness of Types and Ratings of Compactors

IT HAS BEEN SHOWN throughout the preceding text, insofar as test data have permitted, how the compaction characteristics and the operating characteristics of a compactor determine its effectiveness. In summary, satisfactory compaction characteristics require that the compactor be able to compact the soil type to the required unit weight at the required moisture content, at an acceptable degree of uniformity from top to bottom of the construction lifts. Satisfactory operating characteristics require adequate output (in cu yd per hour) to hold costs within limits. They also include compaction of suitable lift thicknesses after an acceptable number of passes, good meneuverability, and the capability of fitting into a sequence of construction operations.

Because operating methods may differ widely, comparisons here are limited to comparison of the compaction characteristics alone. The relative effectiveness of different types or ratings of compactors in terms of compaction characteristics for a single soil type is assessed in terms of the ranges of unit dry weight attained at different moisture contents; and in terms of the maximum dry unit weight and optimum moisture content attained by the compactor.

Comparisons of effectiveness of given compactors on several types of soil require a base other than dry unit weight. There is currently no generally accepted method that is completely satisfactory for determining the relative effectiveness of different types and ratings of compactors on different types of soil. Many engineers hold that the laboratory impact compaction test does not simulate field compaction equally well for all types of compactors on both fine-grained cohesive soils and granular soils having little or no cohesion. Nevertheless, and although admittedly not completely satisfactory for this purpose, relative compaction is used for comparing the effectiveness of compactors because no other better method is known.

Throughout this text, the values of roller maximum dry unit weight and roller optimum moisture content usually represent compaction after a large number of passes in order to make it possible to assess the full potential of the compactor. Where data were available comparisons have also been made of dry unit weight and for percent relative compaction after application of numbers of passes normally employed in embankment construction.

Table 41 prepared from data from tests by the Corps of Engineers, summarizes average maximum dry unit weights for seven ratings of sheepsfoot-type rollers and four ratings of pneumatic-tired rollers for a lean clay soil. Some of the rollers were tested at each of several compactive efforts. The differences in compaction efforts for sheepsfoot-type rollers were obtained by adjusting (a) the contact pressure for a constant tamper foot-contact area; (b) the tamper foot contact area and maintaining constant foot contact unit pressure (by loading the drum); and (c) the number of passes. For pneumatic-tired rollers, the compaction effort was controlled by (a) controlling the wheel load; (b) the tire-inflation pressure; and (c) the tire size (and ply rating).

For sheepsfoot-type rollers of adequate tamping foot unit pressure, the compaction characteristics depend largely on number of passes; the size of the contact area of each tamper foot; and on the over-all contact area of all tamper feet expressed in percent of the area of a strip equal in area to that of a cylindrical surface generated by the periphery of the face of the tamper feet. For pneumatic-tired rollers, it has been shown that maintaining constant tire pressure and changing wheel load had small effect on dry unit weight for the relatively shallow lifts normally employed in construction. Thus, number of passes and tire pressure largely determine compaction characteristics of pneumatic-tired rollers.

Reference to Table 41 shows that practically no variation occurred in the dry unit

TABLE 41

COMPACTION DATA ON A LEAN CLAY SOIL USED IN COMPARING RESULTS OF ROLLING WITH SHEEPSFOOT AND PNEUMATIC-TIRED TYPES OF ROLLERS

Reference Number		Number of Passes	Maximum Dry Unit Weight: AASHO T 99 (pcf)	Maximum Dry Unit Weight: AASHO T 99 (%)	Maximum Dry Unit Weight: Field Compactor (pcf)	Maximum Dry Unit Weight: Field Compactor (%)	Optimum Moisture Content: Lab. (%)	Optimum Moisture Content: Field (%)
	Sheepsfoot-Type Rollers							
46	250 psi max CP.,[c] 7 sq in. CA., 5.5% TCA.,[b] silty clay[a]	6	105.3	100	107.3	101.9	17.9	19.1
46	500 psi max CP., 7 sq in. CA., 5.5% TCA., silty clay	6	105.3	100	106.8	101.4	17.9	18.5
46	750 psi max CP., 7 sq in. CA., 5.5% TCA., silty clay	6	105.3	100	106.8	101.4	17 9	19.1
76	250 psi max CP., 7 sq in. CA., 5.5% TCA., lean clay[a]	6	107.9	100	105.2	97.5	17.0	18.5
76	250 psi max CP., 7 sq in. CA., 5.5% TCA., lean clay	12	107.9	100	106.5	98.7	17.0	17.0
76	250 psi max CP., 7 sq in. CA., 5.5% TCA., lean clay	24	107.9	100	108.2	100.3	17.0	16.0
76	250 psi max CP., 14 sq in. CA.,10.9% TCA., lean clay	6	107.9	100	106.0	98.2	17.0	18.0
76	250 psi max CP., 14 sq in. CA., 10.9% TCA. lean clay	12	107.9	100	107.2	99.4	17.0	16.5
76	250 psi max CP., 14 sq in. CA., 10.9% TCA., lean clay	24	107.9	100	110.2	102.1	17.0	14.8
76	250 psi max CP., 21 sq in. CA., 16.4% TCA., lean clay	6	107.9	100	107 2	99.2	17.0	16.5
76	250 psi max CP., 21 sq in. CA., 16.4% TCA., lean clay	12	107.9	100	109.0	101.0	17.0	15.4
76	250 psi max CP., 21 sq in. CA., 16.4% TCA., lean clay	24	107.9	100	112.5	104.3	17.0	13.5
87	125 psi max CP., 14 sq in. CA., 10.9% TCA., lean clay	12	107.5	100	109 0	101.4	17.8	17.0
87	375 psi max CP., 14 sq in. CA., 10.9% TCA., lean clay	12	107.5	100	109.0	101.4	17.8	17.0
	Pneumatic-Tired Rollers							
87	15,875-lb W.L.,[e] 50 psi TIP[d] Lean clay[a]	8	107.5	100	107 1	99.6	18.0	19.5
87	15,875-lb W.L., 50 psi TIP Lean clay	16	107.5	100	107 4	99.9	18.0	19 2
87	15,875-lb W.L., 50 psi TIP Lean clay	32	107.5	100	108.5	100.9	18.0	19.0
87	25,000-lb W.L., 90 psi TIP Lean clay	8	107.5	100	110.9	103.2	18.0	17.5
87	25,000-lb W L., 90 psi TIP Lean clay	16	107.5	100	111.5	103.7	18.0	17.0
87	25,000-lb W.L., 90 psi TIP Lean clay	32	107.5	100	111.7	103.9	18.0	16.9
87	31,250-lb W L., 150 psi TIP Lean clay	8	107.5	100	113.5	105.6	18.0	16.0
87	31,250-lb W.L., 150 psi TIP Lean clay	16	107.5	100	115.2	107.1	18.0	15.4
87	31,250-lb W.L., 150 psi TIP Lean clay	32	107.5	100	116.6	108.5	18.0	14.7

[a] Lean clay formerly (46) classified as a silty clay. [b] Percent of total contact area generated by a cylindrical surface generated by the periphery of surface of tamper foot. [c] Contact pressure. [d] Tire inflation pressure. [e] Wheel load.

weights produced by sheepsfoot rollers of different foot contact unit pressure but which were otherwise similar (46, 87). Apparently, increasing compaction effort by increasing foot contact unit pressure was ineffective because the increased pressure was absorbed by greater sinkage and thus an increase in total foot area in contact with the soil that effectively decreased unit pressure. However, when the foot contact unit pressure was constant and the compaction effort was increased by increasing size of tamper foot and by increasing the number of passes, the increased compaction effort was effective in increasing roller maximum dry unit weight for the lean clay soil (76). For the pneumatic-tired rollers increasing the compaction effort by increasing the tire pressure and number of passes produced increased values of dry unit weight.

The data in Table 41 permit direct comparisons of the compaction characteristics of the two types of rollers on a given lean (silty) clay soil. If number of passes is used as a basis for comparison (the text indicates methods for comparing on the basis of number of coverages) and the lowest number of passes is used (6 passes for the sheepsfoot and 8 passes for the pneumatic-tired rollers for the second series of tests (76), maximum dry unit weights and percent relative compaction for the 250-psi sheepsfoot roller (76) would be 105.2, 106.0 and 107.2 pcf, respectively. This would be equivalent to 97.5, 98.2, and 99.2 percent relative compaction, respectively. Twenty-four passes of the sheepsfoot roller produced 100.3, 102.1, and 104.3 percent relative compaction. Similarly, the values for the lowest number of passes of the pneumatic-tired compactor would be 99.6, 103.2, and 105.6 percent relative compaction. Thus, for any number of passes, the pneumatic-tired roller of the rating employed produced slightly greater dry unit weights than did the sheepsfoot roller of the rating employed. However, the data do not indicate that sheepsfoot rollers could not have been designed that would have produced dry unit weights equal to or greater than those produced by the penumatic-tired rollers.

Table 42 summarizes some of the data from tests performed by the British Road Research Laboratory. These tests were performed on several soils; tests of five types of compactors being tested on four soils. In the British tests, comparison is made on the basis of percent relative compaction after "full compaction;" that is, compaction to refusal or compaction by many passes, usually 32 or 64 in number, to reveal the full capabilities of the compactor.

Comparison is made between the maximum percent relative compaction attained

TABLE 42

COMPACTION DATA ON FOUR BRITISH SOILS USED IN COMPARING RESULTS OF COMPACTION BY FIVE DIFFERENT TYPES OF COMPACTORS[a]

Type and Rating of Roller[b]	Heavy Clay (CH) Maximum Dry Unit Weight (pcf)	Heavy Clay (CH) Maximum Dry Unit Weight (%)	Heavy Clay (CH) O M C (%)	Sandy Clay (CL) Maximum Dry Unit Weight (pcf)	Sandy Clay (CL) Maximum Dry Unit Weight (%)	Sandy Clay (CL) O. M C. (%)	Well-Graded Sand (SW) Maximum Dry Unit Weight (pcf)	Well-Graded Sand (SW) Maximum Dry Unit Weight (%)	Well-Graded Sand (SW) O. M. C. (%)	Gravel-Sand-Clay (GW) Maximum Dry Unit Weight (pcf)	Gravel-Sand-Clay (GW) Maximum Dry Unit Weight (%)	Gravel-Sand-Clay (GW) O M.C. (%)
British Standard Compaction Test	99	100	24	109	100	16	121	100	11	129	100	9
Modified AASHO Compaction Test	116	117.2	16	126	115.6	12	130	108.4	9	138	107.0	7
3-Wheel-Type Smooth-Wheel Rollers												
9.5-ton (311-186-lb[b]) roller	104	105.1	20	116	106.4	15	132	109.1	9	138	107.0	7
3.08-ton (186-80-lb) roller	95	96.0	21				127	105.0	10	134	103.9	8
Sheepsfoot-Type Rollers												
5.5-ton club-foot type roller	107	108.1	16	118	108.3	12	-	-	-	130	100.8	6
5.04-ton taper-foot type roller	107	108.1	15	118	108.3	13	-	-	-	128	99.2	5
Pneumatic-Tire Rollers[c]												
British standard compaction test	99.8	100	22.8	109.4	100	16.5	124.4	100	10.2	129.5	100	9.2
2,985-lb wheel load, 36-psi tire pressure	100.7	100.9	23.2	110.7	101.2	17.8	126.8	101.9	9.7	132.2	102.1	8.2
4,978-lb wheel load, 80-psi tire pressure	106.4	106.6	21.1	116.9	106.9	15.3	128.2	103.1	9.2	134.8	104.1	6.2
11,200-lb wheel load, 90-psi tire pressure	107.1	107.3	20.7	117.1	107.0	14.7	129.8	104.3	9.0	134.0	103.5	7.1
22,400-lb wheel load, 90-psi tire pressure	108.3	108.5	19.7	119.2	109.0	14.4	130.5	104.9	9.0	135.5	104.6	6.9
22,400-lb wheel load, 140-psi tire pressure	110.7	110.9	18.5	119.8	109.5	13.8	131.9	105.2	9.0	138.5	105.4	6.4
Vibrating Base-Plate Compactor												
480-lb single unit, hand propelled	-	-	-	-	-	-	128	105.8	10	127	98.4	9
1,480-lb single unit, self-propelled	103	104.0	21	116	106.4	15	135	111.6	8	141	109.3	6
1,570-lb single unit, self-propelled	87	87.9	20	114	104.6	16	130	107.4	9	137	106.2	7
3,350-lb single unit, self-propelled	-	-	-	-	-	-	129	106.6	9	135	104.7	8
4,480-lb single unit, self-propelled	98	99.0	17	-	-	-	128	105.8	9	137	106.2	7
Vibrating Rollers												
480-lb hand-propelled-21-lb[d]	-	-	-	-	-	-	124	102.5	11	123	95.3	8
760-lb single drum, self-propelled, 27-lb	92	92.9	28	100	91.8	16	127	105.0	9	132	102.3	8
5,400-lb tandem with vibr front roll, 68-lb	96	97.0	21	-	-	-	133	109.9	7	139	107.8	6
8,620-lb single drum-towed unit, 119-lb	106	107.1	21	119	109.2	14	137	113.2	7	145	112.4	6

Note Maximum dry unit weights given as (%) are percent of British Standard 1377 1948 which is generally similar to AASHO T 99 Method C. [a]All data from reference (129) except as noted. [b]Roller rated according to weights or compressions normally employed in reference that was source of data For example a three-wheel roller normally is rated by gross weight and lb per in. width of drive and guide rolls respectively. [c]All data from reference (127). Note that all values of laboratory maximum dry unit weight differ slightly from those given above, as they were taken directly from plots of moisture content vs dry unit weight. Thirty-two passes were employed on 9- and 12-in loose depths. [d]Dead weight of vibratory roll expressed as pounds per inch of width of roll.

by the five types of compactors ranging from two ratings of rollers in each of the 3-wheel-smooth-wheel and sheepsfoot types to 6, 5, and 4 ratings of pneumatic-tired rollers, vibrating base-plate compactors, and vibrating rollers, respectively. The value of dry unit weight given in Table 42 for which each percent relative compaction is given is the maximum produced by the compactor at the optimum moisture content for a given compactor and soil type. In Table 43 the greatest value of maximum dry unit weight is listed for each compactor and soil type.

Because one of the objectives of the British tests was to test each compactor by compacting each soil to "full-compaction" the data in Table 43 provides a means for determining the potential of each of the types and ratings of compactors on the four

TABLE 43

MAXIMUM DRY UNIT WEIGHT EXPRESSED AS PERCENT RELATIVE COMPACTION[a] PRODUCED BY FIVE TYPES OF COMPACTORS ON FOUR TYPES OF SOILS IN TESTS BY BRITISH ROAD RESEARCH LABORATORY

Type and Rating of Compactor	Heavy Clay	Sandy Clay	Well-Graded Sand	Gravel-Sand-Clay
3-wheel, 9.5-ton smooth-wheel roller	105.1	106.4	109.1	107.0
5.5-ton, clubfoot-type sheepsfoot roller	108.1	108.3	-	100.8
22,400-lb wheel load, 140-psi tire pressure, pneumatic-tire roller	110.9	109.5	105.2	105.4
Vibrating base-plate compactor, 1,480-lb single-unit type	104.0	106.4	111.6	109.3
Vibrating roller, 8,620-lb single-drum towed-type, 119 lb per in. of width of roll	107.1	109.2	113.2	112.4

[a]Percent of British Standard maximum dry unit weight. The British test is generally similar to AASHO T 99 Method C.

types of soils. Table 43 shows that for the heavy clay and the conditions of the tests there is a difference between the lowest value (104.0 percent) and the highest value of maximum dry unit weight (110.9 percent) of 6.9 percent relative compaction. The very heavy high tire pressure pneumatic-tire roller produced the highest degree of compaction (110.9 percent). The relatively lightweight clubfoot-type sheepsfoot roller yielded 108.1 percent compaction. It is possible that by adjusting the size of the tamper foot and the unit contact pressure of the tamper foot that it could be made to yield a value equivalent to that produced by the pneumatic-tire roller. It is also possible that a vibrating roller loaded to a greater weight could also have produced results comparable to those produced by the heavy pneumatic-tired roller. Thus, while for the ratings of rollers used, the sheepsfoot and pneumatic-tired types yielded the greatest unit weights, the evidence indicates that similar unit weights could have been produced by use of heavier smooth-wheel and vibrating-type rollers. Had those data been available, decisions as to the "most suitable" type and rating could be made on the basis of uniformity of compaction and output in cubic yards per hour. This would involve lift thickness and number of passes.

An analysis of the unit weights attained by the various compactors indicated in Table 43 on the sandy clay shows that although the heavy pneumatic-tired roller and the vibrating roller produced the greatest unit weights, it is possible that the maximum unit weights produced by the other three types of compactors could have been increased by employing a heavier smooth-wheel roller, a more appropriate tamping foot size and unit pressure for the sheepsfoot roller, and possibly by a more suitable rating of base-plate-type vibrating compactor. The foregoing statement is based on the relatively small differences between extremes in maximum dry unit weight attained by the various compactors (109.5-106.4 pcf = 3.1 pcf). In other words, the types of roller is not nearly so critical for the sandy clay as for the other soil types.

For the well-graded sand the vibrating compactors were markedly superior in attaining high unit weight and in compacting thicker lifts. The vibratory compactors were also superior in compacting the gravel-sand-clay. A slightly heavier smooth-wheel roller may have attained greater unit weight on both the sand and gravel-sand-clay but stage compaction may have been necessary to develop soil strength to support the heavier rollers.

Control of Compaction During Construction

THE ENGINEER is charged with determining if a construction satisfies the plans and specifications that state the requirements for compaction (including moisture control). There are three methods in use for stating minimum (and in some cases also maximum) requirements for compaction. They are: (1) controlling soil dry unit weight, (2) controlling compaction effort, and (3) a combination of (1) and (2). Each of the methods can be made to produce compaction that is equally satisfactory. Each has advantages and disadvantages. Each requires different procedures for the engineer to insure that the quality requirements intended by the plans and specifications are satisfied. Thus, each requires different methods of administration.

For Method (1) uniform and specific procedures for inspection, sampling and testing can be written, which, when followed, make it possible to distinguish work of acceptable quality from work that does not meet requirements. Method (2) places on the engineer the full burden of determining both minimum and maximum requirements for compaction. He may or may not employ tests to measure unit weight or moisture content depending on the number of and quality of his personnel, his background of experience, and knowledge of compaction equipment and its potentials. In any instance, control of quality may involve both testing and inspection judgment. For this reason a large part of this bulletin is devoted to the presentation of test results from full-scale field compaction experiments. It is hoped that these results will benefit the engineer assigned the task of control of compaction, irrespective of the nature of the plans and specifications for compaction. A few exemplary items that concern aids to judgment are discussed under "Checking Construction Operations." Test methods employed are discussed under "Checking Compaction Results."

CHECKING CONSTRUCTION OPERATIONS

Inadequate or non-uniform compaction results from (a) an insufficient number of compactors for the excavating, hauling and spreading equipment; (b) improper type; or (c) improper size and rating of compactors, as well as improper operation of compactors. Familiarity with the compaction characteristics of the compactors and the output of all equipment on various soil types may forewarn the engineer of inspection and testing problems that may arise.

For example, for a given type of sandy soil and three different compaction specification requirements, two or possibly three types of compactors may each individually produce adequate results economically. For intermediate requirements, perhaps only two types of compactors yield adequate unit weight. Very high unit weight requirements may be obtained only by vibratory compaction. The contractor may find it economical to employ stage compaction using two types of equipment or two ratings of a given type to attain adequate compaction. For example, if this existing equipment includes lightweight (low tire pressure) and heavy weight (high tire pressure) pneumatic-tire rollers, he may choose to employ stage compaction. In doing this he would use the near maximum tire pressure that the soil would support in the lightweight small-wheel roller to increase the unit weight of the soil until it would support the heavy roller with higher tire pressure and larger tires with which he would obtain the specified high unit weight. The use of this method would involve lift thicknesses different than normally used and also would involve differences in methods of inspection and testing.

The nature of dumping and spreading operations may have much influence on attainment of adequate compaction and equipment output; and, may also influence the methods used in checking construction operation. Dumping in windrows, piles, or lifts results in three different degrees of exposure (surface area). If, for example, the time period between dumping and compacting is long, sufficient evaporation may take place in a clay soil to result in inadequate and non-uniform compaction. If the soil contained adequate moisture content when dumped and was spread and compacted immediately, costly watering and processing may have been unnecessary and unit weight attained with much greater ease.

Because of its strong effect on average unit weight for the full thickness of the lift, and on the nature of the unit-weight gradient, lift thickness is usually specified. When unit weight is specified and lift thickness is not specified and rather large lift thicknesses are employed, there may arise question concerning interpretation of the unit-weight specification. Also the use of great depths in which the method of compaction results in rather flat density vs depth gradients may necessitate testing for unit weight at various depths requiring a method of testing that becomes increasingly more difficult as the depth increases. That is particularly true for non-cohesive soils.

If unit weight is not employed as a measure of quality of compaction and measurements are not made of other qualities, there remain few methods for checking construction operations that will give positive evidence whether or not compaction is adequate. Simple observation of the number of passes in scheduling roller travel is one method that can be depended on if size, rating and speed of the compactor, and moisture content are within desirable ranges.

It should never be forgotten that for a road otherwise adequately designed, the smoothness of the riding surface during its useful life bears a strong relation to uniformity of compaction. Degree of coverage is proportional to number of passes except for unusual cases of "tracking" by rollers as, for instance, certain sheepsfoot rollers have tamping foot spacing that results in the tamping feet finding the same impressions left by previous trips.

Some soils, when compacted to satisfy compaction requirements, for example to 95 percent of AASHO T 99 maximum unit weight, are not sufficiently stable to carry large capacity loaded hauling units. An example is an organic silt. When material of that nature is overstressed as indicated by cracking and the formation of waves ahead and behind a roller, it is difficult to estimate from visual inspection the effect of overstressing on unit weight. This should in most instances involve extra testing as proof of the effectiveness of the method finally employed to compact it satisfactorily.

Among the many problems involving moisture content is that of placing, compacting and hauling over excessively wet soils that may be placed at unit weights that satisfy the specifications. If stability is also a problem, these soils must be relegated to a use where their stability is not critical. Drying has been done successfully by the use of kilns similar to those used in drying aggregates. However, most drying has been by exposing the greatest surface area possible by windrowing, then mixing and re-exposing the soil.

Another method that has been used successfully in many instances is alternate layer construction, where a layer of wet soil of optimum thickness for both compaction and stability (for example, 12 in. deep) is covered with a layer of dry or otherwise stable soil. This layer should also be of a thickness that permits its satisfactory compaction plus the compaction of the underlying wet layer with minimum reduction in strength due to manipulation of the wet layer. The adjustment of the thicknesses of these layers can, at times, be made to yield results better than expected by the uninitiated.

The mixing in of stable soils with wet soils (for example, sands with wet silts and silty clays) can also be used. Wet soils can often be placed in the outer part of the embankment where they will not endanger the stability of the roadbed section and where they will dry sufficiently to attain the necessary stability before the embankment is built to full height.

Soil compacted at moisture contents sufficiently wet of optimum to produce springing may in some instances markedly increase in stability over night or in a few days as air is released from the fill and pore pressure is reduced. The placement of special materials (for example, boulders and rock slabs from layers of limestone interbedded with shales) can do much to aid in controlling compaction, especially in checking results.

The engineer and those of his staff who inspect compaction can well be on the alert to discover areas of low unit weight. First, it is useful to have a policy regarding frequency of testing for dry unit weight after it has initially been established that the compactor can satisfy specification requirements. This policy can include minimum frequency of testing for each element of the road structure; that is, the embankment, the subgrade (to adequate depth), the backfill, the base courses and other elements. This includes testing at locations of imbedded instrument installations and other special cases where unit weights are needed for evaluation purpose. This policy (for example, for embankments) may require a minimum of one test for each 1,000 cu yd of compacted soil, or for each 3,000 or 5,000, etc., cu yd depending on needs. The policy may then leave it to the judgment of the inspector to decide when and where those and additional tests are to be made. He may employ a Proctor Needle, moisture tests, and other methods to aid his judgment.

Because his problem is in all instances to detect insufficient compaction and in some instances also to detect non-uniform or excess compaction, he is constantly observing areas where compaction may be of doubtful quality. Some of these areas may be where:

1. Oversized rock is contained in the fill;
2. Frozen materials were placed;
3. Material differs markedly from normal materials;
4. Improper type and rating or compactor was employed;
5. Compactor may have lost ballast;
6. Compactors have been turned at end of trip;
7. Junctions occur between tamped, and rolled or vibrated soils;
8. Embankment operations are concentrated;
9. Dirt-clogged rollers (sheepsfoot type) were used;
10. An insufficient number of passes were applied;
11. Lift thickness was excessive; or
12. Moisture content was insufficient or in excess.

CHECKING COMPACTION RESULTS

Field compaction results are normally specified in terms of unit weight and moisture content. Various means are used to specify the degree of compaction required. These include percent compaction (relative compaction), percent density, compaction ratio, relative density, percent porosity, and percent air voids. To check compaction results, however, the following four basic steps are necessary:

1. Representative sampling;
2. Determination of in-place unit weight and moisture content;
3. Determination of desired or control unit weight and moisture values; and
4. Comparison of in-place values with control values.

Step (3) may seem out of order because many organizations perform compaction tests for unit weight control values prior to construction. The problem remains, however, of identifying the soil on which the in-place tests were made so that the proper values are used. The most foolproof way of determining these values is to use the material from the test hole and perform a compaction test on that material.

If moisture content-unit weight curves are available for the local soils, the soil tested must then be identified so the proper curve is used in determining the control unit weight and moisture content. One of the best methods for identifying the soil is to perform a one-point compaction test. The method consists of compacting the soil in a standard 1/30-cu ft mold determining the wet unit weight and moisture content, plotting these two values on the set of moisture content-unit weight curves for local soils, and observing which compaction curve the data fit. For example, suppose the curves shown in Figure 83 represent the moisture content-unit weight relationships for three samples taken from one borrow pit. If the field moisture content and the wet unit weight of the recompacted sample plot as point A, the soil is identified with sample No. 2 (Fig. 83).

The soil can also be identified by its penetration resistance and wet unit weight (as recompacted in a standard mold). This is typified by the Ohio (19) and Wyoming (52) methods. Another method, devised by Humphres (102) for samples of granular material, identifies the mixture and the proper control unit weight by the percentages of coarse and fine aggregate. Possibly the simplest method involves the use of glass jars containing local soil samples at optimum moisture. The inspector can compare the appearance and the "feel" of the sample with the standard soils. The difficulty arises when the sample is different from the standards.

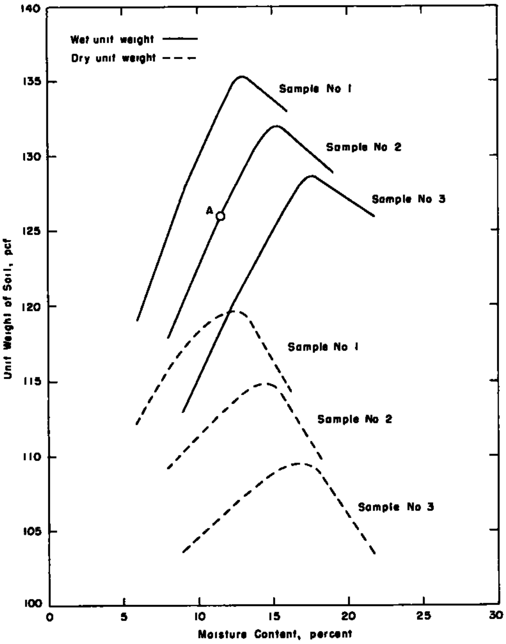


Figure 83. Typical wet and dry unit weight curves of three soil samples for use in field control of compaction. (Point A represents the moisture content and wet unit weight of a disturbed test sample taken from the compacted earthwork and recompacted in the standard mold.)

Before comparing in-place unit weight and moisture content values with control values, it may be necessary to correct for coarse aggregate. This correction may be necessary when the in-place sample contains coarse aggregate sizes or percentages not represented in the control compaction tests. Standard methods (AASHO Designations: T 99 and T 180 and ASTM D 698 and D 1557) provide for performing the compaction test on the portion passing the No. 4 or the ¾-in. sieve. (Note that Methods C and D of the standard compaction tests provide for replacing the portion retained on the ¾-in. and passing the 2-in. sieve with an equal weight of material between the ¾-in. and the No. 4 sieves. This procedure is intended to provide unit weight and moisture content values applicable to the whole material.) Corrections or calculations can be made either (a) to determine the in-place unit weight and moisture content of the fine fraction for direct comparison to compaction test results, or (b) to determine the desired or control unit weight and moisture content of the whole material so that in-place values of the whole material can be checked. These are discussed under "Correcting for Coarse Aggregate Content."

Sampling

The number of samples required for adequate control depends largely on local conditions and is a matter for the engineer or the inspector to determine. In general, unit weight tests should be made as often as possible during the initial stages of construction to determine the adequacy of the contractor's methods and to familiarize the inspector with the soils. Fewer tests may be required if the soil and moisture content are uniform and the contractor's work is satisfactory; more frequent tests may be required if the opposite is true.

Unit weight and moisture samples should represent conditions for the entire lift thickness. The size of sample necessary for representative sampling depends on the lift thickness and size of aggregate. If the entire depth of lift cannot be sampled due to limitations of the sampling equipment (as is the case with drive tube samples and nuclear surface gages), additional deeper samples should be taken or a study made to determine how unit weight varies with depth. The absolute minimum diameter of unit weight test holes in fine-grained soil should be 2 in., a 4-in. diameter is preferable; for coarse-grained material, the minimum diameter should be three times the maximum size aggregate. For example, if the maximum size aggregate is 2 in., the hole should be 6 in. in diameter. Generally, the larger the test hole, the more accurate is the unit weight determination.

The minimum size moisture sample will also depend on the gradation of the material. Minimum samples of 100 grams are recommended (122) for fine-grained soils and 500-gram samples for material with a maximum size of ¾ in. A suggested rule is: sample weight in grams = 1,000d^2, where d is the diameter of the largest size particle in inches.

Methods for Determining Moisture Content

There are several methods suitable for determining soil moisture content in the field. These methods are given in Table 44 with a summary of their principal characteristics.

Drying for Moisture Loss.—The standard method for determining soil moisture content in the laboratory consists of drying the soil sample to constant weight in an oven at 110 C (230 F); then dividing the loss in weight by the dry weight of the soil.

$$\text{Moisture content} = \frac{\text{Weight of wet soil} - \text{Weight of dry soil}}{\text{Weight of dry soil}}$$

$$\text{or} = \frac{\text{Weight of wet soil}}{\text{Weight of dry soil}} - 1$$

To express moisture content in percent, the value determined must be multiplied by 100.

Although temperature-controlled ovens are currently available on some construction jobs, they require 4 to 12 hours for drying; this may be excessive for close control of compaction.

Small electric forced-draft heaters, as shown in Figure 84, are available, and are practical for use in field laboratories. This type is temperature-controlled and will dry 50-gram samples in 30 min. The necessity for an electric power source has limited its use in the field (35).

TABLE 44

A SUMMARY OF CHARACTERISTICS OF METHODS FOR DETERMINING MOISTURE CONTENT IN THE FIELD

	Methods for Field Moisture Determination														
Characteristics	Oven	Forced draft	Open pan	Alcohol burning	Proctor penetration	Hilf	Compacted wet unit weight	Nuclear	Distillation	Calcium carbide pressure	Calcium carbide loss in wt	Pressure pycnometer	Pycnometer	Alcohol solution	Refractive index
Time (minutes)	720	30	45	35	10	60	10	10	45	10	10	10	10	10	10
Usable with.															
Noncohesive material	Yes	Yes	Yes	Yes	No	No	Partly	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cohesive material	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Usable:															
At sampling site	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
W/o identifying soil	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes
W/o compaction curves	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
W/o calibration curves	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	No	No	Yes	Yes	No	No
Use in field established	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No
References	116	35	26	17, 26	11, 26, 111	99	34	90, 103	116, 14 22	35, 58	116	68	31, 24, 39, 58	50, 116	116
Remarks	Slow, requires electricity	Slow, small samples, electricity	Danger of burning soil, requires core	Requires patience, at least 3 burnings	Determine resistance in mold	Principally for field moisture control	For homogeneous soils only	Expensive, apparatus and procedure in development stage	Requires heat, running water	Heavy clay needs special treatment	Heavy clay needs special treatment	Temperature correction required	Temperature correction, exclusion of bubbles required	Temperature correction important	Development stage

Soil samples can be dried in about 45 min in an open pan over a stove (26). This method is satisfactory only if the operator is cautious in keeping the temperature under control and does not overheat the soil. The use of two pans, one inside the other, has proven useful in preventing hot spots.

The alcohol-burning method (17, 26) consists of mixing sufficient denatured grain alcohol with damp soil to form a slurry in a perforated metal pan, igniting the alcohol, and allowing it to burn until consumed. Soil temperatures are only moderately high (130-160 C) so that if properly done, this method will produce results equivalent to careful laboratory testing. Time required is 10 to 35 min. The suggested procedure is as follows:

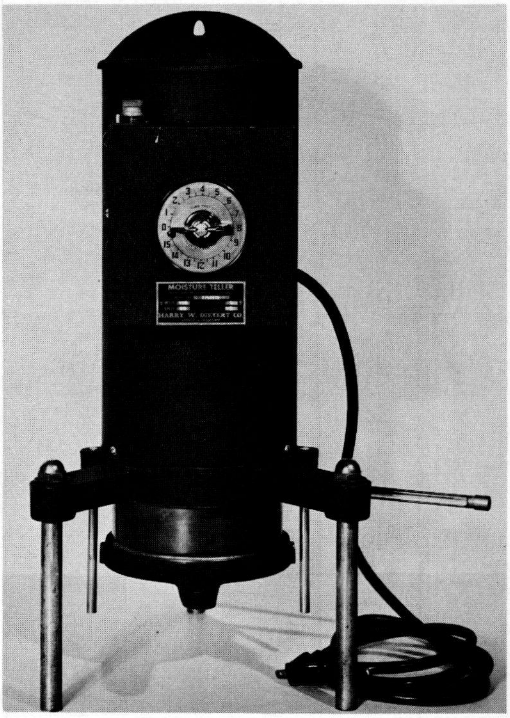


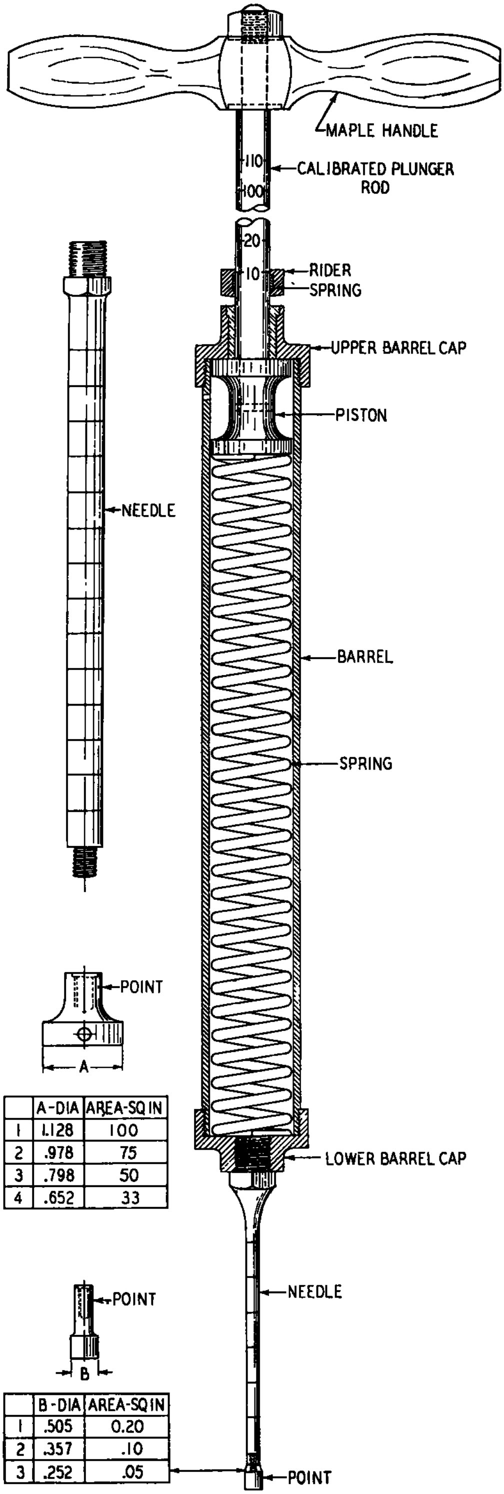
Figure 84. Small forced draft oven.

1. Weigh perforated pan with filter paper in-place in bottom. Record weight.
2. Obtain representative sample of soil.
3. Place sample in perforated pan; weigh and record weight.
4. Place perforated pan in larger pan and stir alcohol into the soil sample with a glass rod until the mixture has the consistency of a thin mud or slurry. Clean rod.
5. Ignite the alcohol in the outer pan and in the sample and burn off all alcohol.
6. Repeat the process three times, or until successive weighings indicate no reduction in weight, each time burning off all alcohol.
7. Weigh perforated pan and dry soil; record weight after final burning. The weight of dry soil equals this weight minus weight of perforated pan and filter.
8. Calculate moisture content as shown previously.

Proctor Penetration Resistance.—The Proctor penetration resistance method consists of (a) taking a soil sample from the rolled earthwork, (b) compacting it into a standard compaction mold, (c) weighing to determine the wet unit weight of the soil, (d) measuring the penetration resistance of the soil in the mold with the soil penetrometer (Fig. 85), and (e) determining the moisture content from a previously established chart that relates wet unit weight, penetration resistance, and moisture content. These steps take about 10 min and the results are sufficiently accurate for most field purposes. The method is suitable only for fine-grained soils, however, because coarse sand and gravel may cause erroneously high resistance readings.

The chart relating wet unit weight, penetration resistance, and moisture content is normally prepared from the results of pre-construction, compaction and penetration tests. During compaction tests, penetration resistance measurements are made on each compacted specimen. After each compacted specimen is weighed for wet unit weight determination, the penetration needle (Fig. 85) is pressed into the soil at a uniform rate of ½ in. per second to a depth of 2½ in. The desired maximum resistance generally occurs as the needle enters the top of the middle layer, at a depth of about 1½ in. Until recently, the depth of penetration was usually specified as 3 in. (27, 11), but the trend has been to reduce this to 2½ in. (119) to prevent penetration into the bottom layer. Typical data from tests on one soil are plotted in Figure 86.

To make the data more usable in the field for moisture determination and for soil



	A-DIA	AREA-SQ IN
1	1.128	100
2	.978	75
3	.798	50
4	.652	33

	B-DIA	AREA-SQ IN
1	.505	0.20
2	.357	.10
3	.252	.05

Figure 85. Soil penetrometer (Proctor type) (26).

identification, a plot similar to Figure 87 is generally made. If, for example, the wet unit weight of a sample recompacted in a compaction mold is 129.4 pcf and the penetration resistance is 950 psi, these data can be plotted as point A and the moisture content read directly as 13.8 percent. The chart can also be used to determine the optimum moisture content and maximum unit weight of the soil tested. This is done by sketching in a compaction curve passing through point A and intersecting the line of optimum conditions at point B. The moisture content at point B is optimum; maximum dry unit weight is the wet unit weight at point B divided by one plus optimum.

The use of typical unit weight and penetration resistance curves by Ohio and Wyoming is discussed under "Use of Ohio and Wyoming Typical Curves."

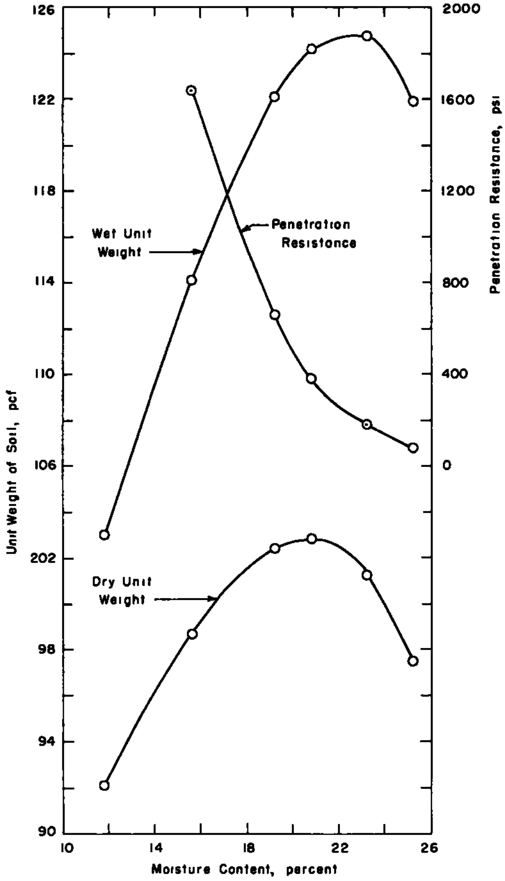


Figure 86. Typical unit weight and penetration resistance curves (26).

Other Methods for Determining Moisture Content.—There are other suitable methods for determining moisture content in the field and these are described briefly. One involves distillation with toluene for actual measurement of the water content; others are based on the correlation of sample moisture content with calcium carbide "pressure," calcium carbide "loss in weight," compacted wet unit weight, specific gravity of damp soil, specific gravity of alcohol-water solution, and refractive index of dioxan-water solution. Two other methods are discussed under "Nuclear Test Methods" and "Hilf's Method for Fine-Grained Soils."

The distillation method (116, 14, 22) for determining moisture content consists of adding toluene (or xylene) to the soil sample, heating the mixture to drive off the water and toluene, condensing the vapor and collecting the distillate. The water is the heavier of the two liquids and can be measured directly in the collection tube. The toluene floats on the water and is recirculated to the still where it prevents the temperature of the mixture from exceeding its own boiling temperature, 110.6 C. The method is accurate but takes about 45 min. The need for a source of running water to cool the condenser generally limits the method to well-furnished field laboratories.

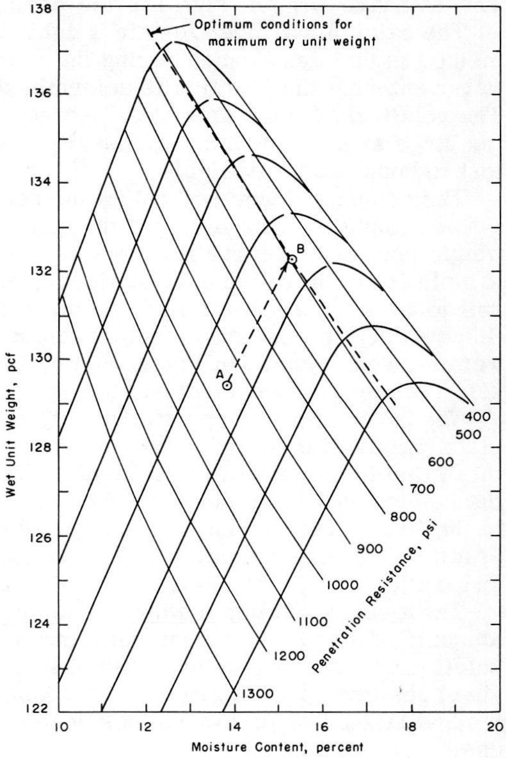


Figure 87. Moisture, unit weight and penetration resistance curves from a specific project for use in compaction control.

The calcium carbide "pressure" method (58, 35) for determining moisture content consists of mixing measured quantities of damp soil and powdered calcium carbide in a closed chamber (Fig. 88) and measuring the pressure developed by the formation of acetylene gas. (Calcium carbide and water combine to form acetylene gas and calcium hydroxide.) The pressure developed is directly related to the amount of water entering into the reaction. If all of the water in the soil does not enter into the reaction, as might happen with a heavy clay, the pressure does not accurately measure the moisture content of the soil. The "pressure" method requires 5 min or less and is suitable for most soils. For heavy clays, some mechanical means for breaking up the soil lumps is required; two steel balls have been added to the apparatus in Figure 88 for this purpose. With this modification, the moisture contents of clay soils, with P.I. values as high as 40, have been determined (130) within 3 percent of the oven-dried value at about optimum moisture content. The small chamber volume of commercial devices restricts sample size and makes them unsuitable for representative samples of coarse granular material.

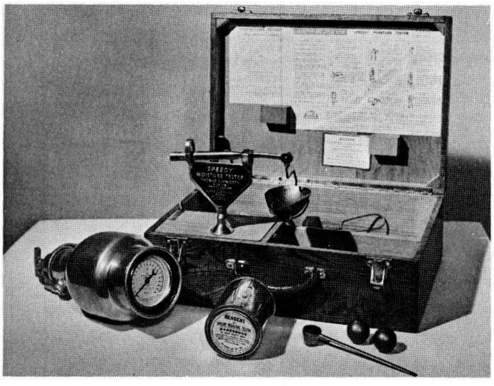


Figure 88. Calcium carbide pressure device for determining moisture content.

The standard sample size for the device in Figure 88 is 26 grams.

The calcium carbide "loss in weight" method (116) differs from the "pressure" method in that gas formed during the reaction is allowed to escape. The amount of water entering the reaction is determined from the loss in weight of the total mixture. The relatively simple apparatus needed for this test makes this method more suitable for large samples than the "pressure" method. No commercial apparatus for this test is known to be available.

The compacted wet unit weight method (34) for determining the moisture content of a soil sample is satisfactory if the soil can be positively identified and the wet unit weight compaction curve for the soil is available. The method consists of taking a sample from the rolled earthwork, recompacting it into a mold, weighing the mold and soil to determine the wet unit weight, and plotting the wet unit weight on the compaction curve. The moisture content can be read off directly. For example, suppose the wet unit weight curve in Figure 86 applies and the recompacted wet unit weight is 120 pcf. The moisture content can be read directly as 18.1 percent.

The pycnometer or specific gravity method for determining moisture content consists mainly of measuring the specific gravity of the damp soil sample and comparing this value to the specific gravity of the dry soil, which was previously determined in the laboratory. This method, of course, depends on positive identification of the soil in the field. The method takes about 10 min and has been shown (24, 31, 39) to be practical for use in the field. The Texas method (68) eliminates errors due to bubbles and froth in the pycnometer by applying 1,200 psi to the system.

The alcohol solution method for determining moisture content consists of mixing set amounts of alcohol and damp soil, measuring the specific gravity of the alcohol-water solution with a hydrometer, and observing the corresponding moisture content on a chart relating specific gravity of alcohol-water solutions to percentage water. The method takes 5 to 10 min and has been shown (50) to be sufficiently accurate for field use.

The refractive index method for determining moisture content consists of mixing set amounts of dioxan and damp soil, filtering off a few drops of dioxan-water solution, measuring the refractive index and observing the corresponding moisture content on a chart relating refractive index of dioxan-water solutions to percentage water. The method has had very limited use but is rapid (about 10 min), and has been shown (116) to be very accurate.

TABLE 45

CHARACTERISTICS OF SIX TEST METHODS FOR DETERMINING IN-PLACE UNIT WEIGHT OF SOIL

Characteristics	Disturbed Methods in Which Test Hole Volume Is Measured by			Undisturbed Methods in Which Sample Is Removed as a		Nondestructive
	Sand Cone	Oil Replacement	Water Balloon	Drive Sample	Block Sample	Nuclear (Surface Type)
Speed	Moderate	Moderate	Moderate to fast	Fast to very fast	Slow	Very fast
Suitability with						
Granular material without cohesion[a]	No	No	No	No	No	Yes
Granular material with cohesion	Yes	Yes	Yes	No	Yes	Yes
Fine-grained cohesive soils	Yes	Yes	Yes	Yes	Yes	Yes
Applicability to initial readings on rough granular surfaces	Initial reading possible on cohesive material, Coffman correction[b] useful	Initial reading not practical	Initial reading simple	Not necessary	Not necessary	Rough surfaces leveled with sand
Precautions necessary	1. Use clean dry sand 2 Calibrate sand often 3 Avoid vibration 4 Use large-diameter holes holes in material with coarse aggregate 5 Do not use with open-graded aggregate in which sand might be lost by seepage 6 Do not use with very wet granular material	1. Use level smooth test site 2 Do not use with open-graded or pervious granular material in which oil might be lost by seepage 3 Pour oil quickly	1 Use large diameter hole in material with coarse aggregate 2 Apply sufficient pressure to water to force balloon to fit test hole, but not distort hole 3 Prevent entrapment of air in impervious materials 4 Balance vertical pressure on base plate and pressure in water balloon	1 Use 3- to 4-in diameter samplers in very dense and coarser-grained soil 2 Insert sampler uniformly fast	1 Do not use unless sample can be removed intact	1 Should be used only by safety-trained operators 2 Check apparatus often
Sample size limited by	Cone size, sand supply	Oil supply	Balloon size, fluid reservoir	Sampling tube	Nothing	Apparatus
Chief advantages	Simplicity, neatness	Simplicity	Simplicity, speed	Simplicity, speed	Large samples with coarse aggregate	Speed
Chief disadvantages	Unit weight variability, possible inaccuracy in coarse granular material	Messiness	Possible inaccuracy in coarse material	Limited to fine-grained soils	Slowness	Initial high cost, apparatus and procedure in development stage
References	101, 89, 114	25, 101	79, 113, 101	48	48	124, 128, 103, 125

[a] Exclude closely-graded or well-graded material with sufficient moisture for apparent cohesion

[b] Consists mainly of adding thin leveling course (89)

Many other methods have been used in determining moisture content in the field and are described in the literature. These include electrical resistivity, electrical capacitance, the Turnbull Drop Test (Australia), temperature rise on addition of sulfuric acid, and several others. Because they have been used on a limited scale they are not described here.

Methods for Determining Unit Weight

There are several methods currently being used for measuring the in-place unit weight of the compacted earthwork. Those most commonly used are given in Table 45 with their characteristics. All of these methods are satisfactory for cohesive fine-grained soils; some are also satisfactory for coarse-grained materials.

Disturbed Methods.—Disturbed sample methods are applicable only with materials in which a hole can be dug and its shape retained. The methods generally consist of five basic steps: (a) leveling the test site and/or making an initial "zero" reading; (b) digging a hole in the compacted earthwork; (c) weighing the material removed; (d) measuring the volume of the hole; and (e) calculating the wet unit weight by dividing the weight of damp soil by the volume of the hole. The dry unit weight is determined by dividing the wet unit weight by one plus the moisture content (expressed as a decimal).

The volume of the hole can be determined by filling it with dry sand, oil, water or any suitable material of known unit weight, then dividing the weight of material used to fill the hole by its unit weight. For example, putty has been used (115). The volume of the hole can also be determined by filling it with plaster of Paris, then removing the hardened cast and measuring its volume directly in an overflow volumeter.

Standard methods for making in-place unit weight tests with sand and oil are descriped in AASHO test designations T 147-54 Method A and T 181-57. Two suggested methods for in-place unit weight tests using water balloons are given in "Procedures for Testing Soils," ASTM, pp. 432-441 (1958). The sand cone, the oil replacement and the water balloon methods have features which limit their usefulness. The methods can be used satisfactorily, however, if their limitations are recognized and proper precautions observed.

The accuracy of the sand cone method is limited mainly by the variability in unit weight of the sand and its inability to completely fill the test hole. The unit weight of the sand deposited in the test hole is affected by the height from which the sand is poured, the amount of vibration present, the moisture content of the sand, the temperature, and the amount of extraneous soil mixed in with the sand. The ability of the sand to completely fill the hole is limited by its angle of repose.

The following precautions should be taken to insure accurate results:

1. Provide a means for depositing sand in the test hole that will be uniform for different operators. The use of a sand cone as shown in Figure 89 has given good results (101).
2. Use clean dry sand that is uniform in size distribution. Standard Ottawa sand, all of which passes the No. 20 sieve and is retained on the No. 30 sieve, has given good results. Some operators have found screened concrete sand to deposit to uniform unit weight.
3. Calibrate sand frequently to determine its weight per cubic foot under varying temperature and humidity conditions. A minimum of twice a day is recommended.
4. Use large-diameter test holes in material with large aggregate to minimize the possible error due to the inability of the sand to surround projecting stones or to fill large cavities in the sides of the hole.
5. Prevent any jarring or vibration from settling the sand in the test hole during measurement or in the container during calibration. Staying 30 ft away from operating equipment is usually sufficient.
6. Do not reuse sand contaminated with soil or water.
7. Do not use the sand replacement test with open-graded aggregate in which sand might be lost by seepage into the spaces between particles.
8. Do not use with very wet pervious material in which bulking of sand due to excessive moisture content is likely.

The accuracy of the oil replacement method is limited mainly by the permeability of the material tested and the ability of the operator to level the test site. Variations in the unit weight of the oil due to temperature changes and different amounts of contained air also affect the accuracy of this method.

The following precautions should be taken to insure accurate results:

1. Calibrate the oil in a container of the same shape and approximate volume as the test hole. Pour the oil into the container at the same rate as used in the field.
2. Level the test site so that the excavated hole can be poured brimfull of oil. A bar level can be used as a guide.
3. Pour the oil quickly into the hole to minimize the tendency for loss by seepage and to allow the same small amount of time for dissipation of air bubbles formed in the oil during pouring as was allowed during calibration of the apparatus.
4. Do not use with dry or open-graded aggregate in which oil might be lost by seepage.
5. Use free-flowing oil: SAE 30 to 40 in warm weather, SAE 20 weight in cold weather.

The accuracy of the water balloon method is limited mainly by the ability of the balloon to fit the hole. This, in turn, is influenced by the stiffness of the balloon, the fluid pressure inside the balloon, the shape of the hole, and the quantity of air trapped between the balloon and the sides of the hole. A typical water balloon is shown in Figure 90.

The following precautions should be taken to insure accurate results:

1. Use appropriate-size device so that balloon is about the size of the hole required.
2. Use large-diameter holes in material with coarse aggregate to minimize error due to poor fit along sides.
3. Use sufficient fluid pressure to force the balloon to fit the hole, but not so much that the hole is distorted or the base plate is lifted off the ground. A pressure of 3 to 7 psi is recommended. The device shown in Figure 91 includes a pump and pressure gauge.
4. Prevent entrapment of air between the balloon and the hole in impervious material. Strings have been used (101) with success. The Washington Densometer (Fig. 92) fills the balloon from the bottom up, thereby flushing the air out to the surface.
5. Balance the vertical pressure on the base plate against the fluid pressure to prevent caving the hole in or blowing the balloon out.

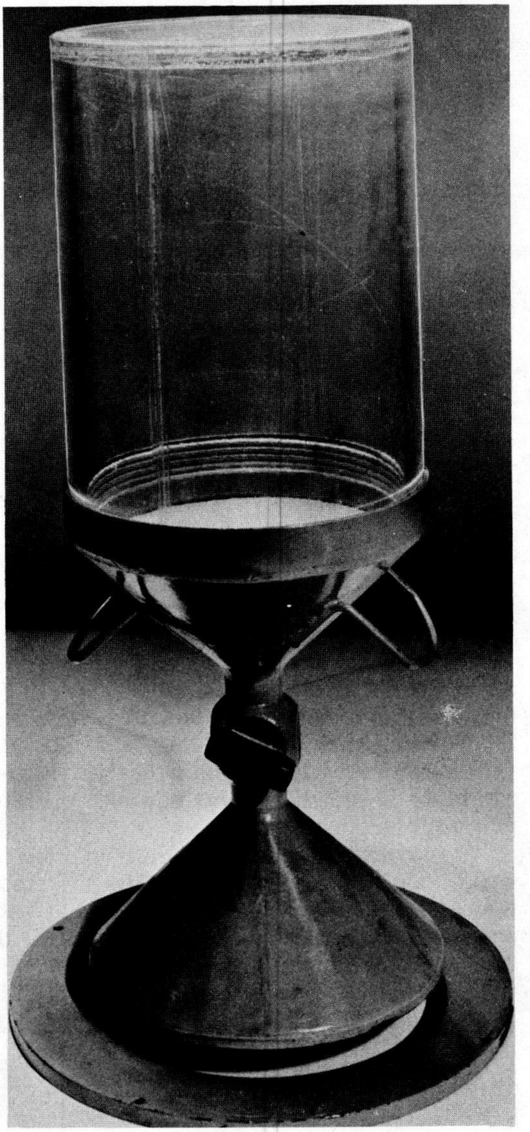


Figure 89. Sand-cone used in sand-replacement method of determining unit weight (101).

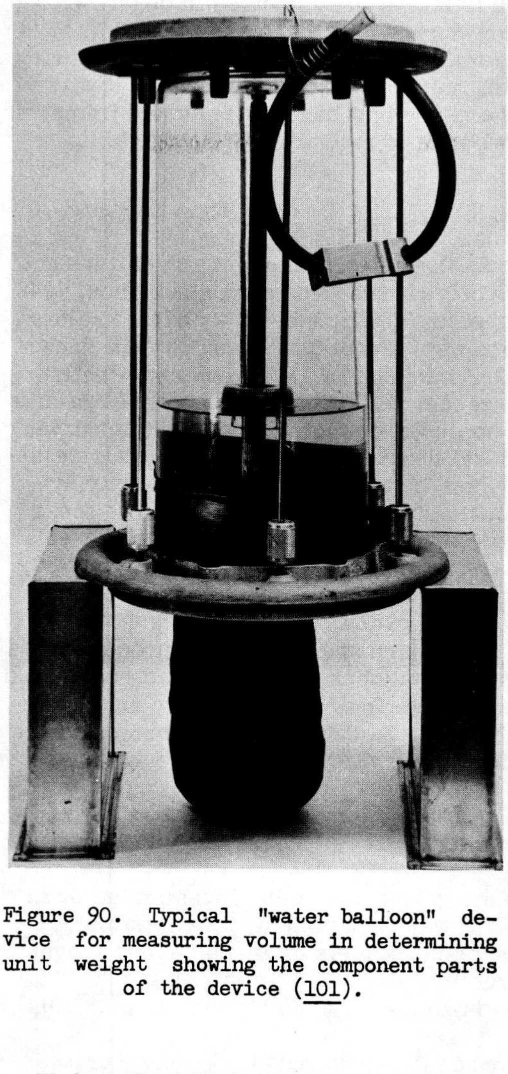


Figure 90. Typical "water balloon" device for measuring volume in determining unit weight showing the component parts of the device (101).

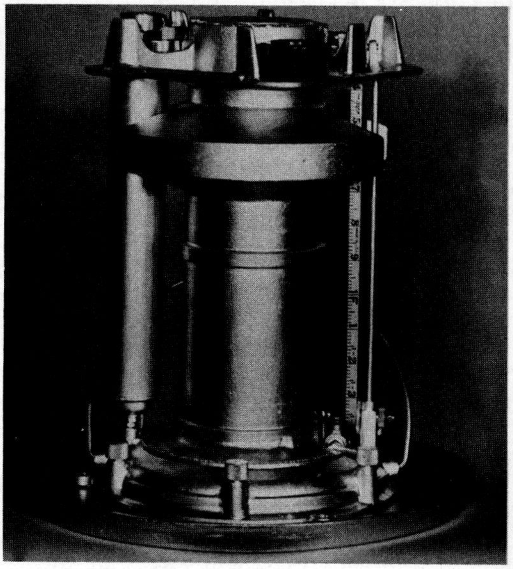


Figure 91. Water balloon with built-in pump and pressure gage (courtesy Rainhart Company).

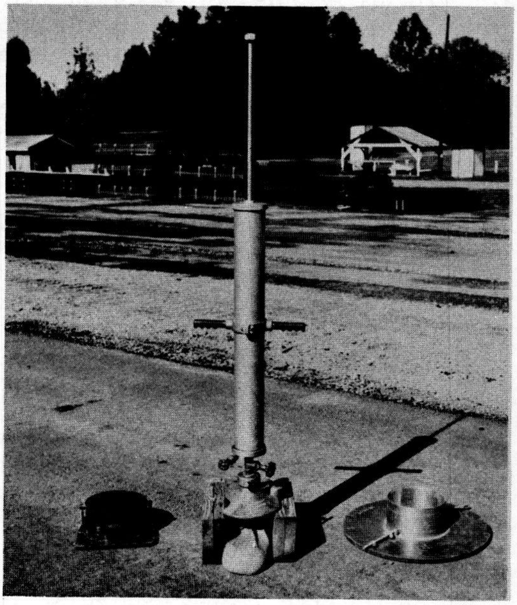


Figure 92. Washington densometer (101).

Undisturbed Methods.—Undisturbed sample methods consist of removing the sample with as little disturbance or distortion as possible, then determining the unit weight of the sample from its weight and volume. Standard procedures for making in-place unit weight tests by the drive sampler and the block method are given in AASHO test designation T 147-54, Method B.

The drive sampler method is suitable for fine-grained soils—clays, silts, and fine sands. The method consists of pushing a short sampling tube into the soil, withdrawing the tube with sample, trimming sample flush with ends of tube, weighing, then calculating the unit weight of the soil by dividing the net weight of the sample by the volume of the tube. Its accuracy is limited mainly by the amount of distortion (compaction of loosening) of the sample caused during drive sampling. In general, the unit weight of loose to medium dense soils tends to be increased and the unit weight of very dense soils tends to be loosened (48). Advance trimming may be used in dense soils to facilitate driving and to reduce sample disturbance.

The block sample method is suitable for any material that will remain intact during sampling. The method briefly consists of cutting out a block of soil, coating it with a known amount of paraffin, weighing to obtain the net weight of the sample and immersing in an overflow volumeter to determine the net volume of the sample, then dividing through for the unit weight.

Nuclear Test Methods

Nuclear test methods for measuring in-place soil-moisture content and unit weight are yet in the development stage. They have received much attention since about 1949 when researchers at Cornell University developed the first probes (54, 67). Nuclear methods for measuring in-place unit weight consist of directing gamma rays of known intensity into the soil material and measuring the intensity of gamma rays reflected back. As the unit weight of soil materials increases, the reflected intensity of gamma rays decreases. Nuclear methods for measuring in-place moisture content consists of directing "fast" neutrons of known intensity into the soil material and measuring the intensity of "slow" neutrons reflected back. "Fast" neutrons are slowed mainly by elastic collisions with hydrogen atoms; the number of "slow" neutrons detected (near the source of "fast" neutrons) is indicative of the moisture content of the soil material. Some commonly used sources of gamma rays are radium, cobalt 60, and cesium 137; the most commonly used source of "fast" neutrons is a radium-beryllium mixture.

There are two basic types of nuclear devices: the probe, which is designed to be lowered into the ground, and the surface gage. Moisture and unit weight probes are lowered to the desired depth in the soil through access tubes driven into the ground and are particularly suited for making measurements at various depths and for making repeated or periodic measurements at the same points. Surface gages are placed on the ground surface and are chiefly used in compaction control. One type of surface gage is shown in Figure 93. The operators, shown in the Figure, are beside the scaler (electronic counter) which is used to determine the average intensity of gamma rays for unit weight, or "slow" neutrons for moisture content. These measurements are made during a time interval of 2 to 5 min.

At present, nuclear apparatus, mainly surface gages, are being investigated by at least 8 highway organizations. The Michigan Highway Department, as an example, designed their own gage and have made extensive check tests on in-place unit weight and moisture determinations on regular construction projects. They report (124) that the results are encouraging, but will continue to use the apparatus on an experimental basis.

The principal advantage of using nuclear surface gages is speed. In-place unit weight tests can be run in about one-fifth of the time required for conventional disturbed-sample methods. In addition, testing can be done without disturbing the soil structure, the methods are applicable to a wide range of materials, even frozen ground, and test results are subject to little variation due to operator differences.

The principal disadvantages of current equipment are high initial cost and uncertain accuracy. The accuracy of the apparatus seems to be debatable; the published data are inconclusive. Claims of accuracy in unit weight measurements vary from plus or minus 0.5 to 5.5 pcf (88).

In October 1959, Pocock, Smith, Schwartje and Hanna (124) reported on the performance of the combination moisture content-unit weight gage developed in Michigan. They analyzed data from one road project that included 159 nuclear unit weight and 172 nuclear moisture determinations and corresponding check tests by conventional methods (water balloon used for unit weight, open-pan method used for moisture content). An analysis of the data showed that 95 percent of the nuclear unit weight determinations were within 5 pcf of the values by conventional methods; 95 percent of the nuclear moisture measurements were within 2.6 percentage points of the values determined by conventional methods. In-place unit weights ranged from 110 to 140 pcf; moisture contents ranged from about 4 to 17 percent.

Figure 93. Nuclear surface gage for measuring in-place unit weight (courtesy Michigan State Highway Department).

In January 1960, Phillips, Jensen and Kirkham of Iowa State University reported (128) the results of a study to determine the reproducibility of the Nuclear-Chicago apparatus. Tests were run on plots of Colo clay compacted to three different unit weights. The analysis of nuclear unit weight measurements showed that 68 percent of the values were within 3.5 pcf of the mean unit weight values. Corresponding unit weight determinations by a drive sampler showed at least as much variation.

In June 1960, Carey, Shook, and Reynolds of the AASHO Road Test staff reported (128B) on the performance of two nuclear gages. They found that in closely controlled laboratory tests, the nuclear gages were equally as accurate in determining unit weight values as the 6-in. water balloon method used. In summarizing the results of their field experiment, however, they reported that the relative accuracy of the nuclear gage, the sand cone, and the water balloon could not be established because the true unit weight of the material, at each test point, was unknown.

This statement, that the true unit weight of the material at each test point was unknown, applies generally to all the field results cited. The results of tests made at different points in the field are affected by the natural variability of the soil and of the compaction process.

In addition, comparisons of field measurements by nuclear and conventional methods are affected by the inaccuracies of the conventional methods and the differences in sample size or samples tested. It is known, however, that the accuracy or usefulness of current surface gages is limited by the following features:

1. Moisture determinations are influenced by hydrogen atoms in certain clays that are not normally driven off at 110 C; therefore, the gage indicates higher moisture contents in some materials than the standard method does.
2. Unit weight determinations are affected by the chemical composition of the materials being tested. Iron oxide, for example, would tend to make the unit weight measurements low; water in the soil tends to make them high.
3. The operator cannot control the depth and/or volume of soil being tested for moisture content and unit weight. The sample size depends on the dimensions of the gage and the moisture content and unit weight of the soil. In unit weight tests, the depth sampled decreases as unit weight increases; maximum depth with currently available apparatus is 4 to 6 in. Moisture sample size decreases with increasing moisture content; maximum depth of sample with current equipment varies from 5 to 15 in. (103).
4. Unit weight determinations are sensitive to air gaps between the gage and the ground surface. Tests by the Bureau of Public Roads (131) indicate a 1/100-in. air gap will reduce the measured unit weight 1 pcf.
5. Other sources of error include the non-uniform disintegration of the radioactive material, reflection from nearby objects of stray radiation that escapes through the top and sides of the gage, and variability in counting time.

Another feature that is a disadvantage is the possibility of excessive radiation exposure of operating personnel. The recommendations of the National Committee on Radiation Protection which are followed by the Atomic Energy Commission should be employed as guides in the use of radioactive materials.

Correcting for Coarse Aggregate Content

Compaction test results may not be directly applicable to checking compaction in the field if the rolled earthwork contains coarse aggregate sizes or percentages different from those tested in the compaction test. A correction or adjustment may be necessary to account for coarse aggregate content.

Some effect of coarse aggregate content on the compaction of soil-aggregate mixtures is shown in Figure 9. The data were obtained from compaction tests, similar to AASHO T 99 Method C, in a 1/30- cu ft mold using a constant compactive effort. They show that:

1. The unit weight of the whole material increases with increasing coarse aggregate content up to a maximum value at some optimum gradation. At higher percentages of coarse aggregate the over-all unit weight decreases; at these higher percentages there may be insufficient fines to fill the voids between the aggregate.
2. The unit weight obtained in the fine fraction is gradually reduced as coarse aggregate content increases up to 25 to 40 percent. At higher percentages, the unit weight of the fine fraction decreases rapidly.
3. The addition of graded aggregate reduces the compaction of the fine fraction much more rapidly than does the addition of single-sized aggregate.

The effect of the maximum size of aggregate on the unit weight of the whole material appears to be small. Using single-size coarse aggregates, Maddison (28) found that the size used made no difference in the unit weights obtained in the silty-clay-aggregate mixtures. For example, the upper dashed curve in Figure 9 fits his results using 1-in. to ¾-in. coarse aggregate and, also, it fits his results using ¾-in. to ½-in. and ½-in. to ⅜-in. coarse aggregate. Using graded aggregate to determine the effect of maximum size, the Civil Aeronautics Administration (64) tested crushed limestone, slag, and gravel with maximum aggregate sizes ¾ in. and 1½ in. (Fig. 94). The unit weights obtained on the two sizes of limestone and slag were about the same. Unit weights of the 1½-in. maximum size gravel, however, were considerably greater than the ¾-in. maximum size gravel. The difference is due partly to the higher specific gravity of the "1½-in. to ¾-in." fraction (2.70 vs 2.56). Tests by the Bureau of Reclamation (97) showed that the unit weights obtained for clayey gravel with 3-in. maximum size were somewhat greater than those obtained for clayey gravel with ¾-in. maximum size gravel; the difference due possibly to better total gradation and less particle interference.

The optimum moisture content of the whole material is reduced as the percentage of coarse aggregate increases.

To account for coarse aggregate content, a correction can be made either (a) to the field measurements or (b) to the laboratory test results.

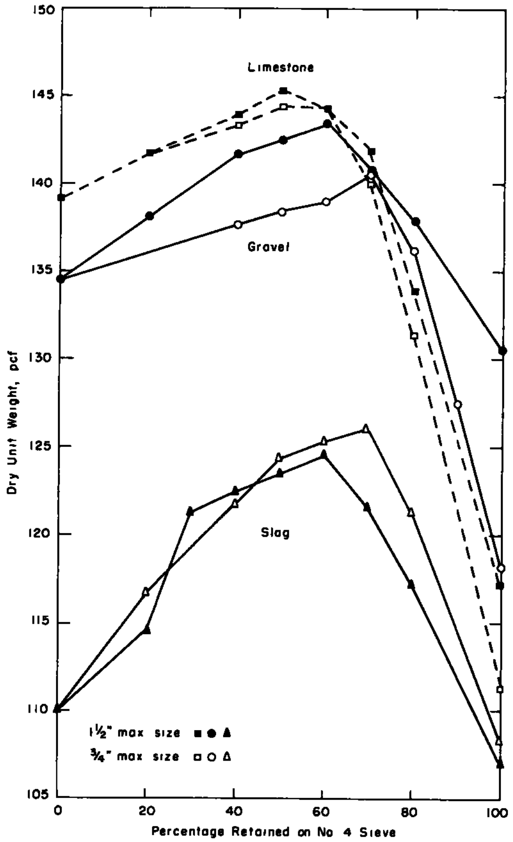


Figure 94. Effect of maximum size aggregate on maximum unit weight of graded materials (64).

When construction specifications make reference to the results of the standard test; that is, that the rolled earthwork should be compacted to at least 95 percent of the maximum unit weight determined by the standard compaction test (AASHO T 99 T 180), then the first type of correction is indicated.

Correcting Field Measurements for Coarse Aggregate Content.—Correcting field measurements for coarse aggregate content is aimed at determining the in-place unit weight and moisture content of the fine fraction for direct comparison to compaction test results. At least three methods of correction can be used for determining the in-place unit weight and moisture content of the fine fraction and are applicable to materials that contain up to about 60 percent coarse aggregate, as long as there are sufficient fines to fill the voids in the coarse aggregate.

It should be realized, however, that compaction of the fine fraction is reduced somewhat by the presence of coarse aggregate. The field compactive effort which is sufficient to obtain 95 percent of maximum dry unit weight in a fine-grained soil will not generally be sufficient to obtain the same unit weight in that fine-grained soil in a soil-aggregate mixture with appreciable coarse aggregate. If the in-place unit weight tests are used as a measure of uniformity of compactive effort, then some decrease in unit weight of the fine material should be expected and allowed for in soil-aggregate mixtures. However, because the stability of the fine fraction may greatly influence the stability of the whole material at coarse aggregate contents less than about 60 percent, higher field compactive efforts may be necessary for design purposes.

Three methods of correction for determining the in-place unit weight and moisture content of the fine fraction are presented as follows:

The first and simplest method consists of measuring directly the in-place unit weight and moisture content of the fines. The coarse aggregate or stones in the material removed from the test hole are put back in the hole, then the fines remaining are weighed and the net volume of the test hole is determined. The oil replecement method is suitable for measuring the volume of the hole with stones in the bottom. If a can and spout are used in the sand replacement method, the stones can be returned to the hole during pouring. Generally, the sand replacement and water balloon methods are not satisfactory for measuring the net volume of the test hole when the stones are piled on the bottom.

The second method is similar to the first in that the coarse aggregates are separated from the material excavated. The weight of the fines are determined directly; the net volume occupied by the fines is determined by subtracting the volume of the coarse aggregate from the total volume of the test hole. The volume of the coarse aggregate can be determined directly by using an overflow volumeter (see AASHO Designation T 147-54) or indirectly by dividing the weight of coarse aggregate by its unit weight (specific gravity x 62.4). For wet unit weight calculations, use bulk specific gravity (saturated surface-dry basis); for dry unit weight calculations, use bulk specific gravity (oven-dry basis). The moisture content of the fines can be determined by direct sampling of the fines.

The third method for obtaining the in-place unit weight and moisture content of the fines requires the following determinations: (1) unit weight and moisture content of whole material, (2) percentage of coarse aggregate, and (3) bulk specific gravity of the coarse aggregate. The unit weight of the fine fraction can be derived from the basic equation that states the total volume of material equals the sum of the volumes of the fine fraction (including all voids) and coarse fraction (with no voids):

$$\frac{W}{\gamma_d} = \frac{P_f W}{\gamma_f} + \frac{P_c W}{\gamma_c} \qquad (1)$$

in which

W = oven-dry weight of whole material, lb;

P_f = percentage by weight of fine material (passing the No. 4 or ¾-in. sieve) in the sample, expressed as a decimal;

P_c = percentage by weight of coarse aggregate (retained on the No. 4 or ¾-in. sieve) in the sample, expressed as a decimal;
γ_d = dry unit weight of the whole material, pcf;
γ_f = dry unit weight of the fine material (passing the No. 4 or ¾-in. sieve), pcf; and
γ_c = $G_s \times 62.4$ = bulk specific gravity (oven-dry basis) of the coarse aggregate, pcf.

Solving for γ_f gives:

$$\gamma_f = \frac{\gamma_d \gamma_c P_f}{\gamma_c - \gamma_d P_c} \qquad (2)$$

If, for example,

$$\gamma = 127 \text{ pcf}$$
$$\gamma_c = 2.39 \times 62.4 = 149.2 \text{ pcf}$$
$$P_f = 0.65$$
$$P_c = 0.35$$

then the dry unit weight of the fine fraction (γ_f) is equal to

$$\gamma_f = \frac{\gamma_d \gamma_c P_f}{\gamma_c - \gamma_d P_c} = \frac{(127)(149.2)(0.65)}{149.2 - (127)(0.35)} = 117.6 \text{ pcf.}$$

The moisture content of the fine fraction can be determined from the fundamental equation that states the total weight of water in the whole material is equal to the sum of the weights of water in the fine and coarse fractions or:

$$Ww = P_f W w_f + P_c W w_c \qquad (3)$$

in which

w = moisture content of whole material, expressed as a decimal;
w_f = moisture content of fine fraction (material passing the No. 4 or ¾-in. sieve) expressed as a decimal; and
w_c = adsorption of moisture by coarse aggregate (material retained on the No. 4 or ¾-in. sieve) expressed as a decimal.

Solving Eq. 3 for moisture content of the fine fraction (w_f) gives

$$w_f = \frac{w - P_c w_c}{P_f} \qquad (4)$$

If, for example,

$$w = 0.08$$
$$P_c = 0.35$$
$$P_f = 0.65$$
$$w_c = 0.03$$

the moisture content $w_f = \dfrac{0.08 - (0.35)(0.03)}{0.65} = 0.107$ or $w_f = 10.7$ percent.

For some projects it may be desirable to compute the moisture and unit weight relationships between total samples and fine fractions for a wide range in percentages of coarse aggregate and construct families of curves so values may be read directly from charts. Such charts were prepared by Shockley (38) with fine fraction defined as

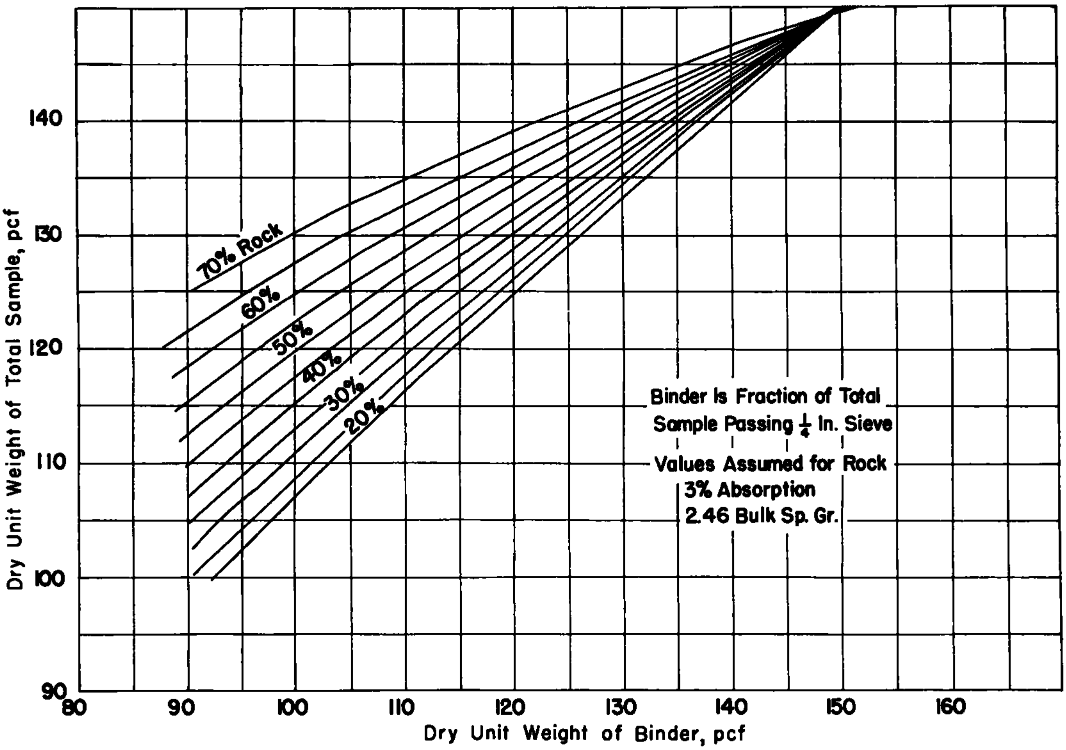


Figure 95. Chart for determining relationship between unit weight of fraction passing the $\frac{1}{4}$-in. sieve and the total sample (38).

material passing the ¼-in. sieve. These charts are reproduced here as Figures 95 and 96. The curves are for coarse aggregate having a bulk specific gravity (saturated surface-dry basis) of 2.46 and an absorption value of 3 percent. (It should be noted that dry unit weight calculations require the use of bulk specific gravity (saturated surface-dry basis) by one plus the absorption.) The use of the curves is illustrated by the following example:

$$\gamma_d = 120 \text{ pcf}$$
$$P_c = 0.50$$
$$w = 0.15$$

To determine (A) the unit weight of the minus ¼-in. material use Figure 95. Enter the scale on the left side of the chart at 120 pcf and continue across to the intersection with the 50 percent plus ¼-in. material line. From that point read directly down to the bottom of the scale to 100 pcf which is the unit weight of the minus ¼-in. material desired.

To determine (B) the moisture content of the minus ¼-in. material use Figure 96. Enter the scale on the left side of the chart at 15 percent moisture content and continue across to the intersection with the 50 percent plus ¼-in. material line. From that point read directly down to the bottom of the scale to 27 percent, which is the moisture content of the minus ¼-in. material

Correcting Laboratory Test Results for Coarse Aggregate. — Correcting laboratory test results for coarse aggregate is intended to determine the proper unit weight and moisture content of the whole material (including coarse aggregate not tested) for direct use in the field.

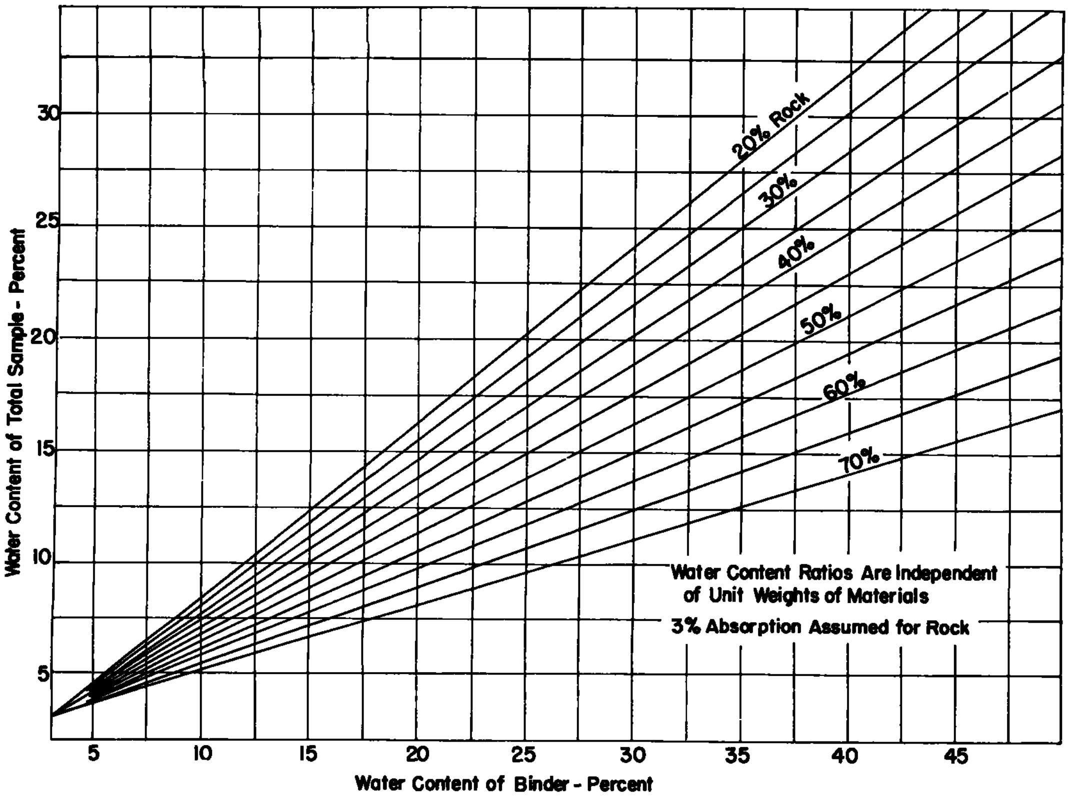


Figure 96. Chart for determining relation between water content of portion passing $\frac{1}{4}$-in. sieve and total sample (38).

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 ¾-in. maximum although larger sizes, up to 1½ 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 ¾-in. sieve. These methods also provide for replacing the coarser material (retained on the ¾-in. and passing the 2-in. sieve) with an equal weight of material between the ¾-in. and the No. 4 sieves. As pointed out previously, the maximum size coarse aggregate appears to have little effect on the maximum unit weight obtained.

Case 1. Where the fine fraction is sufficient in quantity to fill the voids in the coarse fraction.

The theoretical unit weight of the whole material can be calculated for coarse aggregate contents up to about 60 percent—or as long as there are sufficient fines to fill the voids in the coarse aggregate. The formula for the theoretical unit weight is based on Eq. 1 and can be written:

$$\gamma_d = \frac{\gamma_f \gamma_c}{\gamma_f P_c + \gamma_c P_f} \qquad (5)$$

A number of organizations use this formula or some revision of it to calculate the maximum unit weight of the whole material. In such cases, the maximum unit weight of the fine fraction is substituted for γ_f. The value of γ_c is $G_s \times 62.4$ as previously used (G_s = bulk specific gravity, oven-dry basis, for dry unit weight calculations). For example, if the whole material contains 35 percent coarse aggregate (material retained on the No. 4 sieve), the maximum unit weight of the fine fraction is 120 pcf, and the bulk specific gravity (oven-dry basis) of the coarse aggregate is 2.39, the maximum unit weight of the whole material is

$$\gamma_d = \frac{\gamma_f \gamma_c}{\gamma_f P_c + \gamma_c P_f} = \frac{(120)(2.39)(62.4)}{(120)(0.35) + (2.39)(62.4)(0.65)} = 128.8 \text{ pcf}$$

Values of γ_d, determined by the theoretical unit weight formula (Eq. 5), for gravel mixtures are plotted in Figure 97 together with compaction test results obtained by the Civil Aeronautics Administration (64). It is apparent that the the theoretical unit weight formula (Eq. 5) gives excessively high values for the material tested. The unit weight of the fine aggregate was calculated by Eq. 2 and is also plotted. The theoretical unit weight formula will, of course, give the correct unit weight of the whole material only when the fine fraction is compacted to its maximum unit weight, when the coarse aggregate does not interfere with compaction of the fine aggregate.

The theoretical unit weight formula should apply reasonably well to soil-aggregate mixtures with single size coarse aggregate up to about 30 percent inasmuch as, from the evidence in Figure 9, very little reduction in unit weight of the fines occurred up to that point. For graded coarse aggregate mixtures, the theoretical unit weight formula appears to indicate high values for even small percentages of coarse aggregates.

Other tests by the Civil Aeronautics Administration (CAA) on crushed limestone (G_s = 2.65) and slag (G_s = 2.58) with 1½-in. maximum size aggregate gave similar results to the gravel and prompted them to revise the theoretical unit weight formula to:

$$\gamma_d = P_f \gamma_f + 0.9\, P_c \gamma_c \qquad (6)$$

Figure 98 shows how well the theoretical and the CAA formulas predict the unit weight of the graded limestone, gravel, and slag.

It should be recalled that all the data shown have been obtained in the laboratory with constant compactive effort. Local field compaction data should be developed to certify the applicability of the theoretical unit weight formula. Without such certification, note that it agrees best with test results when the coarse aggregate content (or material not tested) is least. When there are insufficient fines to fill the voids in the coarse aggregate, at about 60 percent or more coarse aggregate, the unit weight formulas are not applicable.

Case 2. Where the fine fraction is insufficient to fill the voids in the coarse fraction.

Embankment, subgrade, and base course materials occur in which the minus No. 4 material is not sufficient to fill the voids in the plus 4 material.

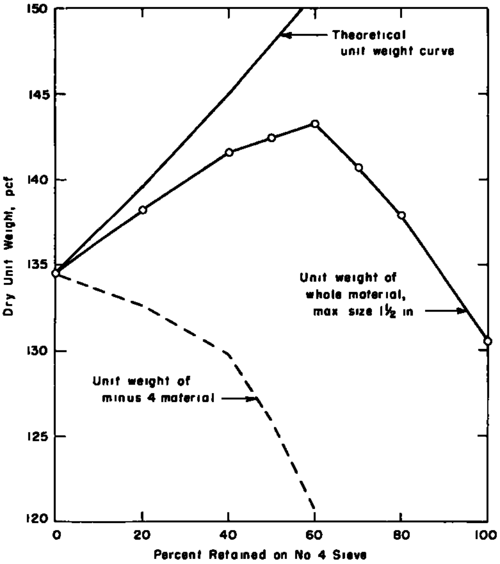


Figure 97. Effect of coarse aggregate content on the maximum unit weight of gravel mixtures compacted in a 6-in. mold, 4.6 in. high (partly from (64)).

Missouri (94) has developed a method for determining the unit weight of crushed rock base course material in such cases. Studies indicated that the average weight of coarse aggregate (retained on a No. 4 sieve) that could be compacted into a cubic foot was equal to 58 percent of the weight of a solid cubic foot of the same kind of rock. The average void content in the coarse aggregate was 42 percent.

To obtain the unit weight of the whole material when the fine aggregate is insufficient to fill the voids in the coarse aggregate, the following formula may be used:

$$\gamma_d = \frac{(0.58)(G_s)(62.4)}{P_c} = \frac{36.2\ G_s}{P_c} \qquad (7)$$

in which

G_s = bulk specific gravity (oven-dry basis) of the coarse aggregate,

P_c = percentage of coarse aggregate, expressed as a decimal.

For example,

given: $G_s = 2.57$

$P_c = 0.65$

the unit weight of the whole material is

$$\gamma_d = \frac{(36.2)(2.57)}{0.65} = 143.2 \text{ pcf.}$$

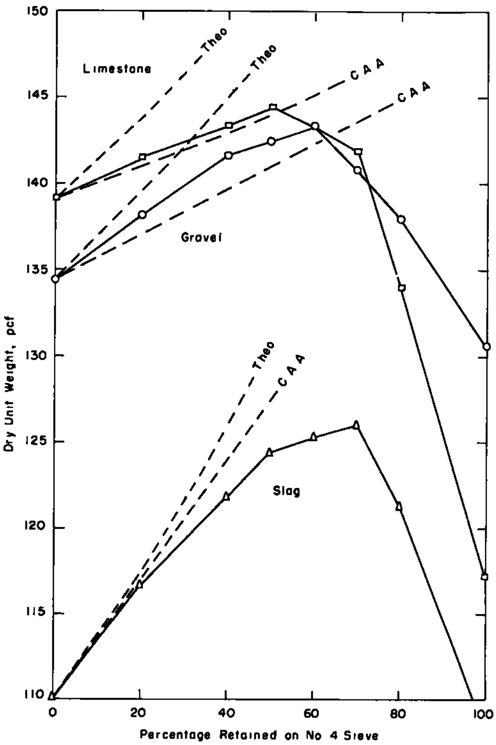


Figure 98. Effect of coarse aggregate content on the maximum unit weight of crushed limestone, gravel, and crushed slag mixtures compacted in a 6-in. mold, 4.6 in. high (64).

Missouri has developed a chart (Fig. 99) for determining the unit weight of crushed rock mixtures for Cases 1 and 2—for percentages of fine aggregate from zero to 100

If, for example, the compacted dry unit weight of the minus No. 4 material is 130.4 pcf, the bulk specific gravity (oven-dry basis) of the coarse aggregate is 2.57 and 47 percent passes the No. 4 sieve, the following steps lead to the unit weight of the whole material:

1. Plot 2.57 specific gravity on the left vertical scale. This corresponds to 160.4 pcf.
2. Plot 130.4 pcf on the right vertical scale.
3. Calculate the third point which is the over-all unit weight for a 50-50 mixture by means of the theoretical unit weight formula.

$$\gamma_d = \frac{\gamma_f \gamma_c}{\gamma_f P_c + \gamma_c P_f} = \frac{(130.4)(160.4)}{(130.4)(0.5) + (160.4)(0.5)} = 143.9 \text{ pcf.}$$

4. Plot 143.9 pcf on the 50 percent line and draw a smooth curve to connect the three points.
5. Note the point at which the 2.57 specific gravity curve intersects the above curve. This is the percentage of minus No. 4 material which exactly fills the voids in the coarse aggregate (37.2 percent).
6. Inasmuch as the percentage of fine aggregate, 47 percent, in the sample exceeds

this, follow the horizontal curve to the right to the percentage found in the sample and read the weight of total material from either vertical scale (144.8 pcf).

If the percentage of fine aggregate had been less than 37.2 percent, for example 35 percent, then the weight of the total material can be found by following the 2.57 specific gravity curve downward to the percentage found in the sample (35) and reading the weight of the total material from either vertical scale (143.2 pcf).

Another method for determining the maximum unit weight of coarse aggregate mixtures is described under "Humphres' Method for Granular Soils."

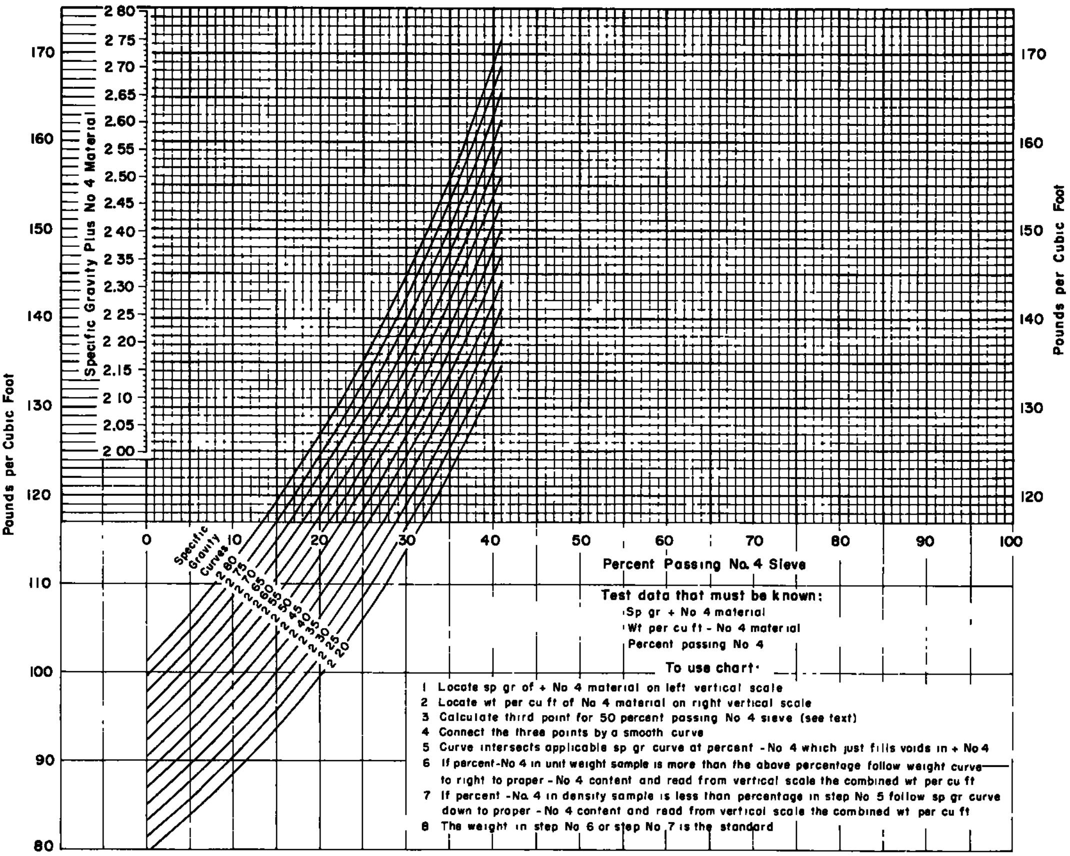
Proof-Rolling or Test-Rolling

A standard definition for the terms proof-rolling or test-rolling does not exist. Proof- or test-rolling infers the use of a roller to test the degree of compaction attained compared to that which is specified, or to test the adequacy of compaction in comparison with the results attained by the use of a roller of a given type and rating. Proof-rolling to date has usually involved the use of heavy to moderately heavy wheel load pneumatic-tire compactors to test the effectiveness of rolling. It has been employed on embankments, in cut section, on subgrades and on base courses.

Proof-rolling or test-rolling may consist of:

1. The application of relatively few passes of a heavy roller on a compacted embankment to

(a) Check the results of normal compaction;



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 99. Chart of weight per cubic foot for crushed rock (94).

(b) Locate areas that were missed or received insufficient coverage during normal compaction;
(c) Correct compaction deficiencies in areas where the existing compaction is inadequate but where the moisture content is proper for adequate compaction; and
(d) Locate areas of low bearing capacity due to excess moisture content.

2. Exploratory testing of subgrade in cut sections, as a means for locating
(a) Undesirable soils not exposed during excavation;
(b) Areas or zones of excessively wet soils not exposed during excavation.

3. Testing of subbases and base courses by the use of a relatively small number of passes of a heavy roller or the testing under a large number of passes simulating that which in the past has been termed "accelerated traffic" testing. The latter may be done by rolling directly on the base or subbase or on a bituminous surface of lesser thickness than that employed in the final construction.

Proof-rolling as discussed further does not include details of its use as mentioned under Item 3.

Compaction, shoving, or excessive deformation under the proof-roller is evidence of low unit weight, excessive moisture, or unsuitable material.

Very large compactors, as shown in Figure 119 are used in proof-rolling to obtain deep stress penetration to test conditions to a depth of 3 to 6 ft. Tire pressures for pneumatic-tired rollers generally range from 50 to 120 psi. Contact pressures, as well as those applied at various depths, should not be so high as to overstress the satisfactory material. The number of passes necessary in proof-rolling depends on the material tested and the stability requirements. Only one pass may be necessary to check out a 5-ft embankment, but several passes may be required over each of the subbase and base courses.

Proof-rolling is useful in checking compaction of earthwork and in correcting compaction deficiencies only when the moisture content is satisfactory. If the moisture content of the earthwork is appreciably dry of optimum, proof-rolling may be of little value in detecting or correcting inadequately compacted material. As reported by Turnbull and Foster (<u>132</u>): "If the moisture content is on the dry side of the proper range for compaction, proof-rolling gives a false sense of security because the layer looks firm and hard; but as the moisture increases [during the service life of the structure] the layer will either lose strength drastically or will compact further under traffic."

The effect of moisture content on the usefulness of proof-rolling can be illustrated somewhat by Figure 100 which shows a proof-roller compaction curve for a specific soil. The compaction curve defines the upper limit to which proof-rolling can increase the unit weight of the soil. Points A, B and C represent three moisture content-unit weight conditions of the soil at the time of proof-rolling; the unit weight is the same in all three cases and is less than the minimum required for satisfactory compaction. (1) The moisture content at point A is too dry for proof-rolling to obtain the minimum unit weight required. Compaction will, however, appear satisfactory under the proof-roller. (2) The moisture content at point B is satisfactory and proof-rolling will increase the unit weight of the soil to a value above minimum required. Proof-rolling at optimum moisture content will also increase the unit weights of soils that have unit weights equal to or that slightly exceed minimum requirements. Construction compaction may appear inadequate in both cases, because additional compaction is achieved under proof-rolling. One method for evaluating the results of proof-rolling in such cases is to compare the compaction obtained by the proof-roller at points of known unit weight with adjacent areas. (3) The moisture content at point C is too wet. Additional compaction will be achieved, but shoving or shearing will occur which will weaken the soil. This material will appear unstable and should be dried to a satisfactory moisture content before being recompacted. If the unit weight represented by point C had been equal to or greater than the minimum required, the results would have been the same.

Care should be taken to prevent overstressing soils that are inherently weak.

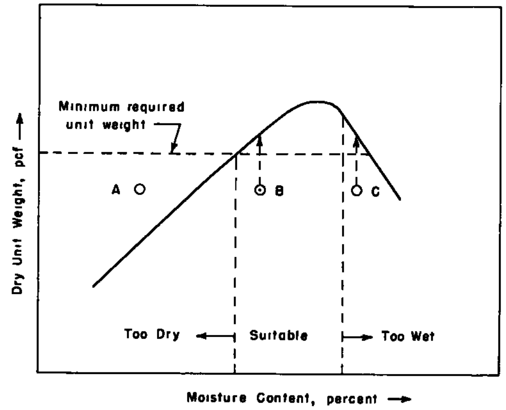


Figure 100. Proof-roller compaction curve showing suitable moisture range.

Some materials, like silt, may be sufficiently stable for design traffic loads when properly compacted, but under the higher stresses of proof-rolling, may shove and lose strength. If this occurs, complete removal and careful recompaction of the material to its original condition of maximum bearing capacity is necessary.

Care should also be taken to prevent overcompaction of expansive subgrade soils which may make them more subject to detrimental swell.

Proof- or test-rolling provides the engineer a means for testing the entire roadway rather than a few selected spots; it reduces the amount of interpolation that is normally required in analyzing test data.

Use of the Ohio and Wyoming Typical Curves

The Ohio and Wyoming State Highway Departments Methods permit the use of one-point compaction tests in the field. Reference is made to typical moisture content-unit weight curves to identify the soil tested and to determine the maximum unit weight and optimum moisture content of the soil.

The Ohio method was developed by Woods and Litehiser (19, 127A). They found that moisture content-unit weight curves have characteristic shapes, the curves for the higher-weight materials assuming steeper slopes and their maximum unit weights occurring at lower optimum moisture contents. Most soils having the same maximum weight per cubic foot have similar moisture content-unit weight curves.

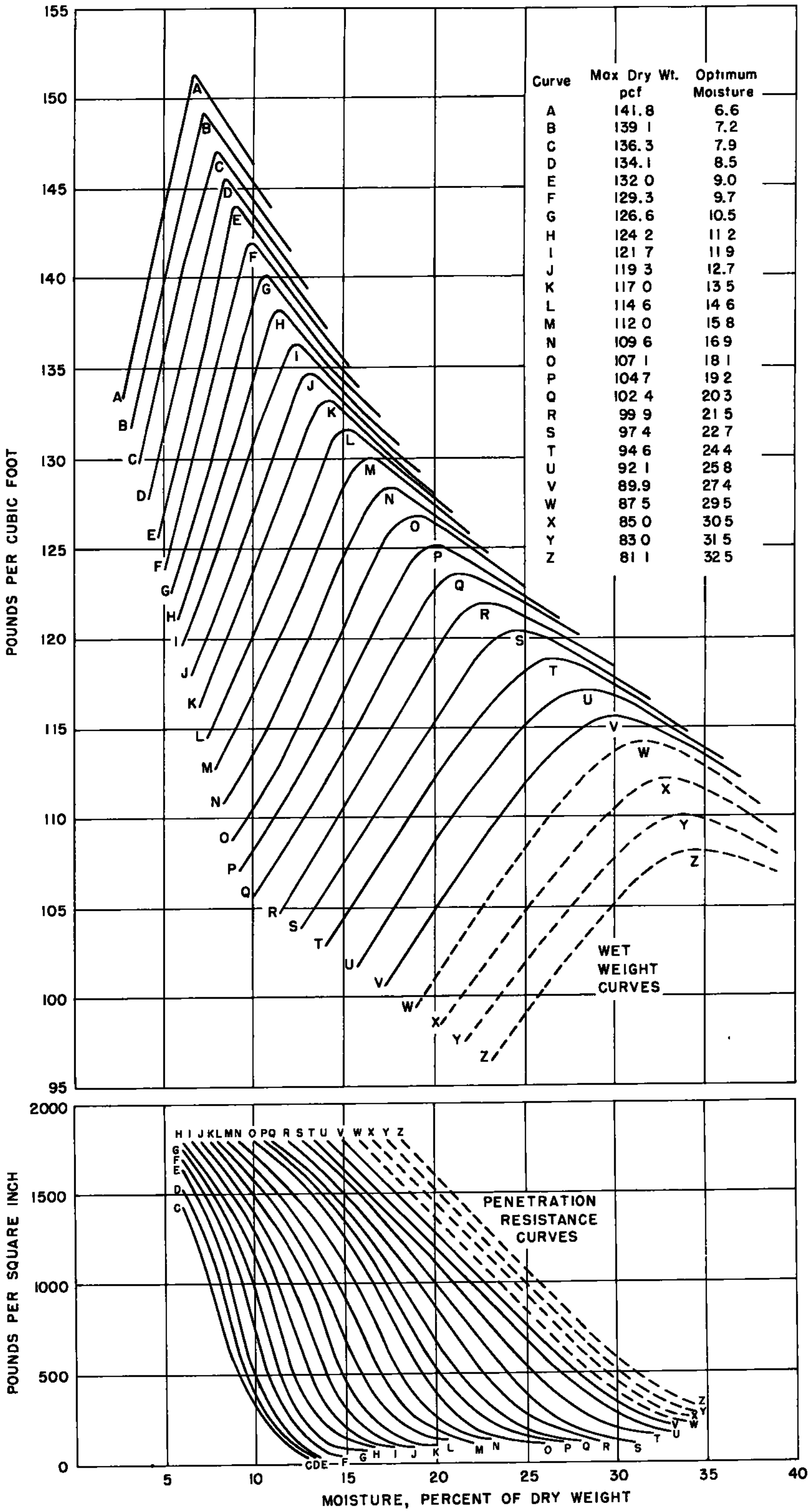
The original set of 9 typical curves was based on the results of 1,088 Ohio soil samples. The samples tested were placed in groups depending on their wet-weight peaks. As additional tests were made, additional typical curves were added. The set in current use, based on 10,000 tests, is shown in Figure 101.

In determining the curve for use with a given soil, the following steps are required: (1) compact the soil into the compaction mold in the standard manner; (2) determine the wet unit weight and penetration resistance; (3) on the set of typical unit weight curves (Fig. 101) draw a horizontal line at the wet unit weight value and on the typical penetration resistance curves draw a horizontal line at the penetration resistance value; (4) note all possible typical curves from which the moisture contents (determined by intersection with the horizontal lines drawn in step (3)) most nearly coincide. The curve for which the moisture contents nearly coincide, is the curve which most nearly approaches the true curve for the material.

For example, let 122 pcf equal the wet weight and 800 psi equal the penetration resistance of the soil compacted in the compaction mold. Tabulating the moisture contents at which the various wet weight curves cross the 122-pcf line and the 800-psi penetration line in Figure 107 gives:

Curve	Moisture Content at 122 pcf	Moisture Content at 800 psi
	Percent	Percent
P	17.5	18.4
Q	19.5	19.3
R	22.5	20.5

An examination of these values indicates that a moisture content of 19.3 to 19.5 percent denotes curve Q as the one which most nearly fits the soil in question.



Curve	Max Dry Wt. pcf	Optimum Moisture
A	141.8	6.6
B	139.1	7.2
C	136.3	7.9
D	134.1	8.5
E	132.0	9.0
F	129.3	9.7
G	126.6	10.5
H	124.2	11.2
I	121.7	11.9
J	119.3	12.7
K	117.0	13.5
L	114.6	14.6
M	112.0	15.8
N	109.6	16.9
O	107.1	18.1
P	104.7	19.2
Q	102.4	20.3
R	99.9	21.5
S	97.4	22.7
T	94.6	24.4
U	92.1	25.8
V	89.9	27.4
W	87.5	29.5
X	85.0	30.5
Y	83.0	31.5
Z	81.1	32.5

Figure 101. Ohio typical moisture content—wet unit weight and penetration curves (courtesy Ohio Department of Highways) (19, 127A).

Wyoming (52) adopted 17 of the Ohio curves, modified them for application to Wyoming soils and added 3 more. It was soon noticed that the moisture content, determined by drying, did not check the moisture content indicated on the standard typical curve chart. The difference in moisture content would, of course, change the corresponding dry weight.

Soils with the same maximum dry unit weight would sometimes differ so much in the slope of curves to the left of optimum that it would not be possible to arrive at a correct maximum dry unit weight and optimum moisture content unless the penetration reading and wet unit weight determinations were made at nearly optimum. To correct for these differences, two additional sets of typical curves were prepared. One of these had flatter-than-normal forward slopes, type A, and the other had steeper than normal forward slopes, type C. Figure 102 shows three typical curve slopes on the dry side of optimum for soils which have the same maximum unit weight and optimum moisture content. The differences in moisture content were accounted for by a special moisture graph placed above the wet unit weight and penetration-resistance curves.

After a sufficient number of four to six-point curves have been determined by test to establish the type of curve (A, B, or C), the number of points may be reduced to one to three and the correct curve used for associating the penetration resistance and wet unit weight to obtain the correct dry unit weight.

It was found from the typical curves that the amount of field moisture required to secure the same percent of compaction with the roller varies with the curve type, that is, it is necessary to work in a narrower moisture range closer to optimum with steep-curve soils (type C) than with flat-curve soils (type A). A method was developed for calculating the approximate minimum moisture content required for a sheepsfoot roller having a contact pressure of 325 psi to obtain 90 to 95 percent of maximum dry unit weight in the field when the moisture is well distributed through the soil and lifts are 5 in. or less loose depth.

Determination of the minimum moisture content is done by (a) determining the curve type, (b) selecting the percent of maximum dry unit weight which will define minimum moisture content requirements, and (c) plotting the dry unit weight thus obtained (Fig. 102) on the dry unit weight curve. The vertical line through that point (Fig. 102) indicates the minimum moisture content. The 95 percent-unit weight point is plotted on this line of minimum moisture content.

The working moisture content is the average of the minimum and optimum moisture contents. The working range is between the two values as is indicated in Figure 102.

The Humphres' Method for Granular Soils

The Humphres' Method (102) consists of establishing the maximum obtainable (obtainable 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 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 described by Hunphres (102) and used to determine maximum unit weight is described in detail in HRB Bulletin 159 (1957). Other methods of vibratory compaction (118)

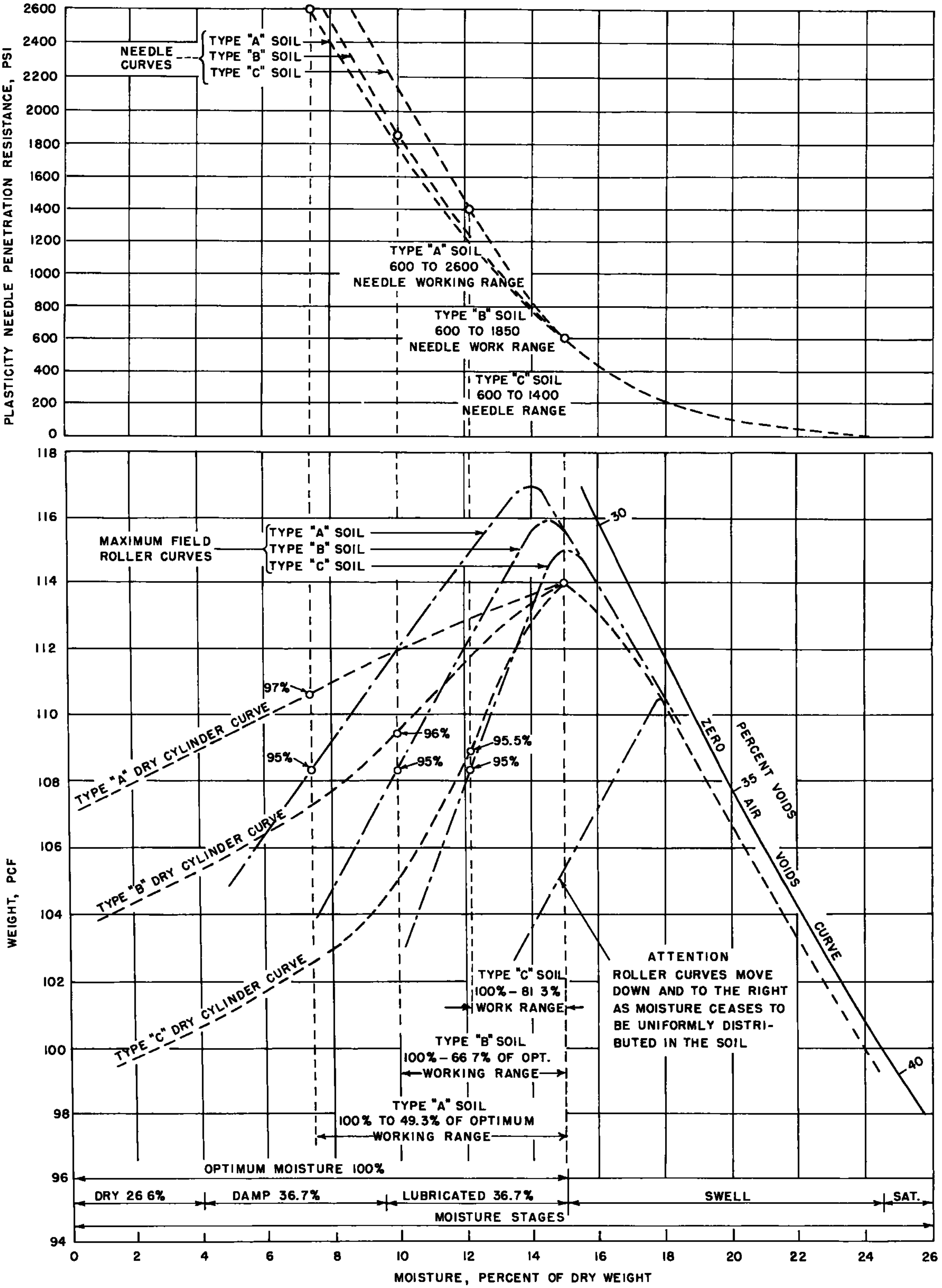


Figure 102. Sample of Wyoming control curves and roller compaction curves for three Wyoming soils (52).

that yield comparable unit weights can also be used in determining maximum unit weight.) The maximum compacted dry unit weight of the fine aggregate will be represented by the symbol $\gamma_f{}^c$ (for $\gamma_{fine}{}^{compacted}$) and the maximum compacted dry unit weight of the coarse aggregate by $\gamma_c{}^c$ (for $\gamma_{coarse}{}^{compacted}$).

4. Determine the loose dry unit weight of each part ($\gamma_f{}^l$; $\gamma_c{}^l$) by gently pouring each through an appropriately-sized funnel into a container of known volume, weighing, and calculating dry unit weight. The following size of sample, pouring device and volume of measure based on maximum particle size may be used (111):

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

5. Determine the solid unit weight of each part ($\gamma_f{}^s$; $\gamma_c{}^s$). 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.

6. Plot the three unit weights, loose, compacted, and solid, for the coarse aggregate and the fine aggregate on a chart (as in Fig. 103) 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 103 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

Fine aggregate:

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

$\gamma_f{}^c = 132$ pcf

$\gamma_f{}^l = 84$ pcf

7. Determine sufficient points to plot each of the curves A, B, C, ...H, as shown in Figure 103, with the aid of the nomographs in Figure 104 and 105 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:

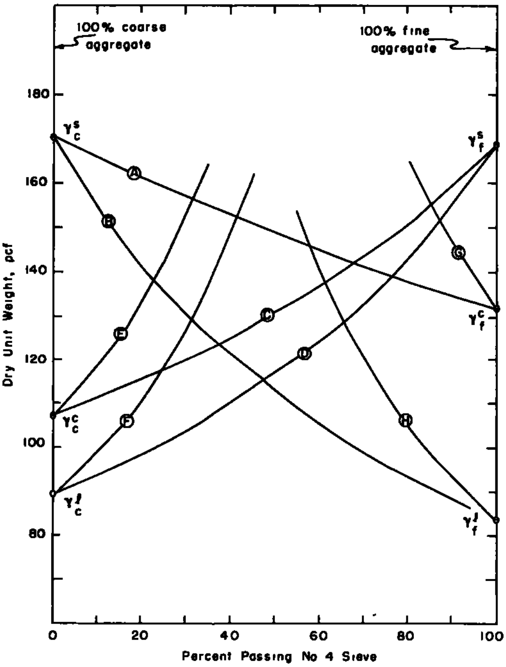


Figure 103. Sample theoretical curves for various combinations of coarse and fine aggregate and for solid, compacted and loose unit weights (after Humphres) (102).

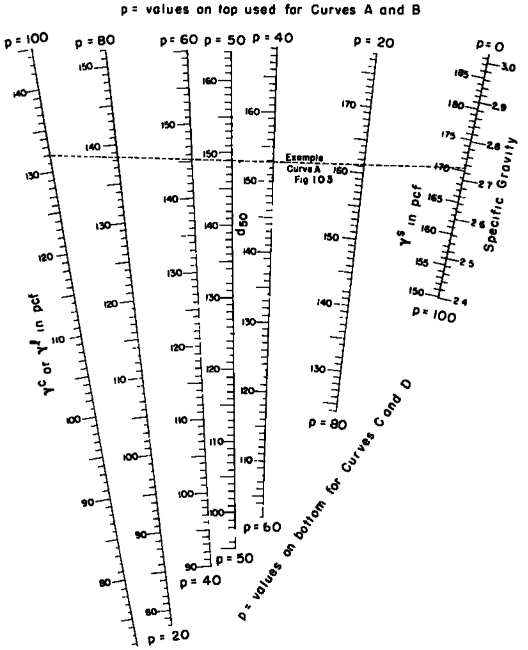


Figure 104. Nomograph for determining unit weight values (γ_p) for curve A, B, C, or D for different values of p, the percentage passing the No. 4 sieve (after Humphres) (102).

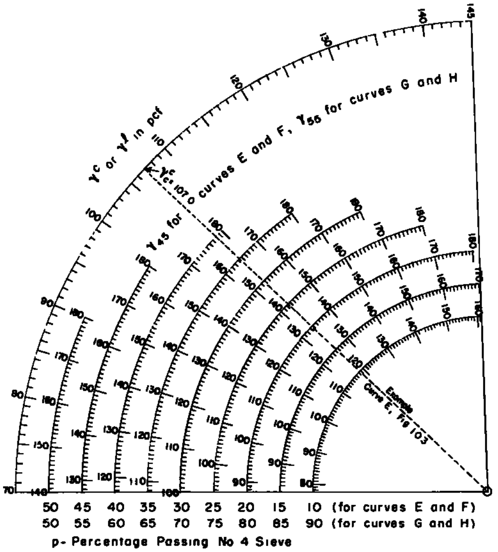


Figure 105. Nomograph for determining unit weight values (γ_p) for curve E, F, G or H for different values of p, the percentage passing the No. 4 sieve (after Humphres) (102).

Curve A:

$$\gamma_p = \frac{\gamma_c{}^s\ \gamma_f{}^s}{\left(\frac{p}{100}\right)\gamma_c{}^s + \left(\frac{1-p}{100}\right)\gamma_f{}^c} \quad \text{(Theoretical unit weight formula)}$$

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. 103) 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:

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

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:

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

Curve E:

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

Curve F:

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

Curve G:

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

Curve H:

$$\gamma_p = \frac{\gamma_f^{\,l}}{\frac{p}{100}}$$

8. Label intersections of the curves (as shown in Figure 106) 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. 106) 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

$\gamma_c^{\,c}$ = 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 pcf.

10. Draw a smooth curve from $\gamma_c{}^c$ 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 $\gamma_c{}^c$, r, o, m, n, and $\gamma_f{}^c$ as shown in Figure 107. 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 107 it can be seen that for the sample material, the maximum unit weight increases rapidly as the fine aggregate content increases from zero to about 35 percent of the mixture. For the higher percentages of fine aggregate, fluctuations in gradation would have less effect on maximum unit weight.

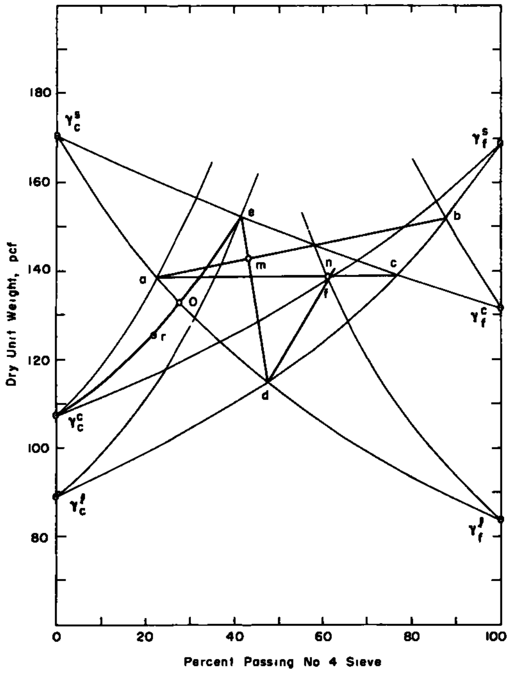


Figure 106. Determination of points (r, o, m, n) for maximum unit weight curve for mixtures of sample materials (after Humphres) (102).

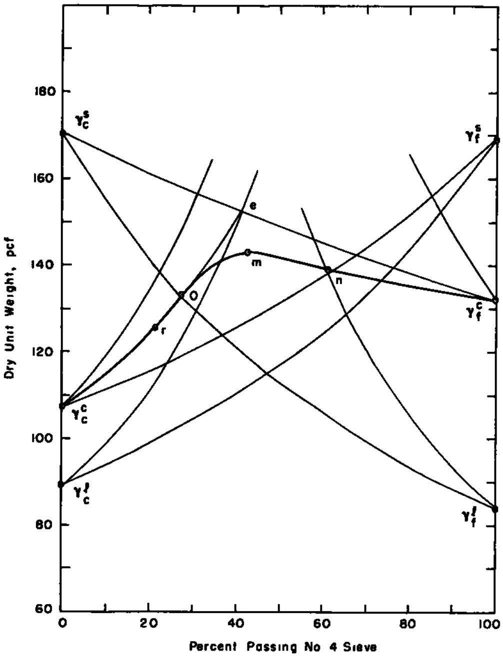


Figure 107. Derived maximum unit weight curve for mixtures of sample materials (after Humphres) (102).

The Hilf Method for Fine-Grained Soils

The Hilf or Bureau of Reclamation method (99, 126) for rapid compaction control consists basically of a 3-point compaction test performed in the field. The method is best suited to fine-grained soil because the compaction test is performed on minus No. 4 material. The Bureau of Reclamation laboratory compaction test employs a 1/20-cu ft mold. Soil is compacted in 3 layers by 25 blows per layer of a 5.5-lb rammer falling 18 in. This produces a compactive effort of 12,375 ft lb per cu ft which is equivalent to the compactive effort of AASHO Designation: T 99-57 method A (4-in. 1/30-cu ft mold, material passing No. 4 sieve, 3 layers, 25 blows per layer of 5.5-lb rammer falling 12 in.). The method does not require water content determinations and can be completed in one hour or less. Using this method, the inspector in charge of compaction control can determine the exact percentage of standard maximum dry unit weight and a close approximation of the difference between optimum water content and the in-place water content.

The details of the method are given in the following 7 steps:

1. Perform a field unit weight test to determine the in-place wet unit weight of the soil. This value will be used later.

2. To determine the first of three points for a compaction curve, compact a sample of in-place material, passing a No. 4 sieve, at field water content. On a chart (as in Fig. 108) plot the wet unit weight on the zero vertical line. Label this point A.

3. To determine point B, take a 7.5-lb sample of in-place material at field water content, add 0.15 lb of water (2 percent of the wet weight of the 7.5-lb sample), compact, determine the wet unit weight, divide this value by 1.02 to obtain the converted wet unit weight and plot as point B on the +2 percent vertical line. Converted wet unit weight is the wet unit weight divided by 1 + z, in which:

$$z = \frac{\text{weight of water added to sample}}{\text{wet weight of sample}}$$

4. Determine point C by one of the following methods, whichever applies. If point B has a greater unit weight than A, take a 7.5-lb sample of in-place material at field water content, add 0.30 lb of water (4 percent of 7.5 lb), compact, determine wet unit weight, divide by 1.04 to get the converted wet unit weight and plot as point C on the +4 percent vertical line.

If point B is less than A by at least 3 pcf, take a 7.5-lb sample of in-place material, let it dry about 2 percent (2 percent of 7.5 lb), compact, determine wet unit weight and divide by 1-z where z is amount of water lost in drying. (If 2 percent of the wet weight were lost, divide by 1.00-0.02 or 0.98.) Plot converted wet unit weight as point C on the vertical line corresponding to z, the amount of water lost in percent. (If 2 percent were lost, plot on the -2 percent vertical line.)

If point B is less than A, but within 3 pcf, take a 7.5-lb sample of in-place material, add 0.075 lb of water (1 percent of 7.5 lb), compact, determine wet unit weight, divide by 1.01 to get the converted wet unit weight and plot as point C on the +1 vertical line.

5. Fit a parabola through points A, B, and C using one of the following methods. If the plotted points, A, B, and C, are arranged so that the left- and right-hand points are lower than the center point, draw a compaction curve free hand or construct a parabola through the points by the method illustrated in Figure 109 and outlined, as follows.

Construction lines for locating parabola. —

(a) Horizontal base line through A.
(b) Vertical lines through B and through C. Point D is intersection of base line and vertical line through B.
(c) AB
(d) Line through D parallel to AB, intersecting the vertical line through C to establish point E.
(e) Horizontal line through E to vertical line through B to establish point F. Note: F corresponds to B if points A, B, and C are equally spaced horizontally.
(f) AC
(g) Line through D parallel to AC, intersecting the vertical line through C to establish point G.
(h) FG, to establish point H at

Sample Compaction Results

Point	A	B	C
Wet Unit Weight, pcf	123.4	128.6	124.6
Water Added, percent	0	2	4
Converted Wet Unit Weight, pcf	123.4	126.1	119.8

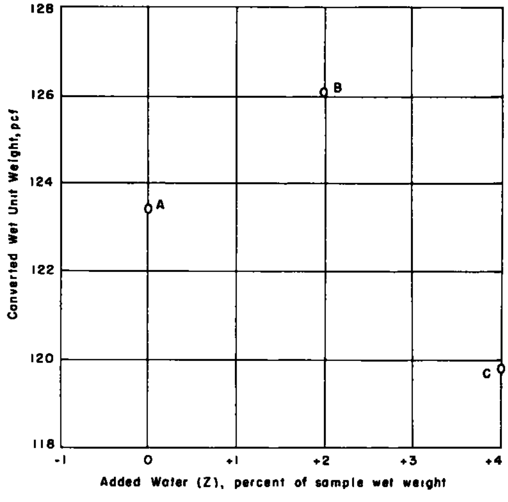


Figure 108. Plot of sample compaction results (126).

intersection with base line.

(i) Vertical line through midpoint of AH. This is the axis of the required parabola.

(j) Extension of AB to axis to establish point J.

(k) Horizontal line from J to vertical line through B to establish point K.

(l) KH which intersect axis at point O, the peak of the parabola.

(m) Parabola through points A, B, C, O, and H.

If the three plotted points, A, B, and C, are within 3 pcf of each other and the left-hand point is highest, some preliminary steps are required before the foregoing construction. These are:

(a') Calculate Y_1/Y_2, where Y_1 is the difference in ordinates of points A and C, and Y_2 is the difference in ordinates of points A and B (see key of Fig. 110).

(b') Determine the horizontal distance (z_m) between point A and the axis of the parabola from the curve in Figure 110.

(c') Plot the mirror images of points A, B, and C on the left side of the axis as points A', B', and C'.

(d') Re-label point C' as A, point A' as B, and point C as H and proceed with parabola construction as outlined previously.

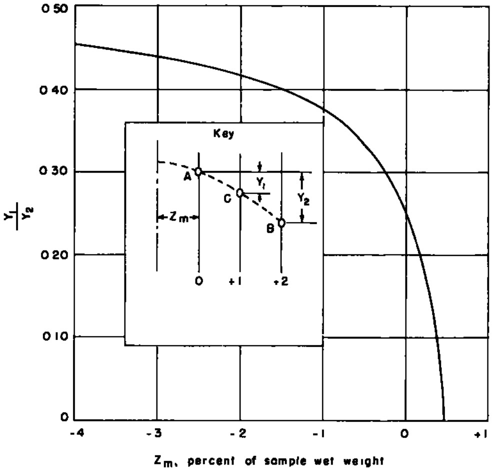


Figure 110. Values of Z_m for locating axis of parabola when in-place water content is close to optimum (126).

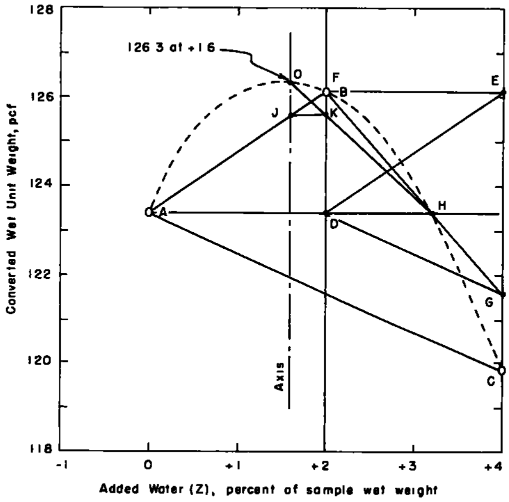


Figure 109. Example of construction of parabola through points A, B, and C (126).

6. To determine the percentage of standard maximum dry unit weight (99) of the in-place material, divide the in-place wet unit weight determined in step 1 by the maximum converted wet unit weight as determined by the peak point (O) of the compaction curve.

$$\text{Percentage of Standard Maximum Dry unit Weight} = \frac{\text{In-place wet unit weight}}{\text{Maximum converted wetunit weight}} \times 100$$

7. The difference between optimum water content and in-place water content can be closely approximated by the z coordinate of the peak point (O) with the addition of a correction. The z coordinate of the example in Figure 109 is +1.6 percent. The correction is obtained by plotting the peak point (O) on either Figures 111 or 112 and noting the correction for that point. The correction for the example

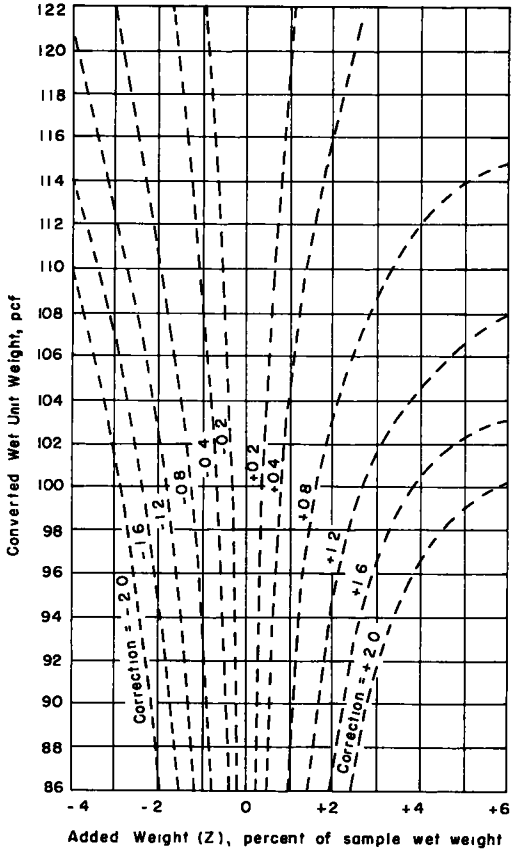


Figure 111. Plot of corrections for use in calculating difference from optimum water content for soils with converted wet unit weights in the 86- to 122-pcf range (126).

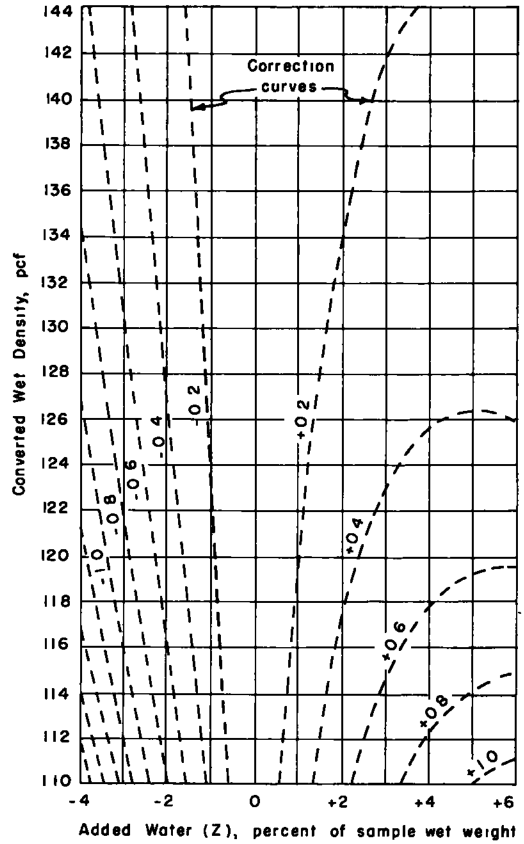


Figure 112. Plot of corrections for use in calculating difference from optimum water content for soils with converted wet densities in the 110- to 144-pcf range (126).

in Figure 109 for coordinates of 126.3 and 1.6, is +0.2. The difference from optimum is then equal to 1.6 + 0.2 or 1.8 percent. The plus sign indicates water to be added in the field to obtain optimum.

In summary, this method can be used to determine the exact percentage of standard maximum dry unit weight and a close approximation of the difference between optimum water content and the in-place water content. Only one water content, the in-place water content need be measured, and after it is available the values of the field dry unit weight, molded dry unit weight at in-place water content, standard maximum dry unit weight, and optimum water content can be calculated for record purposes. The method is best suited to fine-grained soils dry of optimum. Materials containing coarse aggregate and materials wetter than optimum can be checked, but the time required to screen out the plus No. 4 material and to dry back the compaction samples may be excessive.

Other Control Methods

There are other methods that are currently in use that are unique in some manner. Among these are (1) the Ring Method, for measuring in-place density of compacted base courses containing large sizes of coarse aggregate. That method was recently adopted by AASHO as a standard and is listed under AASHO Designation: T 181-57; and (2) the California Test Method, No. California 216 E, March 1960. The California test procedure is given in the California Division of Highways Materials Manual, "Testing and Control Procedures," Volume I, and consists of 14 pages of text, figures and tables. This method includes controls on a "dry weight" basis (method A) and also on a "wet weight" basis (method B). There are similarities between California Method B and the Hilf Method. The California method also introduces a conection involving a coefficient that varies with coarse aggregate content. Efforts have not been made to include all control test procedures currently in use by state highway departments and Federal agencies.

The Use of Statistical Methods

Statistical methods can be very useful in determining compaction requirements and in the analysis of compaction results. Neither time nor space, however, permit adequate coverage of this subject in this bulletin.

Developments in Compaction Equipment

RECENT YEARS have been a period of intense activity in the development of equipment for compacting soil in construction. This period has seen progress in the development of (1) the combination compactor, a combination of two or three types into one machine; (2) the self-propelled tamping-(sheepsfoot-) type roller ranging from nominal in sizes to machines capable of great output, and some capable of being driven at high speeds; (3) the self-propelled base-plate-type vibratory compactor ranging in rating from small single units to large capacity multiple-unit compactors; (4) the vibrating roller—in many sizes and ratings from the single-drum towed type or self-propelled type to the combination rollers with one vibrating roll; (5) the "segmented-wheel" compactor employing a number of large steel pads on each wheel that interrupt the continuous roll effect of the smooth-wheel roller; (6) the grid-type roller; and (7) the wide range in tire pressures and wheel loads available in all types of pneumatic-tired rollers.

Figures 113 to 131 show several of the types of older pieces of equipment that have been improved recently as well as of equipment that has been developed recently and is relatively new on the construction scene.

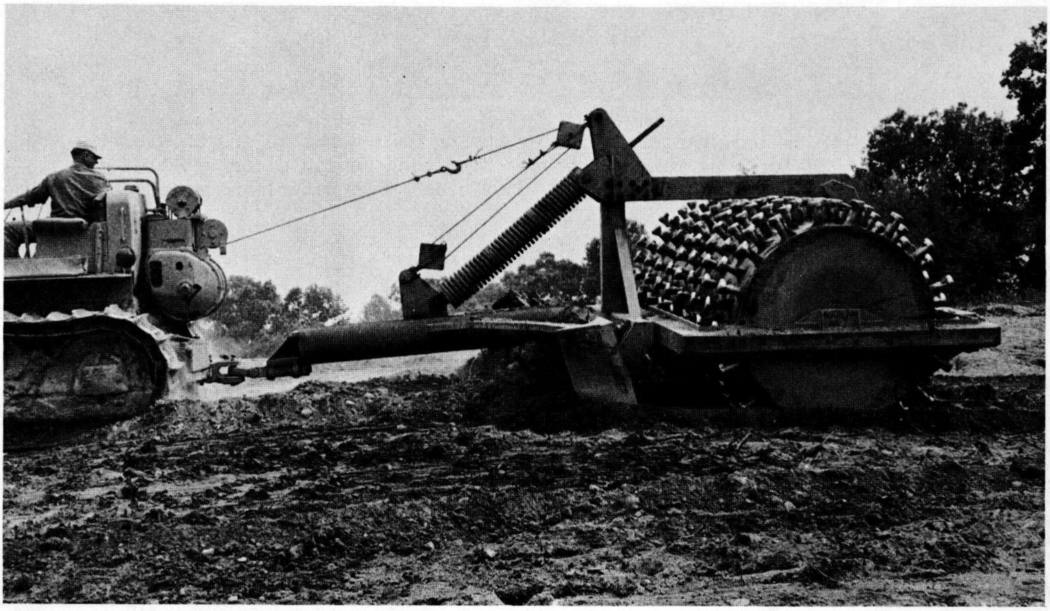


Figure 113. Tamping roller equipped with adjustable level blade to produce a level course while compacting.

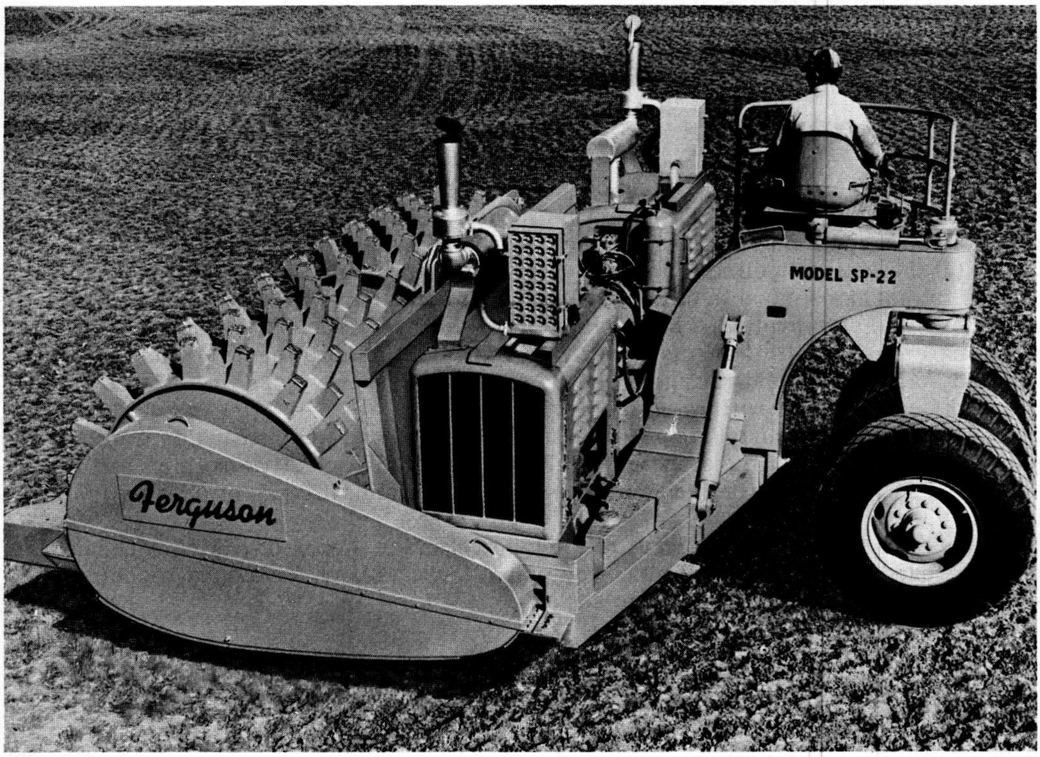


Figure 114. Self-propelled sheepsfoot roller having dual drums 60 in. in diameter and 72 in. wide, 144-9.25-in. long tamper feet per drum each having a contact area of 7.5 sq. in. Contact pressures of 656 psi empty (856 loaded with water) and speeds up to 8 MPH.

Figure 115. 40.5-ton triple-drum self-propelled sheepsfoot roller.

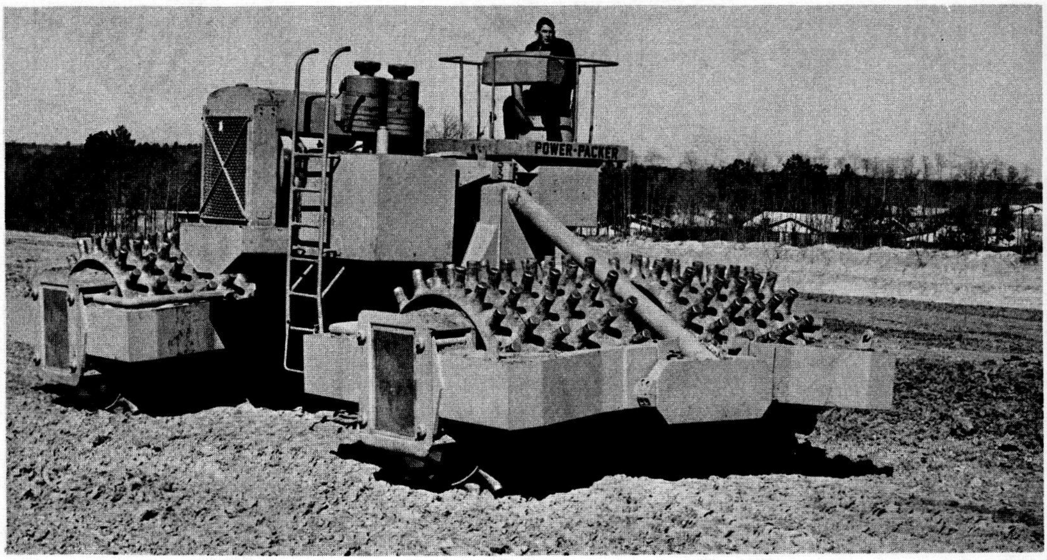


Figure 116. Heavy high-capacity self-propelled sheepsfoot roller equipped with four drums each 60 in. wide and 60 in. in diameter, having 120 feet per drum. Tamper feet are 9 in. long and have 10-sq in. end area. Travel speeds up to 5 MPH.

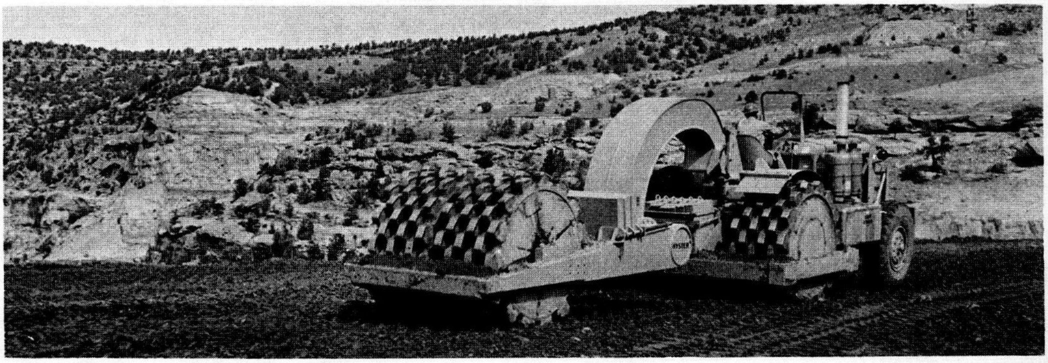


Figure 117. Self-propelled tamping roller having specially shaped tamping feet designed for working speeds up to 15 MPH.

Figure 118. Thirty-ton, 7-wheel, self-propelled pneumatic-tire roller.

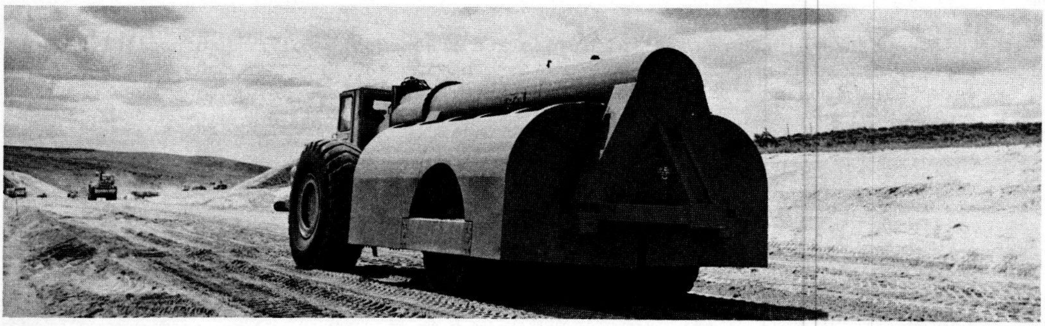


Figure 118A. Fifty-ton 4-wheel self-propelled pneumatic-tired roller equipped for loading with sand or water ballast or both. Weight range is from 37,000 lb (empty) to 115,000 lb (fully loaded).

Figure 119. Four-wheel pneumatic-tire roller. Each wheel and tire assembly is mounted in an independently oscillating weight-box. The 4-section unit shown is available in 15- to 100-ton capacity from 80- to 150-psi tire inflation pressure.

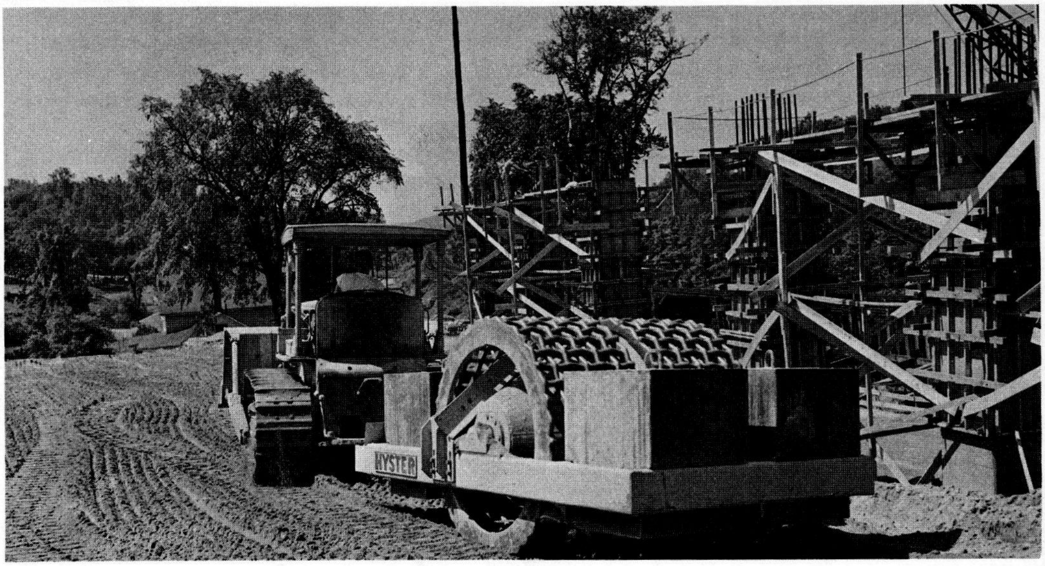


Figure 120. Towed-type dual-drum grid roller having net openings of 3 1/2 x 3 1/2 in. between bars. Roller gross weight may range from 6,200 lb empty to 15,112 lb fully ballasted.

Figure 121. A self-propelled four-wheel-type segmented wheel roller capable of speeds up to 6 MPH.

Figure 122. Multiple-unit vibrating base-plate-type compactor compacting granular base course materials.

Figure 123. Tandem arrangement of multiple-unit vibrating base-plate compactors for high capacity production.

Figure 124. More than one type compactor are often employed on a project. Here a combination of three single-unit towed-type vibratory rollers and a heavy-duty pneumatic-tire roller are seen on the same project.

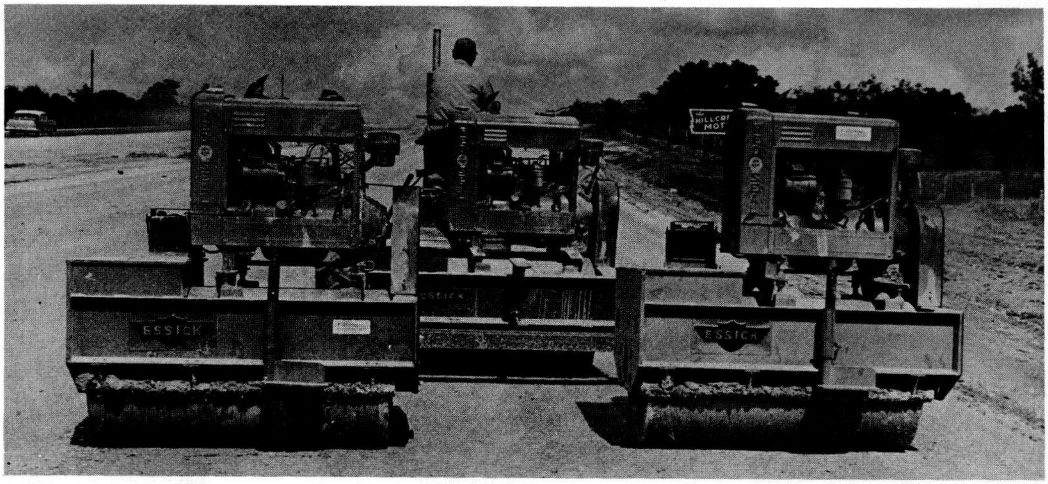


Figure 125. A combination of three single-unit vibratory rollers towed by one tractor.

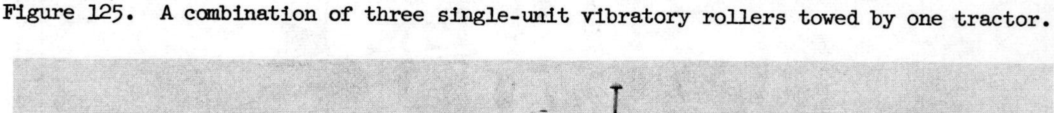


Figure 126. Heavy, single-axle, dual-wheel vibratory, pneumatic-tire compactor.

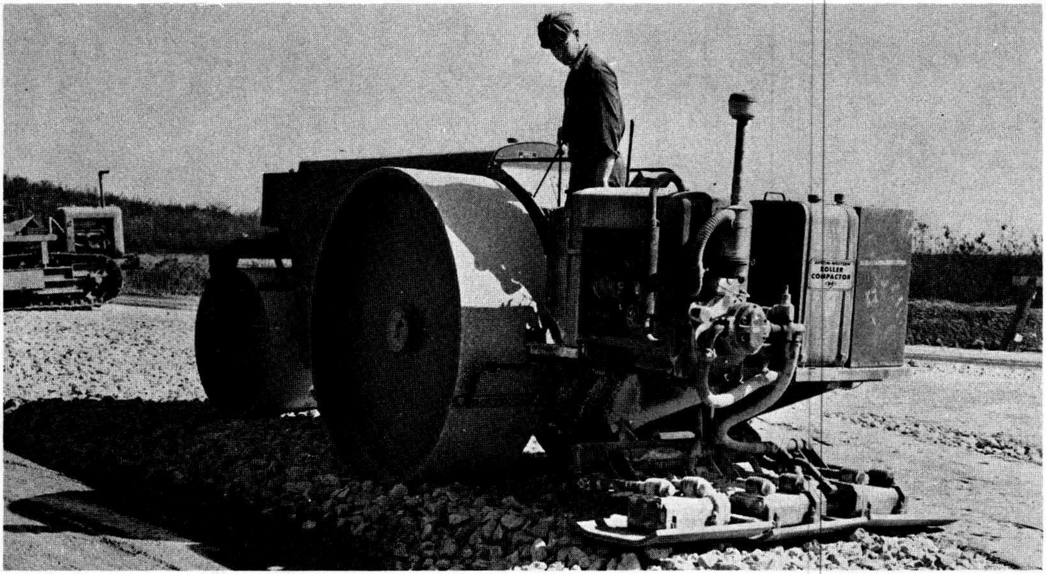


Figure 127. Three-wheel, smooth-wheel-type roller equipped with three supplementary vibrating base-plate-type compactors used in compacting crushed rock base course.

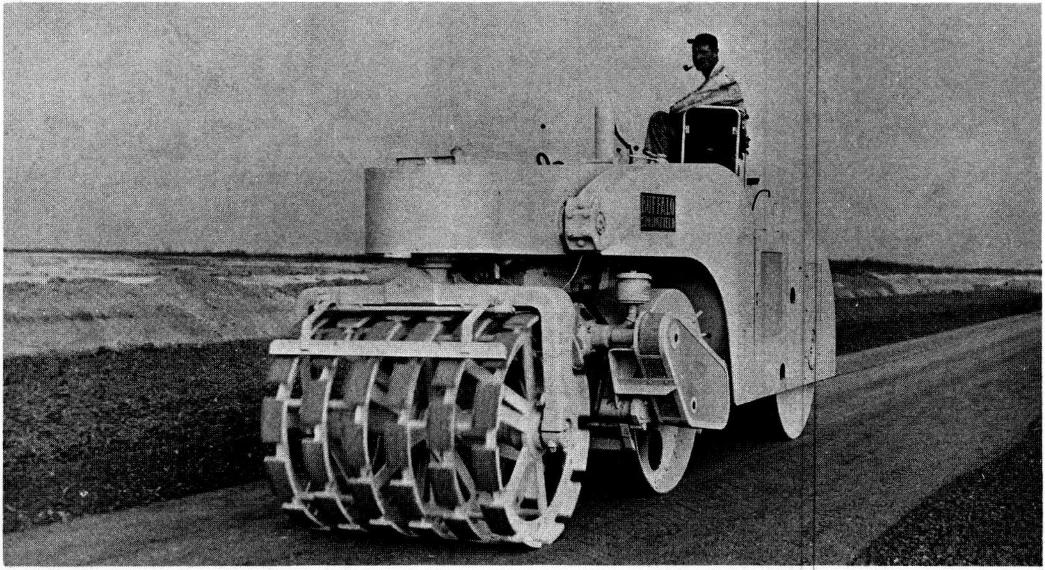


Figure 128. Combination tandem-type roller consisting of a front segmented wheel, a center vibrating smooth-wheel roll and a rear smooth-wheel roll.

Figure 129. Smooth-wheel and pneumatic-tired rollers combined in one unit. These two types of rollers can be used independently or in combination. Working speeds up to 10 MPH. Tire inflation pressures up to 100 psi. Steel roll can be loaded with loads from 120 to 535 lb per in. of width of roll.

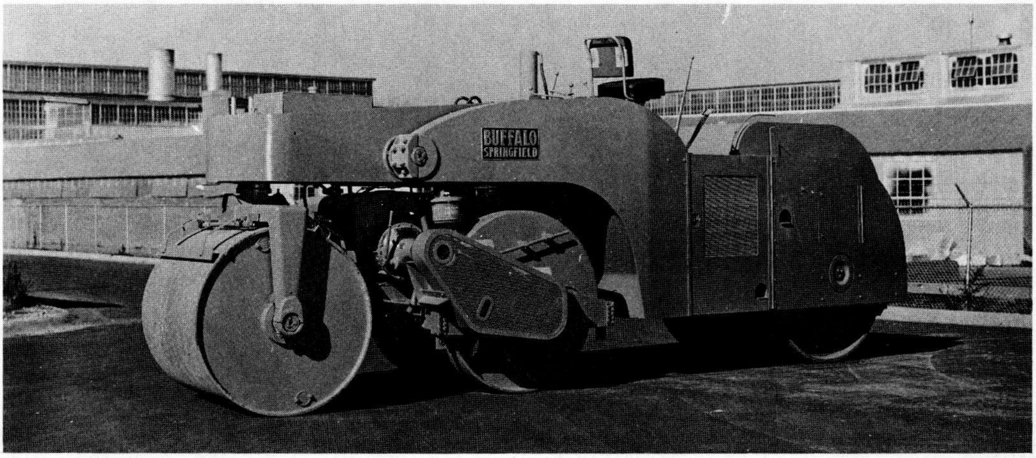


Figure 130. Three-axle tandem roller with center vibratory roll. The center roll can be raised to change the roller to a conventional two-axle tandem roller.

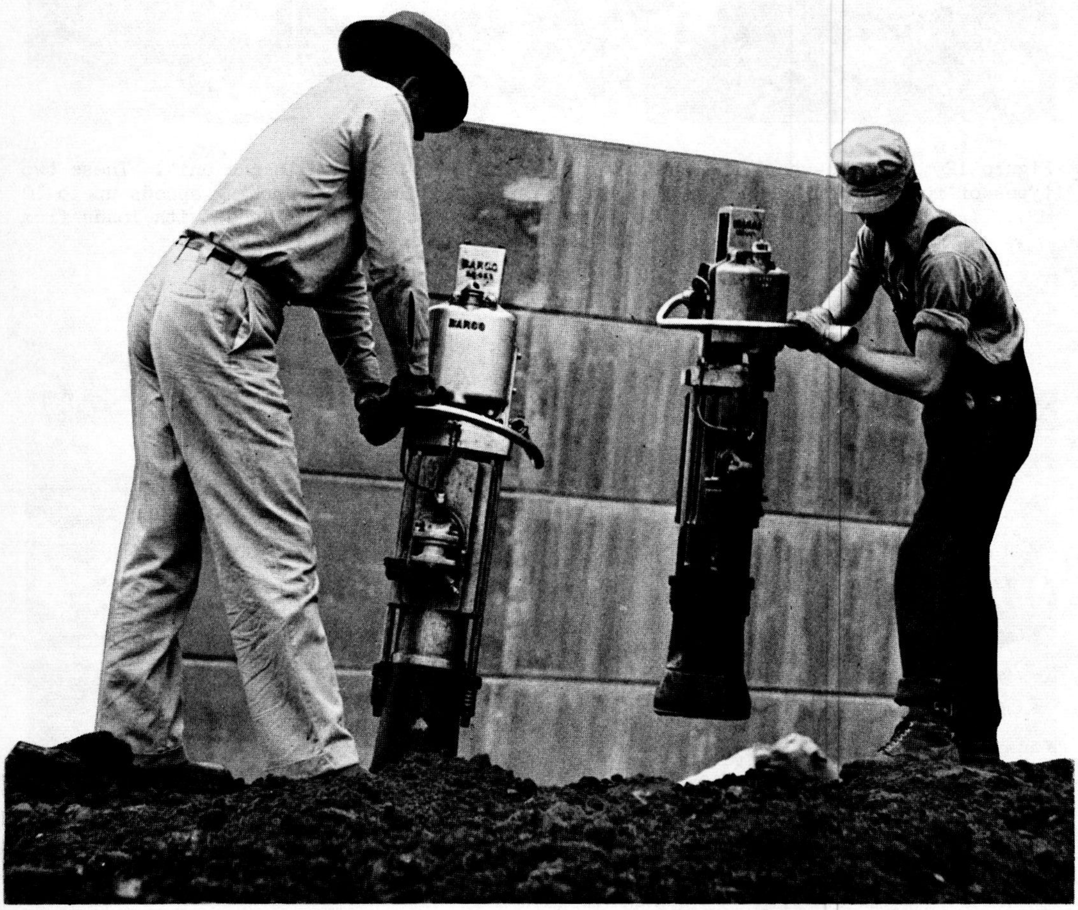


Figure 131. Explosion-type rammers for compacting soil in restricted areas.

Current Practices in Compaction Requirements

CURRENT PRACTICES in compaction of embankments, subgrades and granular bases are presented here in the briefest manner possible. The practices are stated in terms of specification requirements for degree of compaction desired and the type and rating of equipment permissible. These specification requirements are given in Tables 46 - 54, as follows:

Table 46 -	Specification Requirements for Control of Layer Thickness, Compaction and Moisture Content in Embankments (also includes supplementary Tables 46-1 Emb., to and including 46-8).
Table 47 -	Specification Requirements for Control of Compaction and Moisture Content in Subgrades (also includes supplementary Tables 47-1 Subgrade, and 47-2 Subgrade).
Table 48 -	Specification Requirements for Control of Compaction of Granular Bases.
Table 49 -	Specification Requirements for Backfilling of Trenches, Pipe Culverts and Sewers.
Table 50 -	Specification Requirements for Control of Compaction of Structural Backfill.
Table 51 -	Specification Requirements for Tamping-(Sheepsfoot) Type Rollers for Embankment Construction.
Table 52 -	Specification Requirements for Pneumatic-Tire Rollers for Embankment Construction and/or Testing.
Table 53 -	Specification Requirements for Smooth-Wheel Power Rollers for Embankment Construction.
Table 54 -	Specification Requirements for Pneumatic-Tired, and Tandem and 3-Wheeled Power Rollers for Compaction of Granular Bases.

Data on specifications for compaction of (1) Embankments, (2) Subgrades, (3) Base Courses, (4) Structural Backfill, (5) Trench Backfill and specifications pertaining to compaction equipment (Tables 46 to 54) were solicited by letter to the individual state highway departments. The information was received during February and March 1960 and thus is indicative of practices up to that time. Four state highway departments stated that they were then in process of rewriting certain portions of their specifications pertaining to compaction. Data given in the tables previously described are included here for purpose of information. No attempt is made to analyze the data for development of trends or indications of the extent to which changes in compaction requirements and in the design of compaction equipment and its use have taken place since the presentation of similar information in HRB Bulletin 58 in 1952.

TABLE 46

SPECIFICATION REQUIREMENTS FOR CONTROL OF LAYER THICKNESS, COMPACTION AND MOISTURE CONTENT IN EMBANKMENTS

Region and State	Control of Compaction			Control of Moisture Content	Pay Items	
	Thickness of Layer					
	Loose (in.)	Compacted (in.)	Compaction Requirement and Measurement		Compaction	Water
Northeast						
Connecticut, Std. Spec. Jan. 1955	12 max	-	Minimum 90% AASHO T 99	Not specified directly	Incidental	Incidental
Maine, 1960, Suppl. Spec.	8 max	-	Layer method—6 passes by roller each layer. Every 8th layer test rolled one pass.	Moisture content not to exceed optimum. Aerate and dry if necessary.	Incidental	Incidental (Aerating is a pay item)
Maine, Std. Spec., Revision of 1956	12 max	-	Controlled density method—Minimum 90 to 95% AASHO T 99 (see Table 46-1 Emb.)	As directed by the engineer	Incidental	Incidental
Massachusetts, Std. Spec. 1953	12 max	-	Thoroughly compacted. Compaction by 6-passes of 12-ton smooth-wheel roller or min. 17-ton tractor; or by twin-cylinder sheepsfoot rollers if soils are of class A-2 with excess silt or clay or of groups A-4, A-5, A-6, or A-7	Not specified directly	Incidental	-
Michigan, Std. Spec. May 1960	9-18 sand subbase only	-	Controlled density method—Minimum 95% AASHO T 99 on material passing 1-in sieve or 95% Michigan Cone Method.	First 4 feet of embankment material not to exceed optimum moisture at time of compaction. Embankment material above 4 ft not to exceed 2% over optimum at time of compaction.	Incidental	Incidental
	12 max	-	12-in. layer method—Minimum 95% of maximum unit weight determined at existing moisture content.	As required to obtain density	Incidental	Incidental
New Hampshire, Std. Spec. July 1, 1954 and Amend. Apr. 25, 1957	12 max	-	Minimum 95 percent of AASHO T 99	As required to obtain density	Incidental	Incidental
New York, Std. Spec. Jan. 2, 1957	8 max	-	On sand or sand-gravel with less than 20% passing No. 200 sieve minimum 90% AASHO T 99. All densities on minus ¾-in. material. (See subgrade for requirements for top 4 ft.) Added requirement calls for minimum of 6 passes of rollers of 250-450 psi for sheepsfoot; 1,000-2,500-lb per tire for pneumatic and 10 tons minimum for smooth-wheel. For heavier and more efficient types of equipment, number of passes to be determined by the engineer.	As required to obtain density but not less than 3% drier than optimum.	Incidental	(1) Furnish water equipment (2) Applying water per M gallons
Rhode Island, Std. Spec. Revision of 1946	12 max	-	Satisfactory. When density tests are used AASHO T 99-57 and AASHO T 180-57 standards are followed.	Not specified	Incidental	Incidental
Vermont, Std. Spec. 1956	12 max	-	Minimum 6 trips of sheepsfoot or pneumatic-tire roller "Evidence of satisfactory compaction shall consist of 90% of the maximum density."	Provision for drying excessively wet soils. Layers of soft clays shall be reduced to 6 in. with alternate layers of granular material.	Incidental	Incidental-water content of layer is within limits for proper compaction.
Wisconsin. Std. Edition of Spec. 1957	12 max	-	Standard compactio. By hauling equipment and rollers to degree of no further preciable consolidation This method is used unless special compaction is required in contract.	Not specified. Moisture controlled to obtain compaction (not excessively wet or dry).	Incidental	-
	8 max	-	Special compaction—Minimum 95% AASHO T 99. 12-in. max layer thickness permitted if material is granular.	Not specified directly. Controlled as required to obtain minimum density.	Incidental	Incidental
Middle East						
Delaware, Std. Spec. April 1, 1957	6 max	-	Minimum 95% "Modified Proctor Method"	Optimum ± 10%. Provision for drying by disking, harrowing or, turning with blade grader until within limits.	Incidental	Incidental
District of Columbia, Std. Spec. 1957	6 max	-	Not less than 95% of AASHO T 99 Method C except that if clean sand is permitted it shall be compacted to 100% of AASHO T 99 maximum density.	± 2 percentage units of optimum. Provision for drying by evaporation or aeration by use of graders, pulverizers or harrows Must support construction equipment without heaving, rutting, etc.....In the latter event soil must be dried.	Incidental	Incidental
Illinois, Std. Spec. of Jan. 1952	6 max	-	Minimum of 90% of maximum dry density AASHO T 99. Compaction by not less than 6 nor more than 9 rollings of a tamping roller, a pneumatic-tired roller or a 10-ton 3-wheel roller, with maximum speed of 6 mph. Specifications also provide for an item for "water-soaking."	Shall not exceed 110% of optimum. Provision for sprinkling and for non-use of excessively wet material.	Incidental	Paid for as "extra work"
Illinois, Suppl. July 1, 1955	-	4 max	Granular embankment special—Minimum 100% of AASHO T 99 based on minus ⅛-in material	Satisfactory	cu yd	-
Illinois, Jan. 1958 and special provisions	6 max	-	Minimum 90% of AASHO T 99 maximum dry weight. No roller requirements.	No moisture limits except adjacent to structures. Maximum of 110% of optimum adjacent to structures	Incidental	Extra work
Indiana, Std. Spec. of 1960	9 max	-	Minimum 95% AASHO T 99 maximum wet density or dry density, as specified, except that if the material is "decidedly granular" then it should be compacted to at least 90% of maximum density.	As required to obtain density	Incidental	Incidental
Kentucky, Std. Edition of Spec. 1956	12 max	-	Standard compaction—Satisfactory	Near optimum	Incidental	M - Gallons
			Extra compaction—Average density of not less than 95% of AAS-	Near optimum	Incidental	M - Gallons

			HO T 99 with no density below 90%.			
Maryland, Std. Spec. Jan. 1957	8 max	-	Minimum 90 to 100% AASHO maximum density (see Table 46-2 Emb.).	As required to obtain compaction but not to exceed optimum by 2 percentage units. On certain projects it is necessary to limit moisture content to optimum.	Incidental	Incidental
New Jersey, Preliminary to New Revision of Std. Spec.	6 max	-	Rolling or vibrating method—1. Minimum 4 passes of 3-wheel, minimum 10-ton roller; 2. Minimum 5 passes of pneumatic roller having minimum of 225-lb per in. width of fire; 3. Minimum 8 passes of tamping roller with minimum of 200-psi maximum contact pressure; 4. Minimum of 5 passes of 50-ton compactor, or 5. Optimum number of passes of dynamic compactor as determined by evaluation on the job.	Optimum ± 2 percentage units	Incidental	Incidental
			Density control method—Minimum of 95% of AASHO T 99.	Optimum ± 2 percentage units	Incidental	Incidental
Ohio, Std. Spec. Jan. 1, 1959	6 max	-	95-102% AASHO T 99 (see Table 46-3 Emb.). Composition of outer 5 ft of embankment by tamping or pneumatic-tired roller. Remainder by tamping, pneumatic or minimum 10-ton 3-wheel roller. Other types may be used if approved by engineer.	As directed by the engineer. Provision for sprinkling or drying by manipulation. Drying prior to or during compaction to not more than 3 percentage units greater than optimum except that for material that displays pronounced elasticity or deformation under loads shall be reduced in the amount necessary to secure stability.	Incidental	M Gallons
Pennsylvania, Std. Spec. 1960	8 max	-	Soil shall be compacted to 95 to 100% of AASHO maximum density in accordance with Table 46-4 Emb.	Optional—As required to obtain compaction.	Incidental	Incidental
Tennessee, Std. Spec. July 1, 1951	-	6 max	Minimum 95% of AASHO T 99	Shall be compacted at optimum moisture content.	Incidental	M Gallons
Virginia, Std. Spec. 1958	8 max	-	Minimum 95% of AASHO T 99	Shall be compacted at optimum moisture content.	Incidental	Incidental
West Virginia, Std. Spec. 1952	8 max	-	Standard compaction—Thoroughly compacted by use of tamping rollers	- - - -	Incidental	-
			Special compaction—Minimum 90 to 100% of AASHO T 99 (see Table 46-5 Emb.)	Sufficient for compaction	Incidental	M Gallons
West Virginia, Interstate provisions	8 max	-	Minimum 95 to 100% West Virginia Procedure SL-4 (see Table 46-6 Emb.) controlled by in-place field tests according to W. Va. Procedure SL-13. Procedure SL-4 employs a $\frac{1}{10}$ cu ft mold and compactive efforts simulating AASHO T 99.	Optimum moisture content ± 2 percentage units.	Not stated	Not stated
Southeast						
Alabama, Std. Spec. 1950	8 max	-	Minimum 95% AASHO T 99 (density test may be waived on sands). When lightweight rollers are used layers shall not exceed ¾-in. thickness per ton weight of roller.	Sufficient for compaction	Incidental	M Gallons
Florida, Std. Spec. April 1, 1959	8 max	-	Minimum 100% AASHO T 99-57	As required for compaction	Incidental	Incidental
Georgia, Std. Spec. May 1, 1956	6 max	-	Minimum 95% AASHO T 99	As required to obtain compaction	Incidental	Incidental
Mississippi, Std. Edition of Spec. 1956	6 max	-	Clayey soils, minimum 90% of AASHO T 99	Satisfactory	Incidental	Incidental
			Sandy soils, minimum 95% of AASHO T 99	Satisfactory	Incidental	Incidental
North Carolina, Std. Spec. Oct. 1, 1952	6 max	-	Minimum 90% AASHO T 99	Proper for compaction	Incidental	Incidental
South Carolina*	6 max	-	Minimum 95% AASHO T 99	At optimum moisture content as determined by the engineer	Incidental	Incidental
South Central						
Arkansas, Std. Spec., Edition of 1959	8 max	-	Compacted evenly and densely by distribution of hauling equipment.	Material shall have right moisture content for proper compaction.	Incidental	Incidental
	8 max	-	Special compaction of earthwork—Min. 95% AASHO T 99.	Substantially that of optimum	Incidental or as a pay item when included in proposal schedule	Incidental
Oklahoma, Std. Edition 1959	8 max	-	Min. 95% AASHO T 99 (requires use of 50-ton test roller)	As required to obtain density	Incidental	Incidental
Louisiana, Std. Spec. July 1955	8 max	-	Min. 95% AASHO T 99	Requirements based on AASHO method T 99	Incidental	Incidental
Texas, Std. Spec. 1951	6 max^{1} to	-	Ordinary Compaction—Until no further evidence of compaction.	As required by the engineer	Roller Hours	M - gallons
	8 max^{1}	-	Controlled density method—THD 84 (Approx. 90 to 100% AASHO T 99). ^{1}6 max for pneumatic-tire rollers, 8 for others.	As required by the engineer	Roller Hours	M - gallons
Texas special "Incentive Compaction" Method—Used on a limited basis	Depends on Equipment		Any method of compaction—Swelling soils compacted not less than 98% nor more than 102% and non-swelling soils not less than 100% of density as determined by compaction ratio method.	THD-110 soil test procedure	Rolling (Subsidiary)	Sprinkling (Subsidiary)
North Central						
Iowa Std. Spec. 1960	8	-	Minimum, 1 pass per inch loose thickness. Moisture and density when specified on plans.	May require 4 discings per lift at not more than 2 hr intervals without extra compensation.	Incidental	M Gallons
Kansas, Std. Edition of Spec. 1955	-	6 max	Type AAA—Min. 100% AASHO T 99	As required by the engineer	Per cu yd for compaction of earthwork, all types	M-Gallons (all types)
			Type AA—Min. 95% AASHO T 99	MR-0, optimum to 5% above optimum		
			Type A—Min. 90% AASHO T 99	MR-3, moisture content not less than 3% below optimum		
			Type B—Compaction with sheepsfoot roller until feet "walk out."	MR-5, moisture content not less than 5% below optimum		
			Type C—6 to 15 trips of sheepsfoot-type roller or 10 to 15 trips of pneumatic-tire roller	MR-90, as necessary to obtain density		

*No reply to questionnaire. Data by authors from standard specifications, November 1, 1955.

TABLE 46 (Continued)

Kansas, Suppl. Spec. 55-498		6 max	Top 12- or 18-in. Type AA as above	MR-0 or MR-5 as noted above	Ditto	Ditto
			Bulk of fill, Type B as above	MR-5 or MR-90 as noted above	Ditto	Ditto
Minnesota Spec. 2110 (9-10-57)	6 - 12	-	Ordinary Compaction· No. of Complete Coverages Layers — Rollers — Vibratory Compactors 3 in. or less — 1 — 1 3 in. to 6 in. — 2 — 1 6 in. to 9 in. — 3 — 2 9 in. to 12 in. — 4 — 2 over 12 in. — 4 — 2 Complete coverage = 2 passes of rollers Complete coverage = 1 pass of vibratory compactor	Not over 115% of optimum	Incidental	Incidental
	6	-	Specified density method—			
			Upper 3 ft — 98% AASHO T 99	65 to 110% of optimum	Incidental	Incidental
			Below upper 3 ft — 95% AASHO T 99	Not over 115% of optimum	Incidental	Incidental
Minnesota Spec. 2110 (5-1-59)	6	-	Specified density method—			
			Upper 3 ft — 100% max density	65 to 102% of optimum	Incidental	Incidental
			Below upper 3 ft — 95% max density	Not over 115% of optimum	Incidental	Incidental
	12	-	Granular soil with vibratory equipment			
Missouri Std. Edition of Spec. 1955	6 max	-	Min. 90% AASHO T 99. However, may use 1/30-cu ft mold, 4-layers and a hammer drop of 18 in for heavy clays when plasticity index exceeds 25. Min. 95% within 100 ft of a bridge.	Determined by the engineer. Sect. 1-31, "This moisture content shall be sufficiently high to guard against later expansion due to the entrance of moisture after expansion, and high enough to facilitate compaction and production of desired density." Sect. 1-29A "Also if necessary in order to obtain required density water shall be added or removed."	Per cu yd-Plan Quantities	Incidental
Nebraska Std. Series of Spec. 1955	12 max	-	Class I—Compacted by hauling equipment	Not specified	Incidental	M Gallons where specified
	6 max	-	ClassII—Rolled at least twice with wheel or tamping type roller	Provision for drying excessively wet soils	Incidental	M Gallons where specified
	6 max	-	ClassIII—Type A min. 90% AASHO T 99	80% of optimum ± 3%	Incidental	M Gallons where specified
			Type B min. 90% AASHO T 99	90% of optimum ± 4%	Incidental	M Gallons where specified
			Type C min. 90% AASHO T 99	Optimum ± 3%	Incidental	M Gallons where specified
			Present practice for use of above classes of compaction is as follows: Class I—For clean sands having more than 90% retained on No. 200 sieve. Class II—For sands having 80 to 90% retained on No. 200 sieve Class III—For soils having less than 80% retained on No. 200 sieve use Type B compaction. For interstate system use Type B compaction with special provision that density must be at least 95% of AASHO T 99			
North Dakota, Std. Spec. Jan. 1956	12 max	-	Standard compaction—Uniformly compacted by grading equipment and rollers.	As directed by the engineer	Incidental	M Gallons
	12 max	-	Extra compaction—Min. 95% AASHO T 99	As required for satisfactory compaction	Incidental	M Gallons
North Dakota, Std. Spec. Jan. 1960	12 max	-	4 ft below finished grade 90% maximum dry density. Less than 4 ft below finished grade 95% maximum dry density in accordance with AASHO T 180 (Sp. Prov. 49A).			
South Dakota, Std. Spec. April 1957	8 max	-	Ordinary compaction—Satisfactory compaction with sheepsfoot rollers or by any method which produces 95% of AASHO T 99 method C.	As ordered by engineer	Incidental	M Gallons
(Used only in connection with County Sec. Projects)			Specified density method—Special provisions will specify percent of T 99 max den. of minus No. 4 material. Min 97% of specified density.	As required to obtain density	Incidental	M Gallons
South Dakota Suppl. Spec. dated 6-25-58	8 in. max in top 12 in.	-	Upper 12 in. of subgrade 92 to 100% AASHO T 99 (see Table 46-7 Emb.). Fills 20 ft or less in height compacted to 92% AASHO T 99 maximum density. For fills exceeding 20 ft in height, that portion of fill 20 ft and more below top of fill is compacted to 96%.	For soils having P.I. not greater than 30, moisture content not to exceed 2% above nor be less than 6% below optimum. For soils having a plastic index greater than 30 moisture content shall not exceed 1% above nor be less than 4% below optimum.	Incidental	M Gallons
Mountain						
Arizona, Tentative Std. Spec. 1959	8 max	-	Satisfactory to engineer	As required by the engineer	Roller Hours	M Gallons
Special Provisions (Supersede Std.)	8 max	-	Min. 95% AASHO T 99	As required to obtain specified density	Incidental	M Gallons

Colorado, Std. Spec. 1-1-1958 Revision of Item 17 under date of 9-26-58	8 max (except where large rock is in excess of 25%		Min. 90% of AASHO modified except for A-1 and A-3 soils. Min. 95% for A-1 and A-3. Min. 95% AASHO T 99 except for soils of A-1 and A-3 groups. Min. 100% AASHO T 99 for soils of A-1 and A-3 groups.	To be dried or wetted as necessary to obtain required compaction	At. unit bid price per cu yd	M Gallons
Idaho, Std. Edition of Spec. 1957	8 max	-	Class A—Min. 100% AASHO T 99 in top foot of subgrade, cuts and embankments and all soil whose max dry weight is less than 110 pcf. For soils having max dry weight in excess of 110 pcf, min. compaction is 95% except on subgrade where 100% compaction is required.	As required for satisfactory compaction to density specified	Incidental	M Gallons
	8 max	-	Class B—Min. 100% AASHO T 99 in top foot of subgrade. All other by routing earth moving equipment.			
	8 max (Emb.) 4 max (top ft subgrade)		Class C—Compacted by routing of earth moving equipment			
Montana, Std. Spec. 1959 Edition	8 max	-	Method I—Compaction by hauling equipment.	As directed by the engineer. Provision for drying wet soils.	Incidental	M Gallons
	24 max	-	Method II—Material containing large stones.	As directed by the engineer	-	-
	8 max	-	Method III—Min. 90 to 100% AASHO T 99 (see Table 46-8 Emb.)	As required do provide density specified	$\frac{\text{Roller hr x width of roller}}{6}$	M Gallons
Nevada, Tentative Std. Spec. for Road and Bridge Construction 1957	8 max for soil 36 max for rock		Min. 90% of California method for soils. For rock, that obtainable by routing equipment.	Sufficient for compaction	Roller Hours	M Gallons
New Mexico, Std. Spec. Edition of 1954	8 max to 24 max^1	-	Min. 95% AASHO T 99	Min. opt minus 5% max as acceptable to the engineer	Roller Hours	M Gallons
	8 max to 24 max^1	-	Embankment without density control—Satisfactorily compacted with hauling and spreading equipment. Note^1 8 max for tamping rollers exerting 500 psi or more. Up to 24 in. for 50 ton (or more) pneumatic-tire roller having inflation pressure of 60-90 psi.	As directed by the engineer	Roller Hours	M Gallons
Utah, Std. Spec. Edition of 1960	8 max	-	Min. 95% AASHO T 99 or T 180.	As required for compaction	Method A—Roller Hr Method B—cu yd or Incidental	M Gallons
Wyoming, Std. Spec. Edition of 1960	None Specified	None Specified	Min. 95% AASHO T 99	At the moisture content specified by the engineer	Per cu yd of Excavation	M Gallons
Pacific						
California, Std. Spec. Jan. 1960	8 max	-	Min. 90% relative compaction, California 5-layer test method. Min. 95% within 2½ ft of finished grade.	As needed to obtain compaction	Incidental	Furnish water equipment and M Gallons
Oregon, Std. Spec. May 1, 1954	8 max	-	Min. 95% AASHO T 99 in upper 3 ft. Min. 90% in remainder.	As required to facilitate compaction. Special provision used when circumstances indicate need for drying.	Incidental	M Gallons
Washington, Std. Spec. of 1957	18 max (except when size of rock requires more)		Rock embankments—Compaction by routing hauling equipment over entire roadway. Also, each layer to have one coverage of 50-ton roller or four coverages of 10-ton roller per 6-in. layer thickness.	To qualify as rock embankment material must contain 10% or more by volume of gravel or stone 4 in. or greater in diameter. ¼-in. minus portion shall be not more than 3% above optimum.	cu yd	M Gallons
	6 max	-	Top 12 in. of rock embankments.			
	24 max	-	Earth embankments^1—Method A. Compaction by routing loaded hauling equipment.	Ditto^2	None	M Gallons
	-	8 max 4 in. max in top 2 ft	Method B—Min. 90% ASTM D-698 below top 2 ft. 95% min. in top 2 ft.	Ditto	cu yd	M Gallons
		ditto	Method C—Min. 95% ASTM D-698	Optimum ± 3%	cu yd	M Gallons
			^{1}When non-cohesive granular soils are used, special provisions require min. 95% of max density as determined by Washington compaction method described in HRB Bulletin 159. ^{2}Provision for drying excessively wet soils.			
Hawaii	8	-	95% required for material between finished grade and 3 ft below finished grade	As necessary to obtain the specified relative compaction.	Paid under excavation per cu yd	Sprinkling M Gallons
	8	-	95% required for material placed 3 ft below finished grade.	As above	As above except at natural ground. Per sq yd.	As above
	8	-	For material having sand equivalent of 25 or greater compaction to 95% regardless of depth	As above	Incidental to price for excavation	As above
Alaska	8	-	Min. 95% of AASHO T 99 method C or one roller per 150 cu yds per hour.	Not specified. No provision for drying excessively wet soils.	Incidental to other items	When used—M Gallons Providing a water plant paid for in lump sum

TABLE 46-1

(EMB.) (MAINE)

Maximum Density (pcf)	Minimum Percent Compaction
100 to 115	95
115 to 117.5	94
117.5 to 120.0	93
120.0 to 122.5	92
122.5 to 125.0	91
125 or higher	90

TABLE 46-3

(EMB.) (OHIO)
EMBANKMENT SOIL COMPACTION REQUIREMENTS

Condition I		Condition II	
Fills 10 ft or less in height, and not subject to extensive floods.		Fills exceeding 10 ft in height, or fills of any height subject to long periods of flooding[1].	
Maximum Laboratory Dry Weight (pcf)	Minimum Field Compaction Requirements (Percent of Laboratory Maximum Dry Weight)	Maximum Laboratory Dry Weight (pcf)	Minimum Field Compaction Requirements (Percent of Laboratory Maximum Dry Weight)
Less than 90.0	-[2]	Less than 95.0	-[3]
90.0 - 102.9	100	95.0 - 102.9	102
103.0 - 109.9	98	103.0 - 109.9	100
110.0 - 119.9	96	110.0 - 119.9	98
120.0 and more	95	120.0 and more	96

[1] Where Condition II applies to any portion of the embankment below a horizontal plane through subgrade elevation at pavement centerline on any cross-section, all portions of soil embankment throughout the total width and depth on that cross-section shall be compacted in accordance with Condition II requirements.

[2] Soils having maximum dry weights of less than 90.0 pounds per cubic foot are considered unsuitable and shall not be used in embankment.

[3] Soils having maximum dry weights of less than 95.0 pounds per cubic foot are considered unsuitable and shall not be used in embankment under Condition II requirements.

TABLE 46-2

(EMB.) (MARYLAND)
EMBANKMENT SOIL COMPACTION REQUIREMENTS

Maximum Laboratory Dry Weight[1] (pcf)	Minimum Field Compaction Requirements (% of Dry Wt)
Condition I: Fills 10 ft or less in height and not subject to extensive floods.	
89.9 and less	-[2]
90.0 - 99.9	100
100.0 - 109.0	95
110.0 - 119.9	95
120.0 - 129.9	90
130.0 and more	90
Condition II: Fills exceeding 10 ft in height, or subject to long periods of flooding.	
89.9 and less	-[3]
95.0 - 99.9	100
100.0 - 109.9	100
110.0 - 119.9	98
120.0 - 129.9	95
130.0 and more	95

[1] AASHO Designation T 99.

[2] Soils having maximum dry weights of less than 90 lb per cu ft will be considered unsatisfactory and shall not be used in embankment.

[3] Soils having maximum dry weights of less than 95 lb per cu ft will be considered unsatisfactory and shall not be used in embankment under Condition II requirements.

TABLE 46-4

(EMB.) (PENNSYLVANIA)
EMBANKMENT SOIL COMPACTION REQUIREMENTS

Condition I		Condition II	
Embankment 10 Ft or Less in Height and Not Subject to Extensive Flooding		Embankment Exceeding 10 Ft in Height or Subject to Extensive Flooding	
Max Dry Weight[1] (pcf)	Minimum Field Compaction Requirements (Percent of Max Dry Weight)	Max Dry Weight[1] (pcf)	Minimum Field Compaction Requirements (Percent of Max Dry Weight)
Less than 90.0	-[2]	Less than 95.0	-[3]
90.0 - 99.9	100	95.0 - 99.9	100
100.0 - 109.9	95	100.0 - 109.9	100
110.0 or more	95	110.0 or more	95

TABLE 46-5

(EMB.) (WEST VIRGINIA)

Maximum Density Obtainable by AASHO Method T-99-49 (pcf)	Minimum Compaction Required Percent of Maximum Density
90 - 99	100
100 - 119	95
120 and over	90

TABLE 46-6

(EMB.) (WEST VIRGINIA)
EMBANKMENT SOIL COMPACTION REQUIREMENTS

Class of Soil	Condition I Fills Not Subject To Inundation	Condition II Fills Subjected to Periods of Inundation
Determined by AASHO MI45	Percent of Maximum Density Determined by West Virginia Procedure SL-4	Percent of Maximum Density Determined By West Virginia Procedure SL-4
A-1	100 min.	100 min.
A-3	100 min.	100 min.
A-2-4	100 min.	100 min.
A-2-5	100 min.	100 min.
A-4	100 min.	100 min.
A-5	95 min.	100 min.
A-6	95 min.	100 min.
A-7	95 min.	100 min.

(1) Tests for "in place" density of soil will be made in accordance with Testing Procedure No. SL-13, as revised 9-15-56, West Virginia State Road Commission. In the event of a dispute the results obtained by this method of test shall be final.

Soil, in addition to the above requirements, shall have a liquid limit (AASHO Designation T 89) of 65 or less. The minimum plasticity index number (AASHO Designation T 91) of the soils having liquid limits of 41 to 65 inclusive shall be not less than that determined by the formula—$^{6}/_{10}$ times the liquid limit minus 9 (PI = 0.6, LL - 9.0).

Where Condition II applies to any portion of the embankment or any cross-sectional area all portions of soil embankment throughout the total width and depth of that cross-sectional area shall be compacted in accordance with Condition II requirements.

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[1] Maximum dry weight determined in accordance with AASHO Designation T 99.

[2] Soils having maximum dry weights of less than 90 pcf will be considered unsuitable and shall not be placed in the embankment.

[3] Soils having maximum dry weight of less than 95 pcf will be considered unsatisfactory and shall not be placed in the embankment under Condition II requirements or in the top 8-in. loose layer of the embankment under Condition II requirements, or in the top 8-in. loose layer of embankment which will form a subgrade for pavement, base course, or subbase under Condition I requirement.

TABLE 46-7

(EMB.) (SOUTH DAKOTA)
COMPACTION REQUIREMENT SUPPL. SPEC. 6-25-58

Maximum Laboratory Dry Weight (pcf)	Minimum Compaction Requirements (Percent of Laboratory Dry Wt)
Less than 88	*See note below
88 to 94.9	100
94.9 to 119.9	96
120 or more (sand, sandy gravel, or gravel)	92

*Soils having a max laboratory dry weight of less than 88 pcf shall not be placed in the upper 12 in. of finished earth subgrade.

TABLE 46-8

(EMB.) (MONTANA)
MINIMUM FIELD COMPACTION REQUIREMENTS AASHO M 57

Standard of Compaction AASHO T 99 Method A or C (pcf)	Minimum Compaction Required (Percent of Maximum Density)
90 - 99.9	100
100 - 119.9	95
120 and above	90

TABLE 47

SPECIFICATION REQUIREMENTS FOR CONTROL OF COMPACTION AND MOISTURE CONTENT OF SUBGRADES

Region and State	Compaction Requirements	Depth of Subgrade Compaction	Moisture Control Requirements	Pay Items	
				Compaction	Water
Northeast					
Connecticut Std Specif Jan 1955	Thoroughly and uniformly compacted with min 10-ton roller	Not specified	Not specified	Incidental	Incidental
Maine Std Specif Rev of Jan 1956	Same as for embankments See Table 46-1 Emb (1) Satisfactory (2) Controlled density method Min 90 to 95% AASHO T 99 (see Table 46-1 Emb)	6-in in cuts	As directed by the Engineer	Incidental	Incidental
Massachusetts Std Specif 1953	Satisfactory to the Engineer Special—(Special Provision SP-52-59 p 16)	Not specified	Not specified—opt M C. practicable with types of materials available determined by compaction tests in the field.	Incidental	-
Michigan Std Specif May 1960	Cut sections—min 95% AASHO T 99 (minus 1 in material) or min 95% Michigan Cone Method	9-in Cohesive soils, 18-in Granular soil	As required to obtain density	Unit price per station	Incidental
	Original ground—Min. 90% AASHO T 99 (minus 1 in material) or min 90% Michigan Cone Test)	9-in	As required to obtain density	Unit price per station	Incidental
New Hampshire Std Specif July 1, 1954	Rolled until no further compaction by 3-wheeled min 10-ton roller or min 14-ton tandem roller (min 315 lb per in of width of drive roll)	Not specified	Not specified	Incidental	Incidental
New York Std Specif Jan 2, 1957	Min 100% AASHO T 99 Method C for materials having less than 20% pass No 200 sieve Min 95% for all others Added requirement calls for min of 6 passes of rollers For heavier and more efficient types of equipment number of passes is determined by the engineer after appropriate field tests	Subgrade foundation—fills trapezoid of pavement width plus 2 ft downward and outward on 1 1 slope to 4-ft depth Cuts min depth 6 in below bottom of subbase	As required to obtain density but not less than 3% drier than optimum	Incidental	(1) Furnish water equipment (2) Applying water per M gallons
Rhode Island Std Specif Rev of 1946	Compacted uniformly with min 10-ton roller	Not specified	Not specified	Incidental	Incidental
Vermont Std Specif Jan 1956	Brought to firm unyielding surface by rolling with 3-wheel min 10 ton or a 3-axle tandem min 13-ton roller Provision for use of sheepsfoot rollers where satisfactory compaction is not obtained by other types	Not specified	Not specified	Incidental	Incidental
Wisconsin Std Edition of Specif of 1957	Satisfactorily compacted to uniform density for P C C pvt Use 3- to 5-ton roller	Not specified	As required by the Engineer	Incidental	Incidental
Middle East					
Delaware Std Specif April 1, 1957	Thoroughly compacted and pretested with two complete coverages of rubber-tired rollers or construction equipment having min. wheel load of 15,000 lb	Not specified	Not specified separately Under item "Preparation of Subgrade "	Incidental	Incidental
District of Columbia Std Specif 1957	95% AASHO T 99 Method C except 100% for clean sands	12 in in cuts	Optimum ± 2 and support construction equipment without rutting If rutting occurs soil is dried.	Incidental	Incidental
Illinois Std Specif Jan 1952	Compaction to the satisfaction of the Engineer	Covered by special provisions in special cases	Satisfactory to the Engineer	Incidental	Incidental
Indiana Std Specif 1960	Min 100% AASHO T 99 max dry weight	6 in	Must obtain density	Incidental	Incidental
Kentucky Std Ed of Specif 1956	Same as for embankments				
	1 Standard compaction - satisfactory	6 in	As directed by the Engineer	Incidental	M gallons
	2 Extra compaction - average density not less than 95% AASHO T 99 with no density below 90%	6 in	As directed by the Engineer	Incidental	M gallons
Maryland Std Specif Jan 1957	First rolled with heavy pneumatic-tire roller as directed by the Engineer (see Table on pneumatic-tired rollers) (4,500- to 5,000-lb tire) Finish rolling with 10-ton steel wheel roller	Not specified	As required for embankments	Incidental	Incidental
New Jersey—preliminary to new* revision of Std Specif	If subgrade is constructed under contract—satisfactorily compacted with 3-wheel power roller Min 330 lb per inch width of roll	-	-	Incidental	Incidental
	If subgrade is built under previous contract—5 passes of 50-ton compactor	-	-	Incidental	2 top Incidental
Ohio Std Specif January 1, 1959	98-102% AASHO T 99 (see Table 47-1 subgrades)	E-1 compacted subgrade, 12 in in cuts and fills	Not greater than two percent above optimum. Not greater than optimum for soils that display pronounced elasticity or deformation under construction equipment	Per sq yd of compacted subgrade	M gallons
Pennsylvania Std Specif 1959	Same as for embankment	4 to 9 in	Not more than two percentage points over optimum	Incidental	Incidental
Tennessee Std Specif July 1, 1951	Min of 100% of AASHO T 99 max den	6 min	As required to obtain density	Incidental	Incidental
Virginia Road and Bridge Specif April 1, 1958	Min 95% AASHO T 99	Scarified to depth of 8 in for min two feet beyond edge of pavement and recompacted	As required to obtain density	Incidental	Incidental
Special provisions (April 30, 1957) for interstate only	Min 100% AASHO T 99 on select borrow that will be used unless in-place soil has CBR of 30 or more (Note Usually a subbase material used above subgrade requiring 100% density)	-	-	-	-
West Virginia Std Specif 1952	Compacted to a firm unyielding surface	4 in	Not specified	Incidental	-
W Virginia Interstate provisions	100% of max den as determined by W Va S R C testing procedure uses $^1/_{10}$ cu ft mold and compactive efforts from 12,600 to 13,200 ft lb/cu ft	12 in	Not specified	-	-

*Subgrade is defined here as the surface upon which are placed the pavements and shoulders, generally the top of the subbase

Southeast					
Alabama Std Specif 1950	Min 100% AASHO T 99	6 in	As required to obtain density	Incidental	M gallons
Florida Std Specif April 1, 1959	Min 100% AASHO T 180-57	6 in	As required to obtain density	Incidental	Incidental
Georgia Std Specif May 1, 1956	Min 95% AASHO T 99	6 in. min	As required	Incidental	Incidental
Note Item "Special Subgrade Compaction calls for at least two and not more than three complete passes of 35-ton 4-wheel pneumatic-tire roller over the entire subgrade"					
Mississippi Std Specif Ed of 1956	Min 95% AASHO T 99	6 in.	-	Incidental	Incidental
North Carolina Std Specif October 1, 1952	Min 95% AASHO T 99	6 in	As required to obtain density	Incidental	Incidental
South Carolina*	When required by Spec Provisions, the subgrade between lines 18 in outside the area to be surfaced shall be compacted to a density not less than 95% of AASHO T 99 max dry unit weight	6 in	Soft and unstable material removed If too dry, subgrade is wet by sprinkling		
Note The above information was extracted by HRB Staff Engineer from South Carolina Standard Specifications for Highway Construction November 1, 1955					
South Central					
Arkansas Std Specif Ed of 1959	Min 95% AASHO T 99	Top 8 in	Substantially that of optimum	Incidental	Incidental
Louisiana Std Specif July 1955	Min 95% AASHO T 99	12 in in cut sections	Requirements based on AASHO Method T 99	Incidental	Incidental
Oklahoma Std Ed of Specif 1959	Min 95% AASHO T 99 (Requires use of 50-ton R I test roller)	8 in	As required for compactor	Incidental	Incidental
Texas Std Specif 1951	Same as embankments Approx 90-100% AASHO T 99	6 in.	Slightly above to 5% below optimum	Roller hours	M gallons
North Central					
Iowa Std Specif of 1960	95% of AASHO T 99 plus 2 or minus 4 percentage points	6 in	Optimum plus two or minus four percentage points	Per 100 ft station	Incidental
Kansas Suppl Specif 55-498	Type AA Min 95% AASHO T 99	6 in min	MR-0 mois content, opt. to 5% above opt or MR-5, mois content not less than 5% below opt.	cu yd	M gallons
Minnesota Specif 2110 (9-10-57)	Same as specified density - 98% AASHO T 99	Generally 12 to 18 in in cuts, 24 to 36 in in embankments	Same as for embankment	Incidental	Incidental
Minnesota Specif 2110 (5-1-59)	Same as specified density - Min 100% in upper three feet, min 95% below upper three feet	Generally 12 to 18 in in cuts, full depth in embankments	65% to 102% of optimum when 100% of max den is required Not more than 115% of opt moisture when 95% of max den is required	Incidental	Incidental
Missouri Std Ed of Specif 1955	Same as for embankments min 90% AASHO T 99 Min 95% within 100 ft of bridges	Up to 18 in	As determined by the engineer	Incidental except per cu yd in cut section	Incidental
Nebraska Std Series of Specif 1955	For P C C concrete pvt Min 90% AASHO T 99	6 in	Optimum ± 3%	Incidental	Incidental
Special Provision	Also for bituminous pavement by Spec Provision	6 in.	Max 90% of optimum + 4% /	Incidental	Incidental
North Dakota Std Specif. Jan 1956	Uniformly compacted by grading equipment and rollers	Not stated	A satisfactory moisture content to obtain compaction of at least 95% of the max dry density for the material being used		
South Dakota Std Specif April, 1957	Ordinary roadway shaping–satisfactory compaction	6 in	As required by the Engineer	Incidental	M gallons
Special Provisions June 25, 1958	For fill section 92 to 100% AASHO T 99 (see Table 47-2 Subgrade)	Upper 12 in in fills For cuts, soil is undercut 12 in and the exposed soil compacted according to ordinary compaction of Std Specif (1957)	Soils with P I not greater than 30, M.C. from 2% above to 6% below optimum For P I above 30 moist cont from 1% above to 4% below optimum. Provision for drying	Incidental	M gallons
Mountain					
Arizona Tent Std Specif 1959	Satisfactory to Engineer	Not specified			
Special Provisions (Supersede)	Min 95% AASHO T 99	Min 6 in	As required to obtain specified density	None	M gallons
Colorado Std Specif Jan 1, 1958	Same as embankments (Min 90% AASHO Modified except soils of A-1 and A-3 groups min 95% of Modified) (5 layers, 25 blows per layer, 10-lb hammer, 18-in drop) When Std compact is required, the min field density shall be 95% for all soils except groups A-1 and A-3, which require a min of 100%	Min compaction required at any depth	Optimum	At unit bid price per cu yd for Emb No specific pay item for subgrade	M gallons
Idaho Std Specif Ed of 1957	See compaction of embankments, Classes A and B 100%, Class C routing equipment 4-in layers	12 in.	As required for compaction	None	M gallons
Montana Revision of Std Specif 1959	Same as Emb (1) Satisfactory or (2) Min. 90-100% AASHO T 99 (see Table 46-8 Emb)	Not specified	As directed by the Engineer	$\frac{\text{Hours x roller width}}{6}$	M gallons
Nevada Tent Specif. for Road and Bridge Construction 1957 Ed	Same as for embankments	No separate subgrade item. Top 6 in. of completed subgrade in cuts compacted to same density as required for embankment.	-	-	
New Mexico Std Specif Ed of 1954	100% AASHO T 99 in top 6 in 95% below top 6 in in Emb and to max depth of 18 in. in cuts	Max 18 in in cuts	Not less than optimum minus 5% as acceptable to the Engineer	Roller hour	M gallons
Utah Std Ed of Specif 1960	Refers to AASHO Specification M-57 which calls for min. 100% on Classes A-1, A-2-4, A-2-5, or A-3, and min. 95% on Classes A-2-6, A-2-7, A-4, A-5, A-6 and A-7	Top 8 in same as for embankment Usually depth is specified.	Optimum or less	Method A Roller hours Method B Cubic yards or part of excavation price	M gallons
Wyoming Std Specif Ed of 1960	Same as for embankment	Not specified	As specified by the Engineer	Cu yd Emb compaction	M gallons
Pacific					
California Std Specif 1960	Min 95% of Calif. 5-layer method max den. for depth of 0.5 ft below subgrade	6 in. in cuts	As required for Compaction	Incidental	Furnish water equipment and M gallons
Oregon Std Specif May 1, 1954	Min 95% AASHO T 99	Not specified	As required to facilitate Compaction	Incidental	M gallons
Washington Std Specif. 1957	95% of ASTM D 698 or as specified by engineer	Not specified	As ordered by the Engineer	Roller-hour	M gallons
Alaska	Min 95%/AASHO T 99 Method C	Not specified	Not specified	When on bid schedule roller hours	Providing and maintaining water plant—lump sum M gallons
Hawaii	95% AASHO T 99	Initial 6 in	Sprinkling water required	Incidental	Incidental

TABLE 47-1

SUBGRADE (OHIO)

Maximum Laboratory Dry Weight (pcf)	Minimum Subgrade Compaction Requirements (Percent of Laboratory Maximum Dry Weight)
Less than 102.0	*
102.0 - 109.9	102
110.0 - 119.9	100
120 and more	98

*Soils with a maximum dry weight of less than 102.0 pcf are considered unsuitable for use in the top 12-in. soil layer immediately below the surface of the subgrade and shall be replaced with suitable soil or granular material.

TABLE 47-2

SUBGRADE (SOUTH DAKOTA)

Maximum Laboratory Dry Weight (pcf)	Minimum Compaction Requirements (% of Laboratory Dry Weight)
Less than 88	Do not place in upper 12 in. of grade
88 to 94.9	100
94.9 to 119.9	96
120 or more (sand, sandy gravel, or gravel	92

(Table 48, see pages 168 and 169)

TABLE 49

SPECIFICATION REQUIREMENTS FOR BACKFILLING OF TRENCHES, PIPE CULVERTS AND SEWERS

Group	Requirements		Check
A	Specifications require compaction but do not specify density		25
	Tamping or Vibrating Provisions:		
	Mechanical tamping or vibration only specified		15
	Hand or mechanical tamping allowed		8
	Hand tamping mentioned only		
	Tamping method not mentioned		1
	Depth of Layer or Lift:		
	Not to exceed	Basis	
	4 in.	loose	4
	6 in.	loose	12
	8 in.	loose	3
	9 in.	loose	1
	12 in.	loose	1
	3 in.	compacted	1
	6 in.	compacted	2
	Moisture Control:		
	Provision		14
	No provision		10
	Materials Requirements:		
	Provision for select or approved materials		15
	Provision for granular backfill		6
	Permission to Saturate, Flood, or Puddle		4
B	Specifications require density control		33
	Tamping or Vibrating Provisions:		
	Mechanical tamping or vibration only specified		21
	Hand or mechanical tamping allowed		6
	Hand tamping mentioned only		
	Tamping method not mentioned		4
	Compaction Requirements[1]:		
	Not less than 100% max density (AASHO T 99)[2,4]		5
	Not less than 95% max density (AASHO T 99)[3]		17
	Not less than 90% max density (AASHO T 99)		5
	Not less than 95% relative density (California Method)		1
	Not less than 90% relative density (California Method)		1
	Not less than 95% modified Proctor		2
	Not less than 90 - 100% max density (AASHO T 99)		1
	Not less than 95 - 100% max density (AASHO T 99)		1
	Depth of Layer or Lift:		
	Not to exceed	Basis	
	4 in.	loose	4
	5 in.	loose	
	6 in.	loose	18
	4 to 6 in.	loose	1
	8 in.	loose	8
	6 in.	compacted	3
	Moisture Control:		
	Provision		27
	Material Requirements:		
	Provision for select or approved materials		23
	Provision for granular backfill		12
	Provision to Saturate, Flood, or Puddle[5]		1

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[1] To depth of 1 ft above pipe. Rest of trench in max one-foot layers and compacted to density.

[2] When sand and gravel are used.

[3] When soil has more than 20% minus No. 200.

[4] Top 3 ft 98% remainder 95% for pipe culverts. Sewers—compact density of adjacent ground.

[5] Ponding and jetting permitted if backfill is free draining below a point 4 ft below finished grade if surrounding material will not be softened or damaged.

Note: Some states provide specifications for both Groups A and B specifications.

TABLE 48

SPECIFICATION REQUIREMENTS FOR CONTROL OF COMPACTION OF GRANULAR BASES

Region and State	Thickness of Layer		Compaction Requirements	Control of Moisture Content	Pay Items	
	Loose (in)	Compacted (in)			Compaction	Water
Northeast						
Connecticut Std Specif of January 1955		8	Subbase–single course All thoroughly compacted with 10-ton roller.	Not specified	Incidental	Incidental
		6	Subbase–two or more courses	Not specified	Incidental	Incidental
		-	Rolled gravel base–two courses	Not specified	Incidental	Incidental
		4	Processed gravel base–two courses	Not specified	Incidental	Incidental
Maine Std Specif , Rev of January 1956	-	12 max	Same as for embankments Controlled density method min 90 - 95 AASHO T 99 (see Table 43-1 Emb)	As directed by the engineer	Incidental	Incidental
Massachusetts Std Specif 1953	-	-	Thoroughly watered and rolled	See compaction requirements	Incidental	Incidental
Michigan Std Specif May 1960	Depth limited to max on which specified density can be obtained		Min 100% Michigan Cone Method	As required to obtain density	Incidental	M gallons
New Hampshire Std Specif July 1, 1954	-	12 max	Satisfactory to engineer. Final rolling with 3-wheel, min 10-ton or 3-axle tandem, min 14-ton (min 315-lb per in of width of drive roll)	Provision for sprinkling	Incidental	M gallons
New York Std Specif January 2, 1957		6 max	Min 8 passes of pneumatic-tired roller (1,000 to 2,500 lb per tire) or smooth-wheel roller (10 ton min wt) 100% AASHO T 99 modified for test on minus ¾-in material For heavier and more efficient equipment, No of passes shall be determined by the engineer after appropriate field tests	As required to obtain density	Incidental	(1) Furnish water equipment (2) Applying water per M gallons
Rhode Island Std Specif , Rev of 1946	12 max	-	Fully compacted with 3-wheel, 10-ton roller	As determined by the engineer	Incidental	Incidental
Vermont Std Specif January 1956		5 max	Cr rock base–satisfactory to engineer, 3-wheel min 10-ton roller	As determined by the engineer	Incidental	Incidental
		9 max	Cr rock subbase–satisfactory to engineer, 3-wheel min 10-ton roller	As determined by the engineer	Incidental	Incidental
		12 max or ¼ depth of course	Gravel subbase–satisfactory to engineer, 3-wheel min 10-ton roller	As determined by the engineer	Incidental	Incidental
			Gravel base–satisfactory to engineer, min 7-ton roller	As determined by the engineer	Incidental	Incidental (little used)
			Sand subbase–satisfactory to engineer, satisfactory equipment.	As determined by the engineer	Incidental	Incidental
Wisconsin Std Ed of Specifications 1957		3 to 5*	Granular subbase Standard compaction**–by hauling equipment and rollers to degree of no further compaction **Used unless special compaction is required	Not specified. Moisture controlled to control compaction (Not excessively wet or dry.)	Incidental	-
			Special compaction–min 95% AASHO T 99	Not specified directly Controlled as required to obtain density	Incidental	Incidental
			Gravel or crushed stone base course–same as granular subbase *When required base does not exceed 6 in and placed on loose sand subgrade, may be placed in one layer if compaction can be obtained	Ditto	Incidental	Incidental
Middle East						
Delaware Std Specif April 1, 1957	6 max	-	Selected borrow–min 95% modified Proctor method	± 10 percent of optimum	Incidental	Incidental
District of Columbia Std Specif 1957	6 max	-	Min 100% AASHO T 99 Method C	± 2 percent of optimum	Incidental	Incidental
Illinois Std Specif 1958		4 max	100% AASHO T 99	As required to produce density	Incidental	Incidental
Indiana Std Specif 1960		6	100% AASHO T 99 Method A or C	As directed by the engineer	Incidental	Incidental on subbase M gallons when specified
Kentucky Std Ed of Specif 1956	-	-	Density throughout base course shall be equal to or greater than 85% of solid volume	Optimum as determined by AASHO T 99	Incidental	Included in wt /ton of plant mixed material
Maryland Std Specif January 1957	-	6 max	Subbase–min 95% AASHO T 99	As required by the engineer	Incidental	Incidental
			Stabilized soil base course–satisfactory	As required by the engineer	Incidental	Incidental
			Foundation layer (cr stone or slag)–satisfactory	As required by the engineer	Incidental	Incidental
			Plant mix stab aggr base course–min 100% AASHO T 99 Min one pass 8-ton smooth-wheel roller, min 3 coverages of pneumatic-tire roller	As required by the engineer	Incidental	Incidental
			Sand-aggregate base course–satisfactory	As required by the engineer	Incidental	Incidental
Ohio Construction and Materials Specif January 1, 1959		3 to 6*	Aggregate base course (crushed limestone, slag or gravel)–98% of density determined by a test section established on each project for each material type Each test section is compacted with rollers specified until there is no further appreciable increase in density *6-in if 3-P** pneumatic-tire roller is used, 3-in if 3-P** roller is not used **3-P pneumatic-tired roller requirements are 56,000-lb on 7-wheels tire pressure 75 to 120 psi	Near optimum at time of loading for transportation to site to reduce segregation. Water is added during rolling	Incidental	M gallons
Pennsylvania Std Specif 1959		6 max	Satisfactory to engineer As indicated by non-movement of the C Aggr under the roller, and/or vibratory equipment and finally completing by filling voids with fines (-⅜ in) by means of brooming, compacting and watering	Sprinkled and rolled until a slight wave of excess water and fines forms a grout ahead of the roller.	Incidental	Incidental
Tennessee Std Specif July 1, 1951		5 max	98% of that determined as an average of maximum compaction of the material in use	As directed by the engineer	Incidental	M gallons
Virginia Std Specif April 1, 1958		6 to 8	Min 100% AASHO T 99	Optimum moisture content	Incidental	Incidental
West Virginia Std Specif 1952	4 max to 7 max	-	Satisfactory to the engineer	As directed by the engineer	Incidental	Incidental
Interstate Provisions (Rev. Std. Specif Div II, Section 2 15)			100% AASHO Modified final density controlled by W Va procedure SL-13	Water added during mixing to obtain optimum moisture for compaction as directed by the engineer	-	-

Alabama Std Specif 1950	-	6 max	Min. 100% AASHO T 99	Optimum ± 2 percent	Incidental	M gallons
Florida Std Specif April 1, 1959	As shown on plans		*Min. 100% AASHO T 180-57. *For shell stabilized base, compaction specified by size of equipment and time of rolling.	As required to obtain density	Incidental	Incidental
	*Consider limerock stabilized base and shell stabilized base as a granular base. Shell stabilized base currently specified by Special Provisions.					
Georgia Std Specif. May 1, 1956		2 min 8 max	100% AASHO T 99.	As required for construction	Incidental	Incidental
Mississippi Std Specif Ed of 1956	-	6 max	Min. 105% AASHO T 99.	As required for compaction	Incidental	Incidental
North Carolina Std Specif October 1, 1952	-	8 (Spec Prov)	100% Modified density for all work	Provision for wetting of base	Incidental	Incidental
South Carolina Std Specif for Highway Construction Nov 1, 1955 (Extracted by HRB Staff Engr)	-	8	Not less than 100% of AASHO T 99 max. density.	As near as practicable at optimum moisture content	Incidental	Incidental
South Central						
Arkansas, Prelim to new Rev of Std Ed of 1959	-	6 max	Min 100% mod AASHO T 99 (plus ¾-in material replaced with equal amount of ¾-in. to No 4 sieve aggregate 6 in. diameter mold)	Optimum moisture content	Incidental	Incidental
Louisiana Std Specif. July 1955	5 max	-	100% of max density as determined by laboratory methods.	Optimum moisture content	Incidental	Incidental
Oklahoma Std Ed of Specif 1959	Satisfactory to engineer		Min 95% AASHO T 99.	As required to obtain density	Incidental	Incidental
Texas Std Specif 1951	-	-	Satisfactory to engineer	As required by the engineer	Hours rolling	M gallons
Special "Incentive Compaction" used on a limited basis			100% of density as determined by "Compaction Ratio" Method.	THD-110 soil test procedure	Subsidiary	Subsidiary
Special Specification for Flexible Base (used on a limited basis)	-	6	Compacted to an apparent dry density of the total material of not less than 98% of max dry density as determined by Compactive Effort No. 1 of the general laboratory test for Moisture-Density-Relations for soils THD 83. *13 26 ft lb per cu in.	THD-110 soil test procedure (Den and M C of top 3 in shall be checked and if tests show the density to be more than 2% below the specified minimum, the course shall be reworked as necessary to obtain the specified compaction and moisture content	Subsidiary	Subsidiary
North Central						
Iowa Std Specif Series 1960	-	-	Rolled stone-min. 100% AASHO T 99 Method C. Test rolling for density permitted with steel roller with 325-lb per in. of tire width.	0.95 to 1 05 field optimum which equals 85% to 90% of Proctor* optimum *This is assumed to be AASHO T 99	Incidental	Incidental
Kansas Std Ed. of Specif 1955, supplemental Specific 55-499	-	*4 max	Aggregate-binder base course-min. 100% AASHO T 99 Modified as follows Compaction of minus No. 4 material. Six-in. diam 1/13 cu ft mold, 4 layers, 56 blows per layer, 5 5-lb hammer dropping 12 in	As determined by the engineer	Subsidiary to item manipulation	M gallons
	-	4	Granular subbase-min 95% of max den. by above method *May be increased to accommodate new and improved compaction equipment	As determined by the engineer	Subsidiary to item granular subbase	M gallons
Minnesota Std Specif July 1, 1947 and Suppl No 1, 4-15-53	-	-	Specified density method-min 98% AASHO T 99	As required by the engineer	Base constr (per ton of material)	M gallons
Spec 2201 and 2202 May 1 1959		3 or 6	Specified density 100% of maximum density	Not less than 90% of optimum Not less than 75% of OMC if vibratory equipment is used	Incidental	Incidental in specified density M gallons with "Ordinary Compaction "
Missouri Std Specif Ed of 1955		4 max	Min. 95% AASHO T 99 (on minus No. 4 material).	As required to insure compaction	Incidental	Per 100 gallons
Nebraska Std Series of Specif 1955	-	-	Granular base-min 100% AASHO T 99.	As required to obtain density	Incidental	M gallons
			Crushed rock base-satisfactory to the engineer	As directed by the engineer	Incidental	M gallons
			Granular subbase-min 95% AASHO T 99.	As required to obtain density	Incidental	M gallons
			Granular foundation course-min 90% AASHO T 99 (min. 95% by special provision)	Optimum ± 3%	Incidental	Incidental
Special Provision (Interstate System)			(Not less than 100% of maximum density)	-	-	-
North Dakota, Std Specif January 1956	-	2 - 3	Min. 1.33 x dry loose weight max 140 pcf	As required to permit compaction	Incidental	M gallons
South Dakota, Std Specif April 1957	-	3 max	Stabilized soil-aggregate base-min. den at least 1⅓ times dried loose weight of mix, but not more than 140 pcf	Approach or slightly exceed optimum	Incidental	M gallons
		4 max	Subbase-satisfactory	As ordered by the engineer	Incidental	M gallons
Mountain						
Arizona tentative Std Specif for 1959	-	6 max	Satisfactory	As required by the engineer	Roller hours	M gallons
Special Provisions (supersede)	-	6 max	At least 95% AASHO T 99 max density	As required to obtain specified density	None	M gallons
Colorado* Std Specif June 1, 1952		4 max	Crushed rock	As ordered by the engineer	Hour roller-units	M gallons
Std Specif. January 1, 1958	8 max 10 max	- -	*Class I subbase and selected borrow and *Class II subbase-all types compacted to 100% of an optimum laboratory density *indicates present practice. Std Specif	Optimum as determined by the laboratory Optimum as determined by the laboratory Currently being revised	Contract price per ton including compaction	-
Idaho Std Specif Ed. of 1957	-	-	Satisfactory to the engineer.	As required by the engineer	Roller hours	M gallons
Montana Std Specif of 1959	-	-	Satisfactory	As required by the engineer	$\frac{\text{Hours x roller width (ft)}}{6}$	M gallons
Nevada tent Std. Specif. for Road and Bridge Construction	Type 1 Type 2	6 max 6 max	95% California method.	As required by the engineer	Roller hours	M gallons
New Mexico Spec Prov. of Oct 1, 1956 modifying Std Specif Ed of 1954	-	4 max	Min 95% Modified AASHO T 99 (10-lb hammer, 18-in drop, 5 layers, 1/13-cu ft mold).	As directed by the engineer Not greater than optimum	Roller hours	M gallons
Utah Std Ed of Spec. 1960	5± as on plans	Max 4 as on plans	95% of AASHO T 180 Method D.	As required by the engineer	Roller hours	M gallons
Wyoming Std Specif. Ed of 1960	-	-	Subbase-min. 75% of calculated dry density of a theoretical voidless mixture.	Limits of 5 to 8% by weight of dry material	Tons Compaction included in unit price for subbase and base	M gallons
			Base-min. 77% of calculated dry density of a theoretical voidless mixture.	Same as subbase		
Pacific						
California Std. Specif. January 1960		6 max	Min. 95% California 5-layer method	As ordered by the engineer	Incidental	Furnish water equipment, and M gallons
Oregon Std. Specif May 1, 1954	6 max	-	Uniformly and thoroughly compacted	As required by the engineer	Incidental	M gallons
Washington Std. Specif. 1957		8 max	Selected roadway borrow-thoroughly compacted	As required by the engineer	Roller hour	M gallons
		6 max	Ballast-satisfactory.	As required by the engineer	Roller hours	M gallons
		4 max	Crushed stone, top and base-satisfactory	As required by the engineer	Roller hours	M gallons
(For special situations such as widening, special provisions require compaction to 95 to 100% of max density as determined by laboratory. For test method see HRB Bulletin No. 159)						
Hawaii	6 max		95% relative compaction AASHO T 180	AASHO T 180	Incidental	M gallons
Alaska	According to plans		Min. 100% AASHO T 99 or min of one hour of rolling per 100 cu yd.	As needed	Incidental	When specified - furnish water plant and M gallons

SPECIFICATION REQUIREMENTS FOR CONTR

Region and State	Thickness of Layer		Compaction Requirement	Contro
	Loose (in.)	Compacted (in.)		
Northeast				
Connecticut, Std. Specif. January 1955		6 max	Min. 100% AASHO T 99	As requi
Maine, Std. Specif. January 1956	9 max	-	Thoroughly compacted	As direct
Massachusetts, Std. Specif. 1953	6 max	-	Thoroughly compacted	Not speci
Michigan, Std. Specif. May 1960	9 max	-	Controlled Density Method—min. 95% AASHO T 99 (on minus 1 in. material) or Michigan Cone Method.	
	12 max	-	12-in. Layer Method—min. 95% of max unit weight determined at existing moisture content	Not speci
New Hampshire, Amend. of 4/24/57 to Std. Specif. of July 1, 1954	8 max	-	Min. 95% AASHO T 99	As neces
New York, Std. Specif. January 2, 1957	8 max	-	Min. 100% AASHO T 99 Method C for materials having less than 20% passing No. 200 sieve. Min. 95% for others	As requi less tha
Rhode Island, Std Specif. Rev. of 1946	6 or 12 max	-	Thoroughly compacted. Puddling around catch-basins, inlets, and manholes.	Not speci
Future contracts bridges			95% of maximum density behind abutments and wall	
Vermont, Std. Specif. January 1956	6 max	-	Thoroughly compacted. Evidence of satisfactory compaction shall consist of the attainment of ninety percent of maximum compaction.	Moisture in the li
Wisconsin, Std. Ed. of Specif. 1957	12 max	-	Thoroughly compacted except where special compaction is used in Emb. Min. 95% AASHO T 99.	Not speci
Middle East				
Delaware, Std. Specif. Apr. 1, 1957	4 max	-	Min. 95% Mod. Proctor Method	Optimum
District of Columbia, Std. Specif. 1957	6 max	-	100% AASHO T 99 Method C	± 2% of o
Illinois Std. Specif. January 1958	4 max	-	Min. 90% of max weight AASHO T 99	Not great
Indiana, Std. Specif. 1960	Approx. 4	-	Min. 90% of max wet or dry weight AASHO T 99 for granular materials. Other material 95% min. density	Not speci
			Saturation—Granular material	Saturated
Kentucky, Std. Ed. of Specif. 1956	6 max	-	Maximum density obtainable	To obtain
Maryland, Std. Specif. January 1957	6	-	Same as embankments. Min. 90 - 100% AASHO T 99	As requir greater
New Jersey, Preliminary to New Revision of Std. Specif.	6 max	-	Same as for layers of Emb. except for areas that are inaccessible for heavy equipment then density control employed (min. 95% AASHO T 99)	Optimum
Ohio, Std. Specif. January 1, 1959	4 max	-	For soil 95% AASHO T 99. For granular material compacted to the density established as satisfactory to the engineer based on field density tests.	Sufficient limited than opt
Pennsylvania, Std. Specif. 1959	4	-	Embankments in back of bridge abutments formed of granular material or rock. Compaction to den. specified.	
Tennessee, Std. Specif. July 1, 1951	-	3 max	Thoroughly compacted	
Virginia, Std. Specif. 1958	-	6	Min. 95% AASHO T 99	Excess w.
West Virginia, Std. Specif. 1952	4- to 6 max	-	Thoroughly compacted	
Interstate Provisions			Same as Table on SHD Specif. for sheepsfoot rollers for bridge abutment	
Southeast				
Alabama, Std. Specif. 1950	6 max	-	Min. 95% AASHO T 99	Sufficient
Florida, Std. Specif. April 1, 1959	8 max	-	Min. 100% AASHO T 99 - 57	Sufficient
Georgia, Std. Specif. May 1, 1956	-	6 max	Min. 100% AASHO T 99	
Mississippi, Std. Specif. Ed. of 1956	-	6 max	Same as adjacent Emb. 90 - 95% AASHO T 99	Proper m
North Carolina, Std. Specif. Oct. 1, 1952	6 max	-	Thoroughly compacted	Satisfacto
South Carolina, Std. Specif. for Highway Construction, Nov. 1, 1955 *	6	-	* Min. 90% AASHO T 99 max density	* Provisio soils an
*Extracted by HRB Staff Engineer				
South Central				
Arkansas, Std. Specif. Ed. of 1959	4 max	-	Satisfactory	Not speci
Louisiana, Std. Specif. July 1, 1955	6 max	-	To the specified density of the optimum moisture content	Optimum
Oklahoma, Std. Ed. of Specif. 1959	6 max	-	Min. 95% AASHO T 99	As requir
Texas, Std. Specif. 1951	6 max	-	Same as for embankments 90 - 100% AASHO T 99	As requir
Special-Compaction Ratio Method	-	-	Same as for special for Emb. Swelling soils (PI = 20 or more) 98 - 102%. Non-swelling soils (<20) 100%	As neede
North Central				
Iowa, Std. Specif. 1960	6	-	Thoroughly compacted. At bridge abutments granular materials are required.	
Kansas, Std. Ed. of Specif. 1955	-	6 max	Min. 90% AASHO T 99	As requir
Minnesota, Specif. 2110 of May 1, 1959	6	-	Specified density. Same requirements as 2110 for embankment construction.	
Missouri, Std. Ed. of Specif. 1955	6 max	-	Require 95% in the 100 ft adjacent to bridge ends	As requir
Nebraska, Std. Series of Specif. 1955	6 max	-	Min. 90% AASHO T 99	To facilit
North Dakota, Sp. Prov. 49A December 14, 1959	12 max	-	Four ft or more below finished grade, min. 90%. Less than four feet below finished grade, min. 95% AASHO T 180 - 57.	See AASH
South Dakota, Std. Specif. April 1957	-	6 max	Ordinary compaction—satisfactorily compacted.	Not speci
Suppl. Specif. April 2, 1959 Supersedes Std. Specif. for R.C. pipe only	6 max	-	See Suppl. Specif. April 2, 1959.	Near opti
Mountain				
Arizona, Tent. Std. Specif. 1959	-	-	Min. 95% AASHO T 99. Material requirement sum of P.I. 9% pass. No. 200 sieve not to exceed 23	Moistened compact
Colorado, Std. Spec. January 1, 1958	6 max	-	100% of optimum laboratory density	Optimum
Idaho, Std. Specif. Edition of 1957	6 max	-	Same as embankments	As requir
Montana, Revised Specif. 1959	8 max	-	Thoroughly compacted	As direct
Nevada, Tent. Specif. for R. and B. Construction 1957 Ed.	4 max	-	Min. 90% California Method—Ponding or Jetting not permitted.	As requir
New Mexico, Std. Specif. Ed. of 1954	4 max	-	Min. 95% AASHO T 99	At optimu
Utah, Std. Ed. of Specif. 1960	-	8 max	Same as Emb. Min. 95% AASHO T 99 or T 180	Same as f
Wyoming, Std. Specif. Ed. of 1960	8 max	-	Min. 95% AASHO T 99	Specified
Pacific				
California, Std. Specif. January 1960	8 max	-	Min. 95% 5 layer method	As needed
Oregon, Std. Specif. May 1, 1954	6 to 12	-	Thoroughly compacted	Not specif
Washington, Std. Specif. 1957	6 max	-	Min. 95% ASTM D 698	Not specif
Alaska	6	-	Thoroughly compacted	Moistened
Hawaii	8	-	95% relative compaction	Based on

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L OF COMPACTION OF STRUCTURAL BACKFILL

of Moisture Content	Tamping Equipment and Methods	Compaction	Water
ed to obtain density	Pneumatic tamping not less than 50 sq in. in area. Power rollers, vibrators, puddling permitted.	Incidental	Incidental
·d by the engineer	Power tampers shall exert a minimum blow of 250 ft lb/sq ft of tamping face area.	Incidental	Incidental
ıed	Not specified	Incidental	-
	Not specified	Incidental	Incidental
ied	Not specified	Incidental	Incidental
ary	Power tamping or vibratory devices	Incidental	Incidental
ed to obtain density but not ı 3% drier than OMC	Impact rammers, min. wt. 200 lb, min. ramming foot area 80 sq in., min. blow 200 ft lb, vibrators 3,000 lb impact at min. frequency of 1,100 cpm. Min. coverage 3 passes for rammers or vibrators	Incidental	(1) Furnish water equipment (2) Applying water per M gallons
ıed	May require hand tampers weighing not less than 25 lb with not more than 50 sq in. tamping face area. Air Driven Mechanical Tamper—19 to 29 sq in. tamping foot. Gasoline Driven Mechanical Tampers—55 to 89 sq in. tamping feet.	Incidental	-
:ontent of the layer is within its for proper compaction.	Mechanical tampers. Impact rammers or vibrating compactors.	Incidental	May be required by engineer
ıed directly	Mechanical or pneumatic tampers or vibrators	Incidental	-
! 10%	Approved mechanical tampers	Incidental	Incidental
timum	Mechanical tampers capable of exerting a blow equal to 250 lb/sq ft of tamping area and having a dead weight in excess of 40 lb per sq ft of bearing surface.	Incidental	Incidental
r than 110% of optimum	Mechanical tampers capable of securing compaction of not less than 90% of max density.	Incidental	Incidental
ied	Mechanical tampers or vibrators	Incidental	Incidental
	May permit compaction by saturation except where stone backfill is used saturation is not permitted. Mech. tamping required.	Incidental	Incidental
max density obtainable	Mechanical tampers	Incidental	Incidental
ed for compaction but not han opt. + 2 percentage points	Mechanical tampers or vibratory compactors	Incidental	Incidental
! 2%	Mechanical tampers or vibratory compactors	Incidental	Incidental
for satisfactory compaction, lso, for soil, to not more mum plus 3%.	Approved mechanical compactors except that granular material may be deposited in water to a height not exceeding normal water level. Compaction of granular material with water above normal water level permitted if satisfactory drainage is required.	Incidental	M gallons
-	Approved mechanical tampers	Incidental	-
-	Mechanical tampers	Incidental	-
ter removed before backfilling	Mechanical tampers	Incidental	Incidental
-	25 to 35 lb pneumatic backfill tampers having a piston blow	Incidental	-
except rock is excluded. Other	structural backfill specifications unchanged.		
for compaction	Mechanical tamping	Incidental	M gallons
for compaction	Mechanical tamping	Incidental	Incidental
-	Mechanical tamper	Incidental	Incidental
isture content	Mechanical preferable	Incidental	-
y	Mechanical tamper capable of 185 psf of tamping area per blow.	Incidental	Incidental
ı for drying excessively wet adding water to dry soils.	*Not specified	Incidental	Incidental
ied	Hand or mechanical tampers	Incidental	Incidental
	Mechanical tampers	Incidental	Incidental
ɔd for compaction	Mechanical tampers	Incidental	Incidental
ɔd to obtain density	Mechanical tamps or rammers	Incidental	Incidental
by contractor	Any method	Incidental	Incidental
-	Pneumatic tampers supplied with air at pressure of not less than 100 psi at compressor. Hand tamping within 3 ft of wing wall, parapet wall or spandrel wall.	Incidental	Incidental
·d to obtain density	Mechanical tampers	Incidental	Incidental
	Mechanical tampers	Incidental	-
·d for compaction	By rolling or by hand, or by mechanical tamping and/or rolling.	Incidental	Incidental
te compaction	Mechanical tampers	Incidental	Incidental
) T 180	Not specified	Incidental	Incidental
ed	Mechanical tampers	Incidental	M gallons
ıum	Mechanical tampers	Incidental	M gallons
uniformly sufficient for proper on.	Mechanical and/or pneumatic tamping devices or rolling	Roller hours	M gallons
or material used	Contractors choice	cu yd	Incidental
·d for compaction	Approved power driven tampers	cu yd	M gallons
d by the engineer	Mechanical or hand tamping	Incidental	Incidental
·d by the engineer	Mechanical tamping equipment	Hours rolling	M gallons
n	Mech. tampers, min. 700 blows/min. Tamper head area 19 to 29 sq in., min. blow 1.75 ft lb/sq in.	Per hr of Mech.-tamping	M gallons
ır Embankments	Hand or mech. tampers 6-in. diam. head. Int. combustion and vibratory when results are satisfactory	-	-
ıy engineer	Air tampers in small areas, otherwise selection of equip. is up to contractor.	cu yd	M gallons
to obtain compaction	Not specified	Incidental	Furnish water Equip. and M gal.
ıed	Machine operated tampers of approved design.	Incidental	Incidental
ıed	Air or mech. tampers with total foot area 19 to 29 sq in. or gasoline driven 59 to 85 sq in. 19 - 29 = 1 unit. 59 - 85 = 1½ units.	Tamper hr	Incidental
or dried as needed	Mechanical tampers	Incidental	Furnish water Equip. and M gal.
AASHO T 180	Contractors option	Incidental	Sprinkling

SPECIFICATION REQUIREMENTS FOR TAMPING-(SHEEPS

	Diameter of Drums (in.)	Width of Drums (in.)	Minimum Number of Feet per Drum	Number of Feet per Row	Minimum Spacing of Feet (in. center to center)	Size of Tamping Feet Minimum Contact	
						Length (in.)	Area (sq in.)
Northeast							
Connecticut, Std. Specif. January 1955	-	-	-	-	-	-	-
Maine, Suppl. Specif. 1960	60	60	-	-	-	8	-
Massachusetts, Spec. Prov. SP 52 - 59	-	-	-	-	-[1]	7	5 min.
SP 52 - 58	-	-	-	-	-	7	7 max
Michigan, Std. Specif. May 1960	-	-	-	-	-	-	-
New Hampshire, Std. Specif. July 1, 1956	-	-	-	-	-	-	-
New York, Std. Specif. January 2, 1957	-	-	-	-	-	7	5 min.
Rhode Island, Std. Specif. Revision of 1946	-	-	-	-	-	-	-
Vermont, Std. Specif. January 1956	-	-	-	-	-	7	5 min.
Wisconsin, Std. Edition of Specif. 1957	-	-	-	-	-	-	-
Middle East							
Delaware, Std. Specif. April 1, 1957	-	-	-	-	-	7	4 - 12
District of Columbia, Std. Specif. 1957	-	-	-	-	8	7	5 - 12
Illinois, Std. Specif. Jan. 1958 and Spec. Prov.	-	-	-	-	-	-	-
Indiana, Std. Specif. 1960	-	-	-	-	-	7	5½
Kentucky, Std. Ed. of Specif. 1956	-	-	-	-	-	7	5 min.
Maryland, Std. Specif. 1960 Requirements	48 min.	-	-	-	-	7	4 - 12
New Jersey, Prelim. to New Rev. of Std. Specif.	-	-	-	-	-	6½	-
Ohio, Std. Specif. January 1, 1959	The weights and dimensions of the rolling units, number, spacing and						
Pennsylvania, Std. Specif. 1954	-	-	-	-	-	-	-
Tennessee, Std. Specif. July 1, 1951	-	42 min.	-	-	6 - 10	7	4 - 8
Virginia, Std. Specif. 1958	-	-	-	-	-	-	-
West Virginia, Std. Specif. 1952	-	48 min.	-	-	-	7	-
Interstate Provisions	-	-	-	-	-	-	-
Southeast							
Alabama, Std. Specif. 1950	-	-	-	-	2 per 1.3 sq ft	7	5 min.
Florida, Std. Specif. April 1, 1959	-	-	-	-	-	-	-
Georgia, Std. Specif. May 1, 1956	-	-	-	-	-	-	-
Mississippi, Std. Specif. Edition of 1956	-	-	-	-	6 - 12	7	4 - 10
North Carolina, Std. Specif. October 1, 1952	-	-	-	-	2 per sq ft	7	4 - 9
South Carolina, Std. Specif. for Hwy. Constr. Nov. 1, 1955	-	-	-	-	-	-	-
South Central							
Arkansas, Std. Specif. Ed. of 1959	-	-	-	-	-	-	-
Louisiana, Std. Specif. July 1955	-	-	-	-	-	-	-
Oklahoma, Std. Specif. Ed. of 1959	-	-	-	-	-	-	-
Texas, Std. Specif. 1951	40 min.	42 min.	-	-	6 - 10	7	5 - 8
	60 min.	60 min.	-	-	-[1]	7	6 - 8
North Central							
Iowa, Std. Specif. 1960	-	-	-	-	-	6½	-
Kansas, Std. Ed. of Specif. 1955	-	-	-	-	6 - 12	7	4 - 12
Minnesota, Specif. 2110, 9-10-57	-	-	-	-	-	-	-
Specif. 2110, 5-1 -59	-	-	-	-	-	-	-
Missouri, Std. Edition of 1955 Suppl. Spec. June 1, 1958	Any type of compaction equipment will be permitted provided its clearly well as that required in Sect. 1-32 (Std. Specif.)						
Nebraska, Std. Series of Specif. 1955	-	-	-	-	6 - 10	7	4 - 12
North Dakota, Std. Specif. January 1956	-	-	-	-	-	-	-
South Dakota, Std. Specif. April 1957	60 min.	60 min.	120 min.	4 min.	-	6	4 - 8
Mountain							
Arizona, Tentative Std. Specif. for 1959	-	60 min.	-	-	-	7	5.5 - 8
Colorado, Spec. Prov. "Wetting and Compaction" Std. 3-13-56 and Spec. Prov. "Wetting and Compaction" Modified 3-14-56.	The contractor may use any type of compaction equipment he may deem						
Idaho, Std. Specif. Edition of 1957	-	-	-	-	-	-	-
Montana, Revised Std. Specif. 1959	-	-	-	-	-	-	8
Nevada, Tent. Std. Specs. for Road and Bridge Const. 1957 Edition	40	48 min.	88	-	-	7	5.4
New Mexico, Std. Specif. Edition of 1954	60 min.	60 min.	112 min.	-	13[1]	7	5 - 8
Utah, Std. Edition of Specif. 1960	2 drums min.	2 drums min.	160 min. 240 max.	-[1]	-	7	6 - 8
Wyoming, Std. Specif. Edition of 1960	-	-	-	-	-	-	-
Pacific							
California, Std. Specif. January 1960	-	-	-	-	-	-	-
Oregon, Std. Specif. May 1, 1954	36 min.	72 max.	-	-	6 - 19	7	4 - 9
Washington, Std. Specif. 1957	-	-	-	-	-	-	-
Alaska, (Current Specif.)	60 min.	54 min.	-	-	-[1]	7	5½ - 8
Hawaii, (Current Specif.)	-	-	-	-	-	-	-

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[*] Measured in excavation.

TABLE 51

FOOT) TYPE ROLLERS FOR EMBANKMENT CONSTRUCTION

Pressure by Tamping Feet (psi)	Operating Speed (mph)	Capacity (max cu yd per unit per hour)	Remarks
-	-	-	Not specified
500 min.	-	-	3,400 lb per lin. ft
450[2]	2.5	-	[1]Min. of two tamping feet for each square foot of cylinder surface.
-	2.5	-	[2]With drum ballasted.
-	-	-	Not specified
-	-	-	Not specified
200 - 450	-	-	-
-	-	-	Not specified but permitted
200 - 450	-	-	-
150 min.	-	-	-
-	-	-	The weight, and dimensions of the rolling units, the number, spacing and dimensions of the tamping feet shall be such that specified compaction may be obtained.
200 min.[1]	-	-	[1]Fully loaded
-	-	-	No roller requirements
-	-	-	Approved by the engineer
200 - 450	8 max	200 max[1]	[1]Applies only to standard compaction
Up to 200	5 max	-	-
200 min.	-	-	-
dimensions of the tamping feet shall be such that the specified compaction may be obtained.			
250 min.	-	-	-
200 min.	2 - 3	100	-
-	-	-	Not specified
150 min.	-	-	-
-	-	-	Any approved type of equipment
200 min.	-	-	-
-	-	-	Details of equipment not specified
-	-	-	Not specified
200 min.	-	-	-
200 min.	-	-	-
-	-	-	Not specified
-	-	-	Not specified
-	-	-	Not specified
-	-	-	No requirement on type of equipment except on 50-ton test roller.
125 - 175	2 - 3	-	Item rolling (tamping)
Up to 550	2 - 3	-	Item rolling (heavy tamping)[1] one tamping foot for each 0.65 to 0.7 sq ft of drum area
200 min.	-	-	-
200 min.	-	-	-
200 min.	-	-	-
200 min.	-	-	-
100 min.[1]			[1]Also specifies min. weight of 90 lb per in. of width of drum.
demonstrated by past performance and performance on the project involved, that such equipment will perform equally as			
200 min.	-	-	-
150 min.[1]	-	-	[1]Item unchanged as of March 1, 1960
300[1] - 550[1]	3 - 5	-	[1]300 empty, 550 ready for use
min. 3,000[1]	min. 2.5	200	[1]Min. 3,000 lb on each tamping foot
necessary to obtain the specified density.			
-	-	-	Contractor selects means for obtaining density.
300 min.	-	-	-
105 min.	3 min.	300[1] *	[1]Combination of tamping roller and pneumatic-tired roller.
		400[2] *	[2]Combination of two tamping rollers.
300 - 500	3½ min.	-	[1]Circumferential row.
325 min.	200 - 300[2]	-	[1]At least 20 rows, 8 to 12 ft per row. [2]Feet per minute.
-	-	-	No restrictions on roller rating
-	-	-	Not specified
150 min.	-	-	Specified under Spec. conditions. Den. requirements cont. use of compaction Equip.
-	-	-	Not specified
250 - 500	min. 5	-	[1]Max 12 in. diagonal spacing c. to c. to feet in adjacent circumferential rows.
-	-	-	Equipment left to contractor's option.

TABLE

SPECIFICATION REQUIREMENTS FOR PNEUMATIC-TIRE ROLL

Region and State	Type	Rolling Width (in.)	Gross Weight (tons)	Operating Weight per Tire (lb)	(lb in. w tire
Northeast					
Connecticut, Std. Specif. January 1955	-	-	-	-	
Maine, Suppl. Specif. 1960	Super compactor	-	50	-	1,
Suppl. Specif. 1960	Pneumatic-tire truck type	60	-	-	2
Suppl. Specif. 1960	Rubber tire or constr. equipment	-	-	25,000 min.	
Massachusetts, Std. Specif. 1953	-	-	-	-	
Michigan, Std. Specif. May 1960	4 wheeled	-	25 - 50	-	
New Hampshire, Std. Specif. July 1, 1954	-	-	-	-	
New York, Std. Specif. January 2, 1957	-	-	-	1,000 - 2,500	
Rhode Island, Std. Specif. Rev. of 1946	-	-	-	-	
Vermont, General Spec. Prov. Feb. 9, 1960	-	-	-	1,000 - 2,500	
Wisconsin, Std. Edition of Specif. 1957	-	-	-	-	
Middle East					
Delaware, Std. Specif. April 1, 1957	Single or multiple axle	-	-	-	3
District of Columbia, Std. Specif. 1957	Multiple wheel	-	-	-	20
Illinois, Std. Specif. January 1958 and Spec. Prov.	Min. 9 tires on 2 axles	-	-	-	
Indiana, Std. Specif. 1957	9 wheels, 2 axles	-	-	-	2
Special Projects	4 wheel tires spaced 32 in.	-	50	6,000 - 25,000	
				-	
	2 axle	66	20 - 35	-	
Kentucky, Std. Ed. of Specif. 1956	-	-	-	-	400
Maryland, Std. Specif. 1960 requirements	2 axle, 9 wheel	-	10 min.	-	up
	Single axle, 4 wheel	-	up to 50	5,000 - 25,000	up
	2 axle	-	-	at least 4,500	
New Jersey, Preliminary to new Rev. of Std. Specif.	Light weight type	-	-	-	22'
	Heavy compactor	-	up to 50	min. 25,000^1	
Ohio, Std. Specif. January 1, 1959	The weight of the roller, number and spacing of tires, shall be such that the vary more than 5 psi.				
Pennsylvania, Std. Specif. 1954	-	-	-	1,000 min.	
Tennessee, Std. Specif. July 1, 1951	2 axle, min. 7 wheel	-	8 min.	-	
Virginia, Std. Specif. 1958	-	-	-	-	
West Virginia, Std. Specif. 1952	Single or double axle	The weight, dimensions of the roller, nur			
Southeast					
Alabama, Std. Specif. 1950	2 axle	60 min.	-	-	32
Florida, Std. Specif. April 1, 1959	-	-	-	-	
Georgia, Std. Specif. May 1, 1956	-	-	-	-	
Mississippi, Std. Specif. Edition of 1956	2 axle, 7 wheels or more	-	8 min.	-	
North Carolina, Std. Specif. Oct. 1 1952	2 axle	Approx. 60	-	-	32
South Carolina, Std. Specif. for Hwy Constr. Nov. 1, 1955	-	-	-	-	
South Central					
Arkansas, Std. Specif. Ed. of 1959	-	-	-	-	
Louisiana, Std. Specif. July 1955	-	-	-	-	
Oklahoma, Std. Edition of Specif. 1959	-	-	-	-	
(Section 203—Test Rolling)	Min. 4 wheels	-	-	up to 25,000	
Texas, Std. Specif. 1951	2 axle, min. 9 wheel	Approx. 60	-	-	100
North Central					
Iowa, Std. Specif. Series of 1960	-	-	-	-	
Kansas, Std. Edition of Specif. 1955	Multiple wheel	-	-	-	22
Minnesota, Specif. 2110, 9-10-57 and 5-1-59	-	-	-	-	
Missouri, Suppl. Specif. June 1, 1957	-	-	-	-	
Nebraska, Std. Series of Specif. 1955	2 axle multiple wheel	-	-	-	
North Dakota, Std. Specif. 1960	-	-	-	-	
South Dakota, Std. Specif. April 1, 1957	-	-	-	-	
Mountain					
Arizona, Tentative Std. Specif. for 1959	2 axle tandem, min. 9 wheels	60	-	1,400 min.	
The above Specif. may be changed soon to	2 axle tandem	60	-	2,000	
Colorado, Spec. Prov. 3-13-56 and 3-14-56	The contractor may use any type of compaction equipment he may deem nec				
Idaho, Std. Specif. Edition of 1957	-	-	-	-	
Montana, Std. Rev. Specif. 1959	-	48 min.	-	-	25
Nevada, Tent. Std. Specs. for Road and Bridge Constr. 1959 Ed.	2 axle, min. 9 wheels	60 min.	-	285 - 2,000	
New Mexico, Std. Specif. Ed. of 1954	2 axle, min. 9 wheel	60 min.	-	1,000 - 2,000	
	4 wheel, 50 ton	84 min.	30 - 60^1	-	
Utah Std. Edition of Specif. 1960	4 wheel	-	50	-	
Wyoming, Std. Specif. Edition of 1960	-	-	-	-	
Pacific					
California, Std. Specif. January 1960	-	-	-	-	
Oregon, Std. Specif. May 1, 1954	Multiple axle, multiple wheel	No limit	-	-	150
Washington, Std. Specif. 1957	-	-	-	-	
Alaska, Current Specif.	2 axle	60 min.	-	1,000 - 2,000	
Hawaii, Current Specif.	-	-	-	-	

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*Combination of tamping roller and pneumatic-tire roller.

52

RS FOR EMBANKMENT CONSTRUCTION AND/OR TESTING

Load					
er idth of tread)	(lb per in. width of roller)	Inflation Pressure (psi)	Operating Speed	Capacity (max cu yd per unit per hour)	Remarks
-	-	-	-	-	Not specified
000	-	-	-	-	-
00	2,500	-	-	-	-
r	→	150	-	-	Test rolling
-	-	-	-	-	Not specified
-	-	50 - 90	2.5 - 5	-	Required for test rolling the grade only. Not required for comp. of Emb.
-	-	-	-	-	Not specified
-	-	-	-	-	-
-	-	-	-	-	Not specified but permitted
-	-	-	-	-	-
-	150 min.	-	-	-	-
00[1]	-	-	-	-	[1]Contact on hard surface
min.	-	45 min.	-	-	-
-	-	-	-	-	Not specified
00	-	-	-	-	Towed or self-propelled
-	-	90 - 150	-	-	Used on special projects and/or testing or supplementing compaction of subgrade covered by special provision.
-	-	60 - 90	-	-	Self-propelled
- 600	-	-	8 max	200 max[1]	[1]Applies only to standard compaction
to 300	-	30 min.	10 max	-	-
to 1,200	-	90 min.	5 max	-	-
-	-	90 min.	5 max	-	Same roller required for bituminous concrete and base course
min.	-	-	-	-	-
-	-	90 min.[1]	-	-	At maximum or full load
pecified compaction will be obtained. Tires shall be of equal size and inflated so air pressure from tire to tire shall not					
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	Not specified
iber and spacing of the tires shall be such that the specified compaction may be obtained.					
min.	-	-	-	-	No change to March 3, 1960
-	-	-	-	-	Not specified
-	-	-	-	-	Not specified
-	-	-	-	-	-
min.	-	-	-	-	-
-	-	-	-	-	Not specified
-	-	-	-	-	Not specified
-	-	-	-	-	Not specified
-	-	-	-	-	Not specified
-	-	90 - 150	-	-	For test rolling
- 325	-	-[1]	2 - 6	-	[1]As directed by the engineer
-	-	-	-	-	Not specified
5 min.	-	45 min.	-	-	-
-	200 min.	-			For "Ordinary Compaction" No. of passes, lift specified, or on lifts of 3 in. or less where tamping type roller will not produce further compaction.
-	-	-	-	-	Not specified
00	-	25 min.	-	-	-
-	-	-	-	-	Not specified
-	-	-	-	-	Not specified
-	-	-[1]	5	125	[1]Uniformly inflated ± 5 psi difference between tires.
-	-	90	5	125	
ssary to obtain the specified density.					
-	-	-	-	-	Not specified
min.	-	-	-	-	Not specified
-	43 - 300	-[1]	-	300*	[1]Tire mfr. recommendations with not more than 5 psi variation in any tire.
-	-	-	4 min.	-	-
-	-	60 - 90	2 - 5	-	Shall be designed so full weight can be applied to two outside wheels for proof-testing surfaces with 15 to 20 ton wheel loads.
-	-	90 min.	3 min.	-	-
-	-	-	-	-	Not specified
-	-	-	-	-	Not specified
- 350	-	-	-	-	Specified under special conditions. Density requirement controls the use of compaction equipment.
-	-	-	-	-	Not specified
-	-	Tolerance ± 5 psi	5 min.	-	-
-	-	-	-	-	Not specified

TABL

SPECIFICATION REQUIREMENTS FOR SMOOTH-WHEEL

State and Region	Tandem Type		3-Wheel Type		
	Weight (tons)	Pressure (lb per in. width of roll)	Weight (tons)	Diam. of Drive Rolls (in.)	Width c Drive Rol (in.)
Northeast					
Connecticut, Std. Specif. January 1955	-	-	-	-	-
Maine, Std. Specif. 1960	-	-	-	-	-
Massachusetts, Std. Specif. 1953	-	-	12 min.	-	-
Michigan, Std. Specif. May 1960	-	-	-	-	-
New Hampshire, Std. Specif. July 1, 1954	-	-	-	-	-
New York, Std. Specif. January 2, 1957	-	-	-	-	-
Rhode Island, Std. Specif. Rev. of 1946	-	-	10 ton	-	-
Vermont, Std. Specif. January 1956	-	-	-	-	-
Wisconsin, Std. Edition of Specif. 1957	-	-	-	-	-
Middle East					
Delaware, Std. Specif. April 1, 1957	-	-	-	-	-
District of Columbia, Std. Specif. 1957	-	-	10 min.	68 min.[1]	20 min.
Illinois, Std. Specif. January 1958 and Spec. Provisions	-	-	-	-	-
Indiana, Std. Specif. 1960	-	-	10 min.	-	-
Kentucky, Std. Edition of Specif. 1956	-	-	-	-	-
Maryland, Std. Specif. (1960 requirements)	-	-	10 min.	-	-
New Jersey, Prelim. to New Revision of Std. Specif.	-	-	10 min.	-	-
Ohio, Std. Specif. January 1, 1959	-	-	10 min.	68 min.[1]	18 min.
Pennsylvania, Std. Specif. 1959	10 min.	330[1]	10 min.	-	-
Tennessee, Std. Specif. July 1, 1951	-	-	-	-	-
Virginia, Std. Specif. 1958	-	-	-	-	-
West Virginia, Std. Specif. 1952	-	-	10 min.	-	-
Southeast					
Alabama, Std. Specif. 1950	-	-	10 min.	-	-
Florida, Std. Specif. April 1, 1959	-	-	-	-	-
Georgia, Std. Specif. May 1, 1956	-	-	-	-	-
Mississippi, Std. Specif. Edition of 1956	-	-	-	-	-
North Carolina, Std. Specif. October 1, 1952	10	-	10.	-	-
South Carolina, Std. Specif. for Hwy. Constr. Nov. 1, 1955	-	-	-	-	-
South Central					
Arkansas, Std. Specif. Edition of 1959	-	-	-	-	-
Louisiana, Std. Specif. July 1955	-	-	-	-	-
Oklahoma, Std. Edition of Specif. 1959	-	-	-	-	-
Texas, Std. Specif. 1951	-	-	10 min.	48 min.	20 min.
North Central					
Iowa, Std. Specif. 1960	-	-	-	-	-
Kansas, Std. Edition of Specif. 1955	-	-	-	-	-
Minnesota, Specif. 2110, May 1, 1959	No equipment requirements for "Compaction to specified densi to for compacting lifts 3 in. or less where tamping roller will				
Missouri, Std. Specif. Edition of 1955	-	-	-	-	-
Nebraska, Std. Series of Specif. 1955	-	-	-	-	18 - 24
North Dakota, Std. Specif. January 1956[1]	-	-	-	-	-
South Dakota, Std. Specif. April 1957	-	-	-	-	-
Mountain					
Arizona, Tentative Std. Specif. 1959	8 min.	-	12 min.	-	-
Colorado, Spec. Prov. March 13 and 14, 1956	The contractor may use any type of compaction equipment he				
Idaho, Std. Specif. of 1957	-	-	-	-	-
Montana, Std. Specif. 1959	-	-	-	-	-
Nevada, Tent. Std. Specs. for Road and Bridge Constr. 1959 Ed.	-	184[1]	10 min.	68 min.	24 min.
New Mexico, Std. Specif. Edition of 1954	-	-	-	-	-
Utah, Std. Specif. 1960	10 min.	300 min.	10 min.	-	-
Wyoming, Std. Specif. Edition of 1960	-	-	-	-	-
Pacific					
California, Std. Specif. January 1960	-	-	-	-	-
Oregon, Std. Specif. May 1, 1954	-	-	-	-	-
Washington, Std. Specif. 1957	-	-	-	-	-
Alaska, (Current Specification)	-	-	10 min.	-	-
Hawaii, (Current Specification)	-	-	-	-	-

E 53

POWER ROLLERS FOR EMBANKMENT CONSTRUCTION

f ls	Pressure (lb per in. width of drive roll)	Type Not Specified		Operating Speed (mph)	Capacity (max cu yd per unit per hour)	Remarks
		Weight (tons)	Pressure (lb per in. width of roll)			
	-	10 min.	-	-	-	-
	-	-	-	-	-	Not specified
	360 min.	-	-	Low and Intermed.	-	-
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	-	10 min.	-	-	-	-
	-	-	-	-	-	Distributing of hauling and rolling
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	-	10 min.	-	-	-	-
[1]	330 min.[1]	-	-	-	-	[1]Values are for 10-ton rollers
	-	-	-	-	-	Not specified
	-	-	-	-	-	-
	-	-	-	-	-	Not specified
	300 min.	-	-	3 max	-	-
	330 min.	-	-	-	-	-
[1]	340 min.[1]	-	-	2 max	-	[1]Data are for 10-ton weight rollers
	330 min.[1]	-	-	-	-	[1]"Per lineal inch of tread"
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified or recommended
	-	-	-	-	-	-
	-	-	-	-	-	No change (March 3, 1960)
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	330 min.	-	-	-	-	-
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	325 min.	-	-	2 - 3	-	Item "Rolling" (flat wheel)
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
ty." For "ordinary compaction roller (type not specified) having min. of 200 lb/in. width of roll may be used not produce an increase in density.						
	-	-	-	-	-	Not specified
	275 min.	-	-	-	-	-
	-	-	-	-	-	Not specified. [1]1956 Std. Specif. modified by Forms 49 and 49A, 1959
	-	-	-	-	-	Not specified
	-	-	-	-	-[1]	[1]Tandem 125, 3-wheel 200, grid 200
ay deem necessary to obtain the specified density.						Not specified
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	300 min.	-	-	-	-	[1]On drive roll
	-	-	-	-	-	Not specified
	300	-	-	3	-	-
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	-	-	-	-	-	Not specified
	325 min.	-	-	-	-	-
	-	-	-	-	-	Not specified

SPECIFICATION REQUIREMENTS FOR PNEUMATIC-TIRED AND SMOOT

Region and State	Type	Rolling Width (in.)	Gross Weight (tons)	Operating Weight per Tire (lb)	lb/in. of Width of Tire	lb/in. of Rolling Width	Inflation Pressure (psi)	Operating Speed (mph)	Capacity (max cu yd per unit per hr)
Northeast									
Connecticut Std. Specif. January 1955	-	-	-	-	-	-	-	-	-
Maine Std. Specif. Rev. of January 1956*	-	-	-	-	-	-	-	-	
Massachusetts Std. Specif. 1953 and May 1955 Amendment									
Michigan Std. Specif. May 1960	-	-	-	-	-	-	-	-	-
New Hampshire Std. Specif. July 1, 1954	-	-	-	-	-	-	-	-	-
New York Std. Specif. January 2, 1957	-	-	-	1,000-2,500	-	-	-	-	-
Rhode Island Std. Specif. Rev. of 1946	-	-	-	-	-	-	-	-	-
Vermont Std. Specif. January 1956	-	-	-	-	-	-	-	-	-
Wisconsin Std. Ed. of Specif. 1957	Rolling equipment shall be of sufficient weight and character to accomplish the requirements of the specifications.								
Middle East									
Delaware Std. Specif. April 1, 1957	Select borrow—same as embankment								
									Water-bour
District of Columbia Std. Specif. 1957	Mult. wh.	-	-	-	200 min.	-	45 min.	-	-
Illinois Std. Specif. January 1958	9-tire 2-axle	-	-	-	225 min.	-	-	-	-
Indiana Std. Specif. 1960	2-axle, 9-wh. min.	66 min.	-	-	200 max	-	-	-	-
Special projects	50-ton, 4-wh.	Tires spaced 32 in.	50	6,000-25,000	-	-	90 - 150	-	-
Kentucky Std. Ed. of Specif. 1956	2-axle, min. 9-wh.	-	-	1,000 min.	-	-	-	-	-
Maryland Std. Specif. 1957 or Special Provisions	*2-axle, 7 wh. min.	-	-	3,500-8,000	-	-	120 max	-	-
New Jersey Preliminary to new Rev. of Std. Specif.	Same as for embankment using pneumatic-tired rollers, pneumatic-tired 50-ton compactors, or dynamic (vibratory) compactor.								
Ohio Std. Specif. January 1, 1957	Weight of roller, number and spacing of tires shall be such that the specified compaction is obtained.								
Pennsylvania Std. Specif. 1959	-	-	-	1,000	-	-	-	-	-
Tennessee Std. Specif. July 1, 1951	2-axle min. 7-wh.	-	8 min	-	-	-	-	-	-
Virginia Std. Specif 1958	Any machine or combination of machines or equipment that will handle the material and complete the base meeting these specifications for spreading, moistening, mixing and compacting will be used on approval.								
West Virginia Std. Specif. 1952	-	-	-	-	-	-	-	-	-
Interstate Provisions	2-axle	60 min.	-	1,000-2,000	-	-	-	5 min.	100
Southeast									
Alabama Std. Specif. 1950*	2-axle	60 min.	-	-	325 min.	-	-	-	-
Florida Std. Specif. April 1, 1959	-	-	-	-	-	-	-	-	-
Georgia Std. Specif. May 1, 1956	Min. 9-wh.	-	2,500 min.	(To be loaded as directed)			-	-	-
Mississippi Std. Specif. Ed. of 1956	2-axle, min. 9-wh.	-	8 min.	-	-	-	-	-	-
North Carolina Std. Specif. Oct. 1, 1952	Same as for embankments for all types used. For granular base courses, vibratory equipment is replacing other types. Proof-rolling of bases with heavy pneumatic-tired equipment is specified by special provision all primary and interstate projects.								
South Carolina Std. Specif. 1956	-	-	-	-	-	-	-	-	-
South Central									
Arkansas Std. Specif. Ed. of 1959	Each course shall be compacted by any satisfactory method that will obtain the density herein specified								
Louisiana Std. Specif. July 1955	Rollers may be of any approved type or combination of types that will obtain the required compaction.								
Oklahoma Std. Ed. of Specif. 1959	2-axle	60	5 min.	-	-	-	-	3 - 8	-
Texas Std. Specif. 1951	2-axle, min. 9-wh.	Approx. 60	-	-	100-325	-	-	2 - 6	-
North Central									
Iowa Std. Specif. Series of 1960	*	-	-	-	-	200	60	-	-
Kansas Std. Ed. of Specif. 1955	-	-	-	-	225 min.	-	45 min.	-	-
Minnesota Specif 2201, 2202 May 1, 1959	-	-	-	-	-	-	-	-	-
Missouri Std. Ed. of Specif. 1955	Multi-wh.	-	-	-	200 min.	-	-	-	-
Nebraska Std Series of Specif. 1955	2-axle, multi-wh.	-	-	-	200	-	25 min.	-	-
North Dakota Special Prov. No. 9, March 1, 1956	-	-	5-10	-	225 min.	-	25 - 45	-	-
Spec. Prov. 40-B, Dec. 18, 1959	-	-	5-10	-	225 min.	-	40 - 90	3 max	-
South Dakota Std. Specif. April 1957	-	-	-	-	-	-	-	-	-
Mountain									
Arizona Tentative Std. Specif. 1959	2-axle tandem	60		1,400 min.			*	5	125
Colorado Std. Specif. (being revised)	Present standard specification permits contractor to use any type of equipment he deems necessary to obtain the specified density.								
Idaho Std Specif. Ed. of 1957	Min. 4 wh.	-	-	5,000 min	-	-	-	3 - 5	-
Montana Std. Revised Specif. 1959	2-axle	48 min.	-	-	250	-	-	-	-
Nevada Tent. Std. Specif. for Road and Bridge Constr. 1957 Ed.	9-wh. min.	60 min.	-	285-2,000	-	43-300	*	3 min.	100T/ft hr
New Mexico Std. Specif. Ed. of 1954	2-axle, min. 9-wh.	60 min.	-	1,000-2,000	-	-	-	4 min	-
Special Provision May 9, 1955	4-wh., 50-t.	84 min	30-50	-	-	-	60-90	2 - 5	-
Utah Std. Ed. of Specif. 1960	-	60 min.	-	6,000	-	-	60 min.	3 min.	-
Wyoming Std. Specif. Ed. of 1960	-	-	-	-	-	-	-	-	-
Proof-rolling for granular bases	30-60 t.	84 min.	50	30,000-60,000	-	-	150 min	Min 3	-
Pacific									
California Std. Specif. January 1960	Oscillating	48 max	Variable	Variable 2,000 max			90		
Oregon Std. Specif. May 1, 1954	Other than for crushed stone-type base course, the data given for embankment construction would apply.								
Washington Std. Specif. 1957	2-axle 4-wh. (16 in. min. width)	60-90	4-11 35-50	-	-	-	- 90 max	- Variable load compac	-
Alaska Current Specif.	2-axle	60 min.		1,000-2,000	-	-	Tolerance 5 psi	Min. 5	-
Hawaii									

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[1] A foot-hour is the net length of one lin foot of double-axle roller or tamping drum, measured along its axis, between the outer face of the tires or drum.

E 54

H-WHEEL POWER ROLLERS FOR COMPACTION OF GRANULAR BASES

Gross Weight (tons)	Load (lb/in. of width of drive roll)	Gross Weight (tons)	Load (lb/in. of width of drive roll)	Operating Speed (mph)	Capacity (max cu yd or tons or sq yd per unit per hour)	Remarks
-	-	10 min	-	-	200 sq yd	-
10	-	10	-	-	-	*No change 1960
	400 min.	12 min	400 min.	2.5	175 tons per 8-hr day (3-wh.)	8-hr day (3-wheel)
					350 tons per 8-hr day (tandem)	8-hr day (tandem)
-	-	-	-	-	-	Not specified
14 min.	315 min.	10 min	-	-	-	-
10 min.*	-	10 min.*	-	-	-	*Type not specified
-	-	10 min.	-	-	-	-
-	-	10 min.	-	-	-	10 min. on gravel subbase and crushed stone base
Select borrow—same as for embankment						
d macadam		10 min. or approved vibratory equipment				
-	-	10 min	330 min	-	-	-
6 - 10	200-325	6 - 10	200 - 325	-	-	Vibratory compaction permitted
10 min.	-	10 min	300	-	-	-
-	-	-	-	-	-	Used for testing and supplementary compaction
-	-	10 min.	-	-	-	-
5 - 10**	-	5 - 10**	-	-	-	*Heavy pneumatic-tired rollers used since March 1960 on gravel and stabilized soil aggregate bases and on subbases.
5 - 10**	-	5 - 10*	-	-	-	**Subbase 5 min., stab. soil sand-aggr., and gravel - 10 t. pl. mix stab. aggr. base, 8 t. min.
-	-	10 min.	300 min.	1.5	-	-
10 min.	330 min.	-	-	-	-	-
-	-	10	-	-	-	-
-	-	10 min.	-	-	-	-
-	-	10 min.	-	-	-	-
-	-	10 min.	(For stone or slag macadam)			*No change to March 3, 1960
-	-	-	-	-	-	Not specified
-	-	10 - 14*	-	-	-	*General purpose roller
-	-	-	-	-	-	-
-	-	-	-	-	-	Not specified
-	200 min.	-	200 min.	-	-	-
	-	10 min.	325 min.	2 - 3	-	-
	250	8	250	-	-	*Self-prop. or towed Other types permitted based on end results.
12	-	8 - 12	-	-	-	-
-	-	-	-	-	-	Not specified
min *	-	5 min.*	-	-	-	For finishing top course. Type not specified. *Soil aggregate
8 min.*	200 min.*	-	300 min *	-	-	
*10 min	-	-	-	-	-	-
5 - 8	Roller types not specified.			-	-	*Min. of one each "Large" 10-ton plus one each "light" 5-8 tons
-	200 min.*	-	-	-	-	*For final rolling of top surface. Type not specified.
8 min.		12 min.			Tandem 125 3-wheel 200	*Tolerance from tire to tire ± 5 psi.
						Not specified
-	-	-	-	3 - 5	-	
8 min.	-	10 min.	-	-	-	
-	184 min.	10 min.	300	-	-	*Tire mfr. recommendation
10 min.	325 min	10 min.	325 min	-	-	-
-	-	-	-	-	-	In general use. Supersedes standard specif.
10 min.	300	10 min.	-	200-300 fpm	-	-
-	-	-	-	-	-	Contractor may use any roller to handle compaction
-	-	-	-			
		12 min.	325 min.	For untreated bases the 3-wheel is specified but other types providing adequate compaction may be substituted. For cement-treated base, the 3-wh. type or its equivalent is specif. for breakdown rolling. Subsequent rolling by rubber tire equip		
-	-	10 min.	325 min.			
tor		Grid roller		Two or more drums on common shaft, drums 60 in diam. 30-in wide. Bars 1¼ - 1¾-in. diam. on 4½ - 5½-in. center. Openings between bars 3 in. - 4 in. Weight 30,000 lb min. Speed 4 mph min.		
-	-	Min 10	Min 325	-	-	
		12	325			Routing of hauling equipment supplemented by 3-wh. roller.

Manufacturers Suggested Compactor Tire Loads For Various Inflation Pressures

A STUDY of compactor tire contact pressures used in the past reveals that smooth-tread compactor tires were not capable of exerting pressures of the magnitude exerted by high-pressure truck tires. In order to prevent post construction compaction of asphaltic concrete surfaces by traffic loadings, there is need to compact the newly placed surfaces by the use of pneumatic-tired rollers capable of greater unit contact pressures than those previously available.

Meetings between representatives of the tire industry, manufacturers of compaction equipment, the bituminous pavement industry and highway engineers were held during 1959 for the purpose of determining, on the basis of present knowledge, the characteristics of pneumatic-tired compactors needed for adequately compacting asphalt pavements. Discussions also covered needs for compacting base courses, subgrades and embankments by pneumatic-tired compactors. As a result of the meetings, the Bureau of Public Roads requested the industry to prepare data showing suggested ranges of tire-inflation pressure—tire load relationships for tires for compactor vehicles. The industry, through the Tire and Rim Association, Inc., provided the tabulation of "Tire Loads at Various Inflation Pressures" given in Table 55. These data are for tires for compactor vehicles and are suggested for experimental practice.

In transmitting the data given in Table 55, The Tire and Rim Association stated that "For a given tire size and ply rating, that tire is recommended for use at any load-inflation combination shown on this table providing the tire load does not exceed the underscored maximum. In further explanation of the tabulation the following example is given: In an operation using 13.00 x 24 (18-ply rating) tires at a fixed load, but an inflation pressure varying from 35 to 100 psi, the maximum tire loading should be based on the tire rating at 35 psi which from the table is 9,400 lb."

Although the data in Table 55 were compiled principally for use in rolling asphalt pavements, they are useful in suggesting load-inflation pressure relationships for use in compacting embankments, subgrades and base courses. It has been shown previously in this bulletin that depth of compaction and degree of compaction of soils are dependent on the tire load and the contact pressure.

Data in Table 56 constitute a tabulation of approximate Tire Contact Pressure Ranges of the more commonly used compactor tires based on minimum and maximum loads and inflation pressures recommended by The Tire and Rim Association, Inc. These data were developed by the Bureau of Public Roads from compactor tire engineering data furnished by several tire manufacturers and are intended as average values for the ply ratings shown. In view of minor variations in tire design features, unit ground pressures for tires of different manufacturers may vary by ± 5 percent. For field compaction control, tire engineering data of the applicable tire manufacturer are recommended.

TABLE 55

TIRE LOADS[1] AT VARIOUS INFLATION PRESSURES: MAXIMUM SPEED 5 MPH
(The Tire and Rim Association, Inc., Experimental Practice—Tires for Compactor Vehicles)

Inflation (psi)	Tire Load (lb)							
	7.50-15[3]	7.50-15	9.00-20	13.00-24	16.00-21	18.00-25	21.00-25	30.00-33
35	2,860 (4)	2,940	5,020	9,400	13,120	18,800	24,000	49,500
40	3,090	3,190	5,420	10,180	14,200	20,300	26,000	53,500
45	3,310	3,420	5,810	10,900	15,200	21,800	27,800	57,300
50	3,520	3,640	6,180	11,600	16,190	23,200	29,600	61,000
55	3,740 (6)	3,840	6,540	12,270	17,130	24,500	31,400	64,400
60		4,040	6,870	12,900	18,000	25,800	33,000	67,800
65		4,240	7,200	13,510	18,890	27,050	34,600	71,000
70		4,440	7,530	14,100	19,700	28,300	36,100	74,200
75		4,610	7,830 (10)	14,700	20,500	29,400	37,600	77,200
80		4,790	8,130	15,240	21,300	30,500	39,000	80,100
85		4,950	8,420	15,800	22,100	31,600	40,400	83,000
90		5,130 (10)	8,720 (12)	16,360	22,800	32,750	41,800	86,000
95		5,290	9,000	16,860	23,550	33,800 (24)	43,200	88,600
100		5,450	9,260	17,370 (18)	24,250	34,800	44,500	91,400
105		5,620	9,550 (14)	17,900	25,000	35,800	45,700	94,000
110		5,770 (12)	9,800	18,400	25,660	36,800	47,000	96,500
115		5,920	10,060	18,870	26,300	37,800	48,300	99,000
120		6,070	10,310 (16)	19,350	27,000	38,800	49,500	101,600
125		6,210 (14)		19,800 (22)	27,700 (28)	39,650 (32)	50,700	104,000
130				20,300	28,300	40,600	51,900	106,600
135				20,700	28,900	41,500	53,000	109,000
140				21,200	29,600	42,400	54,200	111,200
145				21,600	30,100	43,200	55,300	113,500
150				22,050 (26)	30,800	44,100	56,400 (44)	115,900 (64)
155					31,400	45,000 (40)		
160					31,950 (36)			

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[1] Numerals in parentheses are ply ratings; underscoring denotes maximum recommended loads for tire sizes and ply ratings shown.

[2] For inflations in excess of 100 psi, consult the rim supplier for rim strength and wheel design.

[3] "Light truck" rim.

TABLE 56

APPROXIMATE TIRE CONTACT PRESSURE RANGES FOR TIRE LOADS AT VARIOUS INFLATION PRESSURES; EXPERIMENTAL PRACTICE—TIRES FOR COMPACTOR VEHICLES
(As Recommended by Tire and Rim Association 2-18-60)

	Tire Load (lb)					
	7.50-15[1,2]	7.50-15[2]	9.00-20[2]	13.00-24[2]	16.00-21	18.00-25
Ply Rating	Contact Pressure[3] (psi)					
6	42 - 56	42 - 58	-	-	-	-
8	-	42 - 80	-	-	-	-
10	-	42 - 86	51 - 85	-	-	-
12	-	42 - 96	51 - 95	-	-	-
14	-	42 - 107	51 - 104	-	-	-
18	-	-	-	50 - 102	-	-
22	-	-	-	50 - 117	-	-
26	-	-	-	50 - 135	-	-
28	-	-	-	-	60[4] - 113	60[4] - 88
32	-	-	-	-	-	60[4] - 100
36	-	-	-	-	60[4] - 133	-
40	-	-	-	-	-	60[4] - 117

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[1] "Light truck" rim.

[2] Indicates available in smooth wide tread. For treaded tires, values shown are for gross contact areas.

[3] Average tire contact pressure on a flat surface.

[4] Data not available for 35 psi inflation. Values shown are for 50 psi inflation.

Note: Prepared by Division of Development, Bureau of Public Roads, from available tire engineering data.

Manufacturers Specifications For Compaction Equipment

THE RESULTS of the 1951-52 survey of available types and ratings of compactors as described by manufacturers specifications were included in an appendix in HRB Bulletin 58. A similar survey was repeated in early 1960 to make it possible to present similar data for this bulletin. Manufacturers were solicited individually by letter and requested to provide the information under the column headings shown in Tables 57 to 75 inclusive. Although it is possible that some manufacturers may have been unintentionally omitted, it is believed that the list is sufficiently complete to indicate the ranges in types and ratings of equipment currently available. However, several manufacturers indicated in their replies that they had under development, new types and ratings of compactors.

TABLE 57

MANUFACTURERS SPECIFICATIONS FOR TANDEM AND THREE-WHEEL TYPES OF SMOOTH-WHEEL STEEL ROLLERS

Manufacturer	Make and Model	Type 3-Wheel, Portable Tandem, and 2- and 3-Axle Tandem	Weight or Range of Weight (tons)	Dimensions of Rolls		Over-All Rolling Width (in)	Roller Compression (lb per lin in. of width of roll)					Range of Speed of Travel (mph)				Remarks
				Guide Roll Diam x Width (in)	Compression Roll Diam x Width (in)		Guide Roll Min	Guide Roll Max	Empty	Compression Roll With Water Ballast	Compression Roll With Wet Sand Ballast	Forward Max.	Forward Min.	Reverse Max	Reverse Min	
Austin-Western Aurora, Illinois	A-W T-33	Tandem	3⅛ - 6	32 x 40	48 x 42	42	67	89	101	154	207	4 46	1.13	4.46	1 13	Towing attachment available as option
	A-W T-53	Tandem	5 - 8	41 x 50	53 x 50	50	97	133	135	195	255	3.3	0 875	3.3	0 875	With 4-speed transmission max speed 5.6.
	A-W T-84	Tandem	8 - 12	48 x 54	60 x 54	54	118	184	187	268	348	3 72	0 99	3 72	0 99	With 4-speed transmission maximum speed 6.25
	A-W T-104	Tandem	10 - 14	48 x 54	60 x 54	54	118	184	254	335	416	3 72	0 99	3.72	0 99	
	A-W 3W-83	3-Wheel	8 - 11	41 x 40	60 x 18	67	127	162	315	366	412	3.73	0 99	3.73	0.99	With 4-speed transmission maximum speed 5.9.
	A-W 3W-102	3-Wheel	10 - 12	44 x 44	69 x 20	75	157	198	328	409	488	4.3	1.14	4 3	1.14	With 4-speed transmission maximum speed 6.77
	A-W 3W-122	3-Wheel	12 - 14	44 x 44	69 x 24	83	157	198	356	434	515	4 3	1 14	4 3	1.14	
																On all A-W rollers except T-33, 2-speed trans with torque converter std equip 4-sqeed with torque convt optional.
Bros, Incorporated Minneapolis, Minnesota	SP-Steel					54	75	175	140	270		11 5	1.85	11.5	1 85	
	Drum Roller		6 - 14	48 x 54	60 x 54											
Buffalo-Springfield Company Division of Koehring Company Springfield, Ohio	KT-7A	2-Axle	3 - 5	30 x 38	40 x 38	36	63	81	107	165	195	5 3	0 5	5.3	0.5	
	KT-8	2-Axle	4 - 6	30 x 38	40 x 38	38	79	96	138	196	226	5 3	0 5	5 3	0 5	
	KT-15A5	2-Axle	5 - 8	40 x 50	53 x 50	50	93	125	151	197		5 4	1 0	5 4	1.0	
	KT-15A6	2-Axle	6 - 9	40 x 50	53 x 50	50	93	125	165	227		5 4	1.0	5.4	1.0	
	KT-15A8	2-Axle	8 - 10	40 x 50	53 x 50	50	115	145	220	265		5 4	1 0	5.4	1 0	
	KT-19A8	2-Axle	8 - 12	48 x 54	60 x 54	54	126	173	186	269		5 6	1.0	5.6	1 0	
	KT-19A10	2-Axle	10 - 14	48 x 54	60 x 54	54	138	189	254	331		5 6	1.0	5.6	1.0	
	KT-16D	2-Axle	5 - 8	40 x 50	53 x 50	50	91	125	153	195		5.0	1 0	5.0	1 0	
	KT-17D	2-Axle	6 - 9	40 x 50	53 x 50	50	91	125	183	225		5 0	1 0	5 0	1.0	
	KT-24D	2-Axle	8 - 14	48 x 54	60 x 54	54	118	172	198	273	407	5 0	1 0	5 0	1.0	
	KT-25D	2-Axle	10 - 16	48 x 54	60 x 54	54	118	172	268	343	337	5.0	1 0	5 0	1.0	
	KX-25E	3-Axle	13 - 20	48 x 54	60 x 54	54	126	180	255	324	383	5 0	1 0	5.0	1 0	
	VM-31D	3-Wheel	10 - 14	44 x 44	69 x 20	6'-4"	141	178	368	435	502	5 0	1 5	5 0	1 5	
	VM-32D	3-Wheel	12 - 15	44 x 44	69 x 20	6'-4"	166	202	422	485	546	5 0	1 5	5 0	1.5	
Douglas Motors Corporation Milwaukee, Wisconsin	Western Duo Roll	2-axle tandem	1 64 - 2 02	20 x 28	24 x 32	32	-	-	100	-	-	-	-	-	-	-
	Western Econo Roll	2-axle tandem	0 68 - 1 01	20 x 28	24 x 32	32	-	-	46	-	-	-	-	-	-	-
	Western Redi Roll	2-axle tandem	0 021 - 0 50	18 x 24	24 x 24	24	-	-	31	-	-	-	-	-	-	-
Galion Iron Works and Manufacturing Company Galion, Ohio	Galion "Chief"	3-W-20"	10 - 12	44 x 44	69 x 20	76	143	192	345	435	-	6 0	0 5	6.0	0.5	Also available with cast (spoke type) rolls
	Galion "Chief"	3-W-24"	10 - 12	44 x 44	69 x 24	84	143	192	301	394	-	6.0	0 5	6 0	0 5	Also available with cast (spoke type) rolls
	Galion "Chief"	3-W-20"	12 - 14	44 x 44	69 x 20	76	143	192	444	518	-	6.0	0 5	6 0	0 5	Also available with cast (spoke type) rolls
	Galion "Chief"	3-W-24"	12 - 14	44 x 44	69 x 24	84	143	192	388	462	-	6.0	0 5	6 0	0 5	Also available with cast (spoke type) rolls
	Galion "Warrior"	3-W-20"	8 - 10	38 x 41	60 x 20	74	123	157	299	363	-	5 5	0 5	5.5	0.5	
	Galion 3-5 ton tandem	2-Axle	3 - 5	34 x 40	48 x 42	42	71	97	102	155	-	5.6	0 5	5 6	0 5	
	Galion 4-6 ton tandem	2-Axle	4 - 6	34 x 40	48 x 42	42	89	114	126	179	-	5 6	0 5	5.6	0 5	
	Galion 5-8 ton tandem	2-Axle	5 - 8	40 x 50	53 x 50	50	104	142	137	211	-	5.5	0 5	5 5	0 5	
	Galion 8-10½ ton tandem	2-Axle	8 - 10½	44 x 50	53 x 50	50	128	164	196	268	-	5 5	0.5	5.5	0 5	
	Galion 8-12 ton tandem	2-Axle	8 - 12	48 x 54	60 x 54	54	121	176	182	272	-	5 5	0 5	5.5	0.5	
	Galion 10-14 ton tandem	2-Axle	10 - 14	48 x 54	60 x 54	54	121	176	260	341	-	5 5	0 5	5.5	0 5	
	Galion 13-20 ton tandem	3-Axle	13 - 20	2-48 x 54	60 x 54	54	0	305	178	371	246/439	5.5	0 5	5.5	0 5	
Holt Equipment, Inc. Independence, Oregon	Holt R-1	2-axle tandem	0.375 - 0 992	18 x 24	24 x 24	24	-	-	-	74 - 128¹	-	2 13	-	-	-	¹With 2½ and 1¼ degrees of roll in contact, respectively.
	Holt R-2 - R-2H - R2HD	2-axle tandem	0 75 - 1.83	24 x 32	30 x 32	32	-	-	-	79 - 158¹	-	2 28	-	-	-	¹With 2½ and 1¼ degrees of roll in contact, respectively.
	Holt R-3 - R-3-D	2-axle tandem	1.27 - 2.72	30 x 34	40 x 34	34	-	-	-	101 - 202¹	-	2 34	-	-	-	¹With 2½ and 1¼ degrees of roll in contact, respectively
	Holt R-3A - R-3AD	2-axle tandem	2 11 - 3 29	30 x 34	40 x 34	34	-	-	-	130 - 260¹	-	2 34	-	-	-	¹With 2½ and 1¼ degrees of roll in contact, respectively
	Holt R-3ADH	2-axle tandem	2 11 - 3 29	30 x 34	40 x 34	34	-	-	-	130 - 260¹		3.50	2.25	-	-	¹With 2½ and 1¼ degrees of roll in contact, respectively
Huber-Warco Company Marion, Ohio	Huber-Warco															
	3-5 ton	Tandem	3 - 5	34 x 40	42 x 48	42	67	94	97	160	-	5.6	0 5	5 6	0 5	
	3-5 ton w/Tow Attach	Tandem	3 - 5	34 x 40	42 x 48	42	63	91	118	180	-	5 6	0 5	5 6	0 5	
	4-6 ton	Tandem	4 - 6	34 x 40	42 x 48	42	83	109	117	182	-	5.6	0 5	5 6	0.5	
	5-8 ton	Tandem	5 - 8	40 x 50	53 x 50	50	96	131	148	214	-	5.75	0 5	5 75	0.5	
	8-10 ton	Tandem	8 - 10	40 x 50	53 x 50	50	129	163	195	255	-	5 75	0.5	5 75	0 5	
	8-12 ton	Tandem	8 - 12	48 x 54	60 x 54	54	114	170	185	278	-	5 5	0.5	5 5	0.5	
	10-14 ton	Tandem	10-14	48 x 54	60 x 54	54	130	161	240	326	-	5 5	0.5	5 5	0.5	
	Huber-Warco															
	10 ton standard	3-Wheel	10 ton	44 x 44	69 x 20	76	146	-	343	-	-	5.75	0.4	5 75	0.4	
	12 ton standard	3-Wheel	12 ton	44 x 44	69 x 20	76	176	-	411	-	-	5 75	0 4	5 75	0.4	
	14 ton standard	3-Wheel	14 ton	44 x 44	69 x 20	76	205	-	479	-	-	5 75	0 4	5 75	0 4	
	10-12 ton variable weight	3-Wheel	10 - 12	44 x 44	69 x 20	76	144	187	349	418	-	5 75	0 4	5 75	0 4	
	12-14 ton variable weight	3-Wheel	12 - 14	44 x 44	69 x 20	76	144	187	427	491	-	5 75	0.4	5 75	0.4	
Littleford Bros , Inc. Cincinnatti, Ohio	125	2-Tandem	1	24 - 28	24 - 32	32	19	38	31	50	-	1¾	1¾	1¾	1¾	
	157	2-Tandem	2 - 3	24 - 32	36 - 34	36	52	63	68	108	-	1¼	1¼	1¼	1¼	
	160	2-Tandem	3 - 5	30 - 36	48 - 38	38	76	98	111	177	-	4	2	4	2	
Rosco Manufacturing Company Minneapolis, Minnesota	Rosco Rollpac	2-axle tandem	⅝ - 1	18 x 28	22 x 30	30	14	21	22	44	55	3	0	3	0	
	Rosco Sta-Pac	2-axle tandem	1 - 2	20 x 30	26 x 40	40	25	30	33	64	96	3.5	0	3 5	0	
Seaman-Andwall Corporation A Subsidiary of the American-Marietta Company Milwaukee, Wisconsin	Am Marietta-Model 500	Tandem	5 - 8	40 x 50	54 x 50	50	100	157	150	205	237	5.2	1	5.2	1	
	Am Marietta-Model 800	Tandem	8 - 12	48 x 54	60½ x 54	54	153	255	216	287	356	5.2	1	5 2	1	
Shovel Supply Company, Inc. Dallas, Texas	2-3 ton	Portable tandem	2 - 3	24 x 30	36 x 32	36	48	58	105	133	150	4.4	2.06	4 4	2 06	Also available in single speed
	3-5 ton	Portable tandem	3 - 5	33 x 40	48 x 42	48	71	102	102	152	187	4.2	1.9	4 2	1 9	With or without torque converter air-cooled or water-cooled engine, gasoline or diesel.
	4-6 ton	Portable tandem	4 - 6	33 x 40	48 x 42	48	89	117	129	181	214	4 2	1.9	4.2	1 9	With or without torque converter air-cooled or water-cooled engine, gasoline or diesel.
	5-8 ton	Tandem	5 - 8	40 x 50	53 x 50	50	85	125	150	220	290	4 5	1.0	4 5	1 0	Available with gasoline or diesel engine
	8-12 ton	Tandem	8 - 12	48 x 54	60 x 54	54	113	162	210	287		5.5	1 0	5.5	1.0	Available with gasoline or diesel engine

TABLE 58

MANUFACTURERS SPECIFICATIONS FOR VARIABLE-WEIGHT SINGLE-DRUM, TOWED-TYPE SMOOTH-WHEEL STEEL ROLLERS

		Type		Dimensions of Rolls			Roller Compression (lb per lin. in. of width of roll)					Range of Speed of Travel (mph)				
							Guide Roll		Compression Roll			Forward		Reverse		
Manufacturer	Make and Model	3-Wheel, Portable Tandem, and 2- and 3-Axle Tandem	Weight or Range of Weight (tons)	Guide Roll Diam. x Width (in.)	Compression Roll Diam. x Width (in.)	Over-All Rolling Width (in.)	Min.	Max	Empty	With Water Ballast	With Wet Sand Ballast	Max	Min.	Max	Min.	Remarks
Martin Company Kewanee, Ill.	Martin GraderrolleR Model GR-42H	Single smooth wheel attaching to rear of motor grader	5		24 x 42	42			28 without transferring weight from motor grader	250 obtained by transferring part of the weight of the motor grader to the roller		As fast as it is practical to travel with the motor grader when rolling.				The Martin GraderrolleR is an attachment for Caterpillar No. 14, 12, 112 and 212 motor graders. The model GR-42HG is designed to attach to other makes of motor graders.
	Martin Tiltable Patcher Model TP	Single smooth wheel roller attaching to rear of trucks	Max of 4¾ depends on wt. of truck		14 x 30	30			18 without transferring weight from truck	250 obtained by transferring part of the weight of the truck to the roller		As fast as it is practical to travel with the truck when rolling.				The Martin Tiltable Patcher is an attachment for all trucks.

TABLE 59

MANUFACTURERS SPECIFICATIONS FOR STEEL-WHEEL TRENCH ROLLERS

			Dimensions of Rolls			Range of Speed of Travel (mph)		
Manufacturer	Make and Model	Weight or Range of Weight (tons)	Diam. (in.)	Width (in.)	Roller Compression (lb per lin. in. width of roll)	Forward	Reverse	Remarks
The Galion Iron Works and Manufacturing Company	Galion Tr (Ballastable)	4.39	60	20	310 Metal Wt 370 Ballasted Wt.	1.5-3.5	1.5-3.5	1100 lb on steering pneumatic tire 1450 lb on adjusting tires (2)

TABLE 60

MANUFACTURERS SPECIFICATIONS FOR SEGMENTED WHEEL POWER ROLLERS

			Dimensions of Compacting Units					Weights and Pressures				Range of Speed of Travel (mph)		
					Pressure Pads			Gross Weight		Maximum[1] Contact Pressure on Pads				
Manufacturer	Make and Model	Over-All Rolling Width (in.)	Wheel Diam. (in.)	Wheel Width (in.)	Length (in.)	Width (in.)	Area (sq in.)	Empty (lb)	Fully Ballasted (lb)	Empty (psi)	Fully Ballasted (psi)	Forward	Reverse	Remarks
Buffalo-Springfield Company Division of Koehring Company Springfield, Ohio	Buffalo-Springfield K-45 Drive Roll	63⅛	69	31¾	13¼	5½								
								32,000	34,600 35,670*	580	627 647*	Infinite range from 1 mph to 5 mph		*Ballasted with calcium chloride
	Guide roll	40	69	23	11⅝	5½								
Wagner Tractor, Inc. Portland, Oregon	Wagner Compactor Model WC-16	Engine end 113 Bogie end 105	61⅛	27¼	10	4	40	50,000	50,000	104	104	0 - 20	0 - 20	

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[1] Method of computation: $P = \frac{GDW}{A}$. P = ground pressure per square inch. GDW = gross drum weight of one drum in pounds. A = total area of one lateral row of pads in square inches.

TABLE 61

MANUFACTURERS SPECIFICATIONS FOR SELF-PROPELLED AND TOWED GRATE-OR GRID-TYPE ROLLERS

			Data on Drums						Gross Weight per Drum or Wheel (lb)					
				Diameter		Width			Empty		Fully Ballasted			
Manufacturer	Make and Model	Over-All Rolling Width (in.)	No. of Drums	Drive Roll (in.)	Towed Roll (in.)	Drive Roll (in.)	Towed Roll (in.)	Size of Grids (in.) x (in.)	Towed Roller	Drive Wheels	Towed Roller	Drive Wheels	Range of Speed of Travel (mph)	Remarks
Hyster Company Portland, Oregon	Model D "Grid" Roller	76	2	-	67	-	32	3⅛ x 3⅛	6,200	-	15,112	-	up to 15	Towed by Cat. DW15 Tractor
H. H. Mundy Corporation Tulsa, Oklahoma	Mundy (EECo) Twin	70	2	-	64	-	32	1⅝ Diam.	6,200	-	20,000	-	0 - 20	Towed grate roller.

TABLE 62

MANUFACTURERS SPECIFICATIONS FOR TAMPING (SHEEPSFOOT) ROLLERS–TOWED TYPE

		Data on Drums			Data on Tamping Feet				Gross Weight of Roller (lb)			Maximum Contact Pressures[5] (psi)			
Manufacturer	Make and Model	No. of Drums	Width[1] (in.)	Diameter[2] (in.)	No. per Drum[3]	Area of One Foot (sq in.)	Length (in.)	No. of Feet on Ground[4]	Empty	With Water Ballast	With Wet Sand Ballast	Empty	With Water Ballast	With Wet Sand Ballast	Remarks
Bros, Inc. Minneapolis, Minn.	M2-5½	2	48	40	112	5½	7	8	6,075	9,940	13,820	138	226	314	
	M2-7	2	48	40	112	7	7	8	6,300	10,140	14,040	112	182	251	
	G2-8	2	60	60	112	7	8	8	15,000	26,000	36,200	268	465	647	
	G26-8	2	72	60	144	7	8	8	20,600	33,500	45,500	368	598	812	
	GR2-9¼T	2	60	60	120	7	9¼	8	20,500	31,200	41,100	366	557	734	
W.E. Grace Manufacturing Co., Dallas, Texas	P104	2	48	40	104	7	8	-	7,200	-	-	129	193	250	Wedge typ
	R-112	2	48	40	112	5.5	7.25	-	6,300	-	-	143	225	305	Sheepsfoo type
	4X5-95	2	48	60	95	7	8	-	13,500	-	-	241	391	650	Replaceab end feet
	5X5-120	2	60	60	120	7	8	-	15,000	-	-	264	455	640	Replaceab end feet
	6X5-136	2	72	60	136	7	8	-	16,250	-	-	290	523	750	Replaceab end feet
	5Y5-120	2	60	60	120	7	8	-	17,000	-	-	304	495	680	Wedge typ
	6Y5-136	2	72	60	136	7	8	-	18,500	-	-	330	563	780	Wedge typ
	5Z6-138	2	60	72	138	7	8	-	18,000	-	-	321	607	880	Wedge typ
	6Z6-148	2	72	72	148	7	8	-	20,000	-	-	357	706	1,030	Wedge typ
Koehring Co. of California, Stockton, Calif.	80	2	48	48	100	6.25	8	4	8,326	12,700	15,580	335	510	620	
	170	2	60	60	120	7	9	4	16,000	23,600	29,650	575	845	1,060	
	280	2	72	60	140	7	10	4	28,270	38,145	44,670	1,000	1,345	1,580	
	330	2	72	72	170	7	10	4	33,550	47,950	57,450	1,185	1,695	2,030	
LeTourneau-Westinghouse Co., Peoria, Ill.	L-W Model 120	2	60	60	120	7.07	8.75	4	17,700	29,360	40,070	626	1,035	1,420	
	L-W Model W	1, 2, 3, or 4	48	42	88	5.06	8	4 per drum	3,220	5,320	6,920	158	262	341	
Littleford Bros., Inc., Cinn., Ohio	1,760	2	48	40	88	6.5	7	8	6,350	10,550	16,044	122	203	309	
	4,840	2	48	40	105	7.07	8	4	8,194	12,014	15,844	290	425	549	
	6,060	2	60	60	120	7.07	8	4	19,020	29,948	41,020	680	1,070	1,466	
McCoy Co., Denver, Colo.	McCoy USHD-55	2	60	60	120	6 or 7	8¼	4	15,000	25,075	35,313	1,500	-	-	
	McCoy USHD-65	2	60	72	138	6 to 9	8¼ or 9¼	4	23,500	36,959	50,500	2,350	-	-	
Shovel Supply Co., Inc., Dallas, Texas	Ferguson towed 112	2	48	40	112	5.5	7	8	6,340	10,200	14,080	150	242	320	
	112W	2	48	40	112	5.5	8	8	9,500	12,575	16,340	216	286	371	
	112W 48	2	48	48	112	5.5	8	8	10,500	15,680	21,592	239	356	485	
	Ferguson-Gebhard 120	2	60	60	120	6.25	8	8	15,200	25,920	36,320	305	517	725	
	22	2	72	60	144	6.25	8	8	21,450	33,585	45,000	425	685	900	
Tampo Manufacturing Co., San Antonio, Texas	S-2	2	48	40	112	6	7	8	6,100	10,000	-	127	208	-	
	H-2	2	48	40	112	6	7	8	6,300	10,175	-	132	212	-	
	H2R	2	48	40	96	7	7	8	7,100	10,975	14,550	127	196	260	
	H2WL	2	48	40	96	7	7	8	6,550	10,425	13,950	116	185	250	
	H2WH	2	48	40	104	5½	7	8	6,750	-	14,500	150	240	330	
	H2I	2	48	40	88	5	8	8	6,230	10,100	-	116	252	-	
	H2O	2	60	40	112	6	7	8	6,630	-	15,870	138	238	330	
	502	2	60	60	120	6	7	8	14,400	-	34,080	300	515	710	
	502R	2	60	60	120	7	8	8	16,800	-	36,480	300	484	650	
	502WL	2	60	60	120	7	7	8	14,850	-	34,500	265	448	616	
	502X	2	60	60	120	6	9¼	8	21,600	-	41,000	450	665	855	
Yuba Consolidated Industries, Inc., Southwest Welding and Manufacturing Division, Alhambra, Calif.	Yuba-South-West 2DL-96R	2	48	40	96	6	7	8	5,600	9,250	13,140	116	192	273	
	2DL-96S	2	48	40	96	6	7	8	5,935	9,585	13,475	123	200	280	
	2DM-120R	2	60	60	120	6	8	8	14,000	24,375	34,750	291	507	723	
	2DM-120S	2	60	60	120	6	8	8	14,960	25,335	35,710	311	527	743	
	2DH-RR	2	60	60	120	7	9¼	4	20,300	30,010	40,450	725	1,071	1,444	
	2DH-WS	2	60	60	120	7	9¼	4	21,700	31,410	41,850	775	1,121	1,494	
	55-RR	2	60	60	120	7	9¼	4	23,000	32,710	43,150	812	1,168	1,541	
	55-WS	2	60	60	120	7	9¼	4	24,400	34,110	44,550	871	1,218	1,591	

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[1] Length of each drum. [2] Diameter without feet. [3] Number of feet shown is standard. Some manufacturers are prepared to furnish more or fewer feet and special shapes and sizes of tamper feet. [4] Number in one row multiplied by number of drums per unit; for example, two or three drums operating side by side. [5] Based on one row of feet in contact with ground. [6] All models can be furnished with feet with larger end areas if desired. All models except Model 112 can be equipped with replaceable caps on feet.

TABLE 63

MANUFACTURERS SPECIFICATIONS FOR TAMPING (SHEEPSFOOT) ROLLERS—SELF-PROPELLED TYPE

Manufacturer	Make and Model		Data on Drums			Data on Tamping Feet				Gross Weight of Roller (lb)			Maximum Contact Pressures[5] (psi)			Range of Speed of Travel (mph)				Remarks
			No of Drums	Width[1] (in)	Diameter[2] (in)	No per Drum[3]	Area (sq in)	Length (in)	No of Feet on Ground[4]	Empty	With Water Ballast	With Wet Sand Ballast	Empty	With Water Ballast	With Wet Sand Ballast	Forward Max	Forward Min	Reverse Max	Reverse Min	
American Steel Works Kansas City, Missouri	American	MD96	2	48	40	112	5 5	7	8	6,200	9,907	13,243	141	225	301	10	-	5	-	
		MB48	1	48	40	112	5 5	7	4	3,385	5,238	6,906	154	238	314	10	-	5	-	
		MDB96	2	48	40	88	5.5	7¼	8	6,585	10,292	13,628	150	234	310	10	-	5	-	
		MSB48	1	48	40	88	5 5	7¼	4	3,450	5,302	7,192	156	241	327	10	-	5	-	
		MT144	3	48	40	112	5 5	7	12	9,400	14,960	19,964	142	227	303	10	-	5	-	
		AD96	2	48	60	90	7	7	6	9,740	18,062	25,552	232	430	608	10	-	5	-	
		ADB96	2	48	60	90	5 5	7¼	6	10,730	19,052	26,542	325	577	804	10	-	5	-	
		AD120 - 5548	2	60	60	120	5 5	7¼	8	11,850	22,563	33,522	269	513	762	10	-	5	-	
		AD120 - 1149	2	60	60	120	7	7	8	10,550	21,283	32,222	188	380	575	10	-	5	-	
		ADB120	2	60	60	120	6 25	8	8	16,500	27,361	37,384	330	547	748	10	-	5	-	
		ADC120	2	60	60	120	6 25	8	8	18,860	29,718	39,741	377	594	795	20	-	8	-	
Bros, Incorporated Minneapolis, Minnesota		SP-3DT	3	60	60	112	9½	9¼	12	81,000	Do not ballast	Do not ballast	7,105	-	-	-	-	-	-	Self-propelled
R G LeTourneau, Inc Longview, Texas		M50-55	4	60	60	120	10	9	24	80,000	Not used	Not used	333	Not used	Not used	5	0	5	0	Self-propelled with diesel-electric power DC electric motor and gear reduction inside each drum Credited with two passes per trip. Seat and controls swivel for operation in either direction Eliminates turning on fill Electric drive permits infinite control of speed and power
Shovel Supply Company, Inc Dallas, Texas	Ferguson, Self-Propelled	SP-112W 48	2	48	48	112	5 6	8	8	16,350	21,660	27,500	263	378	510	5	1	5	1	
		SP-22	2	72	60	144	7 5	9¼	8	52,400	64,400	-	656	856	-	8	1	8	1	

[1] Length of each drum.

[2] Diameter without feet.

[3] Number of feet shown is standard Some manufacturers are prepared to furnish more or fewer feet and special shapes and sizes of tamper feet

[4] Number in one row multiplied by number of drums per unit, for example, two or three drums operating side by side

[5] Based on one row of feet in contact with ground

TABLE 64

MANUFACTURERS SPECIFICATIONS FOR SELF-PROPELLED AND TOWED HIGH-SPEED TAMPING ROLLERS

Manufacturer	Make and Model	Over-All Rolling Width (in)	Data on Drums					Data on Tamping Rollers				Weights per Wheel or Drum				Speed of Travel (mph)	Remarks
				Diameter		Width		Number of Feet Per Drum				Empty		Fully Ballasted			
			No of Drums	Drive Roll (in)	Towed Roll (in.)	Drive Roll (in.)	Towed Roll (in.)	Drive Roll	Towed Roll	Diameter of Rollers (in.)	Width of Rollers (in)	Drive Wheel (lb)	Towed Drum (lb)	Drive Wheel (lb)	Towed Drum (lb)		
Hyster Co , Portland, Oregon	DW20A Tamping compactor	122	4	53	53	32	32	90	90	67	32	11,575	6,300	22,340	18,250	Up to 15	
	Model D Tamping compactor	76	2	-	53	-	32	-	90	67	32	-	6,400	-	17,175	Up to 15	Towed by Cat. DW15 Tractor

TABLE 65

MANUFACTURERS SPECIFICATIONS FOR PNEUMATIC-TIRED ROLLERS—TOWED TYPE

		Gross Weight (lb)				Compaction Per Lin. In. of Roller Width (lb)			Tire Size and Inflation Pressure Data			No. of Wheels		Wheel Loads (lb)			Range of Speed of Travel (mph)	
										Recommended Tire Pressure				Weight Per Wheel (lb)[1]				
Manufacturer	Make and Model	Empty	With Water Ballast	With Wet Sand Ballast	Rolling Width (in.)	Empty	With Water Ballast	With Wet Sand Ballast	Tire Size and Ply (standard)	Max (psi)	Min. (psi)	Front	Rear	With Roller Empty	With Water Ballast	With Wet Sand Ballast	Forward	Reverse
Littleford Bros , Inc., Cinn., Ohio	9W40	2,500							7.50 x 15 x 4	28	24	4	5	278				
	13W80	3,400							7.50 x 15 x 4	28	24	6	7	262				
	50T4	20,000	100,000						18.00 x 25 x 20			4		5,000	25,000			
Rosco Manufacturing Co., Minn., Minn.	Rosco																	
	Cr-9	2,850	8,475	14,600	58½	49	145	250	7.50 x 15 x 4	35	30	4	5	316	941	1,622		
	Cr-13	3,700	11,200	19,300	84	44	133	230	7.50 x 15 x 4	35	30	6	7	285	861	1,485		
Shovel Supply Co., Inc., Dallas, Texas	Towed																	
	RT-900	2,950		20,700	68	44		306	7.50 x 15 x 4 and 6	36-55	25-25	4	5	328		2,300		
	RT-1100	3,630		25,300	83	44		306	7.50 x 15 x 4 and 6	36-55	25-25	5	6	330		2,300		
	RT-1300	3,900		29,900	88	44		306	7.50 x 15 x 4 and 6	36-55	25-25	6	7	330		2,300		
	RT-100-S	20,000		100,000	110	250		1,250	18.00 x 25 x 24 and 40	90-150	55-55	4 center		5,000		25,000		
Tampo Manufacturing Co., San Antonio, Texas	R-9	2,700		17,700	60	45		295	7.50 x 15 x 4	35	20	4	5	300		1,965	5-15	
	R-11	3,400		25,000	84	40		297	7.50 x 15 x 4	35	25	5	6	309		2,270	5-15	
	R-13	3,500		25,100	84	41		299	7.50 x 15 x 4	35	20	6	7	270		1,930	5-15	
	P1OA	3,700		18,950	84	44		226	7.50 x 15 x 4	35	20	4	6	370		1,895	5-15	
	50	19,000		100,000	114			1,250	18.00 x 25 x 24	95	50	4		4,750		25,000	To 5	
	56	19,700		112,000	114			1,250	18.00 x 25 x 24	95	50	4		4,750		25,000	To 5	
Yuba Consolidated Industries, Inc., Southwest Welding and Manufacturing Division, Alhambra, Calif.	SR-9	2,350	6,975	18,000	60	39	116	300	7.50 x 15 x 4	35	20	4	5	261	775	2,000		
	SR-13	3,150	9,900	26,000	84	37	117	309	7.50 x 15 x 4	35	20	6	7	242	761	2,000		
	C-25	13,850	27,600	48,170	86½	160	319	556	14.00 x 20 x 16	80	70		4	3,271	6,900	12,042		
	C-50	32,450	67,450	111,680	118	275	571	946	18.00 x 25 x 24	90	80		4	8,112	16,862	27,920		
	C-75	36,450	73,950	122,250	126	289	586	970	21.00 x 25 x 24	80	70		4	9,112	18,487	30,562		
	C-100	37,500	75,000	123,300	126	297	621	1,022	21.00 x 25 x 44	150	90		4	9,375	18,750	30,825		

[1] Wheel load is weight divided by number of wheels.

TABLE 66

MANUFACTURERS SPECIFICATIONS FOR PNEUMATIC-TIRED ROLLERS—SELF-PROPELLED TYPE

Manufacturer	Model	Gross Weight (lb)			Rolling Width (in)	Compaction per lin in of Roller Width (lb)			Tire Size and Inflation Pressure Data			No of Wheels		Wheel Loads (lb) Weight per Wheel (lb)[1]			Range of Speed of Travel (mph)	
		Empty	With Water Ballast	With Wet Sand Ballast		Empty	With Water Ballast	With Wet Sand Ballast	Tire Size and Ply (Standard)	Recommended Tire Pressure Max (psi)	Recommended Tire Pressure Min (psi)	Front	Rear	With Roller Empty	With Water Ballast	With Wet Sand Ballast	Forward	Reverse
American Steel Works	9W "Road Runner"	2,750	7,368	18,000	60	38	102	250	7.50 x 15 x 4	34	34	4	5	306	819	1,341	to 20	5
Kansas City, Missouri	13W "Road Runner"	3,700	10,814	26,000	86	36	104	250	7.50 x 15 x 4	34	34	6	7	285	832	2,000	to 20	5
	11WG "Road Runner"	8,300	16,850	26,000	84½	94	195	295	7 50 x 15 x 4	34	34	5	6	755	1,532	2,364	to 19	to 12
	4BW "Road Runner"	19,500	-	100,000	108	269	-	1,382	18 00 x 25 x 24	90	90	4 Center		4,875	-	25,000	to 20	5
Bros, Incorporated	R45 and R45W	2,300	6,855	11,425	62	37	110.5	184	7 50 x 15 x 4	34	25	4	5	255.5	761.6	1,269	15	-
Minneapolis, Minnesota	R67 and R67W	3,200	9,876	16,575	87	36 7	113.5	181	7 50 x 15 x 4	34	25	6	7	246	759	1,205	15	-
	450	17,160	80,403	104,028	108	153 3	744	963	18 00 x 25 x 24	90	70	4	0	4,290	20,100	26,007	5	-
	SP-54B	6,000	13,164	21,600	68	88 2	194	318	7 50 x 15 x 4	36	25	5	4	666 6	1,462	2,400	0 - 20	0 - 20
	SP-730B	22,150	36,800	60,000	85	260	433	706	13 00 x 24 x 18	100	30	3	4	3,164	5,257	8,571	0 - 16	0 - 16
Buffalo-Springfield Company	PSR-9	7,000	13,300	20,650	68	-	-	-	7 50 x 15 x 6	60	35	4	5	778	1,478	2,293	0 - 15	0 - 15
Division of Koehring Company	PSR-30	23,400	39,575	60,260	86	-	-	-	13.00 x 24 x 18	100	60	3	4	3,340	5,650	8,600	0 - 19.4	0-19 4
Springfield, Ohio																		
Douglas Motors Corporation	12SP	-	14,750	22,250[2]	68	-	220	332[2]	7 50 x 15 x 6	55	-	4	5	-	1,515	2,472[2]	0 - 16	0 - 16
Milwaukee, Wisconsin																		
The Galion Iron Works and	12-ton	9,000	18,000	24,750	60	125	250	344	7.50 x 15 x 4 (Optional)	35	-[3]	5	4	1,000	2,000	2,750	0 - 16	0 - 16
Manufacturing Company									7.50 x 15 x 6 (Optional)	55	-[3]							
Galion, Ohio									7.50 x 15 x 10 (Optional)	90	-[3]							
W.E. Grace Manufacturing Company	11H	6,500	-	21,000	84	77 3	-	250	7 50 x 15 x 4	35	28	5	6	590	-	1,990	1⅛ - 14	Same
Dallas, Texas	9H	6,000	18,000	20,000	68	88	264	295	7 50 x 15 x 6	45	30	4	5	666	2,000	2,222	1⅛ - 10	Same
	30B	20,000	-	60,000	88	226	-	681	13.00 x 24 x 18	100	60	3	4	2,857	-	7,571	2⅛ - 12	-
									13 00 x 24 x 36	150								
H H Mundy Corporation	9VV[4]	6,500	13,250	20,000	68	90	184	278	7 50 x 15 x 4	36	20	5	4	720	1,470	2,220	15	15
Tulsa, Oklahoma	11VV[4]	10,000	20,000	30,000	83	114	227	341	7.50 x 15 x 6	55	20	6	5	910	1,820	2,730	15	15
	13VV[4]	13,000	26,500	40,000	98	125	256	385	7.50 x 15 x 6	55	20	7	6	1,000	2,040	3,080	15	15
	11VVS	19,000	35,500	50,000	88	181	336	475	9 00 x 20 x 10	75	25	6	5	1,730	3,220	4,550	13.6	13.6
	13VVS	20,000	40,000	60,000	104	161	321	482	9 00 x 20 x 10	75	25	7	6	1,540	3,080	4,620	13 6	13.6
Rosco Manufacturing Company	SR-904	6,600	13,165	19,730	69½	95	189	284	7.50 x 15 x 4	35	30	5	4	733	1,463	2,192	2 6 to 14	4 1 to 14
Minneapolis, Minnesota	SR-9-T2	6,800	13,375	19,950	69	98½	193	289	7.50 x 15 x 4	35	30	5	4	755	1,486	2,216	0 to 15	0 to 15
Seaman-Andwall Corporation	5620	15,000	31,740	42,010	92	163	345	458	7 50 x 15 x 6	60	35	8	9	885	1,865	2,470	2.03 - 15.9	2 03 - 15.9
A Subsidiary of the American-Marietta Company																		
Milwaukee, Wisconsin																		
Shovel Supply Company, Inc.	Ferguson, Self-Propelled																	
Dallas, Texas																		
	SP-10	7,170	-	21,470	68	100	-	298	7 50 x 15 x 4, 6 and 10	36-55-95	25-25-25	4	5	797	-	2,385	2 to 12	2 to 12
	SP-12	8,600	-	24,800	83	98	-	282	7.50 x 15 x 4, 6 and 10	36-55-95	25-25-25	5	6	782	-	2,255	2.5 to 12	2 5 to 12
	2511	16,500	-	50,000	96	150	-	455	9.00 x 20 x 10-12 and 14	85-95-110	30-30-30	5	6	1,590	-	4,545	2 to 14.5	2 to 14 5
	3507	21,700	-	70,000	96	238	-	767	13.00 x 24 x 18-22	90-120	45-45	3	4	3,100	-	10,000	2.5 to 12	2 5 to 12
Tampo Manufacturing Company	SP91	6,700	12,330	20,000	72	26[5]	34[5]	40[5]	7.50 x 15 x 4	35	25	4	5	745	1,370	2,220	0 - 11	0 - 11
San Antonio, Texas	SP111	8,500	15,600	24,000	88	30[5]	49[5]	52[5]	7.50 x 15 x 6	55	25	5	6	775	1,420	2,180	0 - 20	0 - 20
	SP900	15,000	22,000	28,000	64	52[5]	80[5]	85[5]	7.50 x 15 x 10	100	40	4	5	1,660	2,450	3,110	0 - 20	0 - 20
	SP1030	20,000	39,250	60,200	94	47[5]	81[5]	90[5]	9 00 x 20 x 12	100	40	5	6	1,818	3,570	5,470	0 - 15	0 - 15
Yuba Consolidated Industries, Inc.	VP-11	8,020	14,582	22,000	84	95	173	261	7 50 x 15 x 6	55	20	6	5	729	1,325	2,000	0 - 15	0 - 15
Southwest Welding and Manufacturing Division	PR-11	11,000	19,437	29,720	84	131	231	353	7.50 x 15 x 10	90	20	5	6	1,000	1,767	2,701	0 - 13	0 - 13
Alhambra, California																		

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[1] Wheel load is weight divided by number of wheels. [2] When loaded with steel ballast compaction per in of rolling width is 358 lb, wheel load is 2,545 lb and gross wt is 24,000 lb. [3] Galion Mfg. Co.—Depends on speed and load. [4] Mundy Corporation—Models 9VV, 11VV and 13VV may be discontinued next year All models are present production design [5] Tampo Mfg Co —Compaction for self-propelled pneumatic rollers is shown in pounds per square inch of tire contact area

TABLE 67

MANUFACTURERS SPECIFICATIONS FOR TWO-AXLE AND THREE-AXLE TANDEM SELF-PROPELLED ROLLERS WITH VIBRATORY ROLL

				Dimensions of Rolls			Roller Compression[1] (static weight)(lb per in. of width of roll)			Vibration Characteristics		Range of Speed of Travel (mph)				
												Forward		Reverse		
Manufacturer	Make and Model	Type-Two- or Three-Axle	Weight or Range of Weight (tons)	Guide Roll Diam. x Width (in.)	Drive Roll Diam. x Width (in.)	Vibration Roll Diam. x Width (in.)	Guide Roll	Drive Roll	Vibration Roll	Frequency or Range of Frequency (cpm)	Range[2] of Amplitude (in)	Max	Min.	Max	Min	Remarks
	(All ABG)															
Allgemeine Baumaschinen-Gesellschaft (Combined Agencies Corp.), Washington, D C. (made in Germany)	LW "Micky"	2	1.2-1 4	24⅛ x 30¾		24⅛x30¾	28.6		43	4,000		1.9	0 7	1 9	0 7	
	MW	2	2.5-2.8	29 5x35 5		29 5x35 5	62		94	2,250 - 3,450		1.85	0.65	1.85	0 65	
	SW	2	4 2-4.5	33.5x39 5		33.5x39 5	72		145	2,400 - 3,400		2 6	0.55	2 8	0 57	
	Alexander	2	7.5-9 0	43 4x53.3		43.4x53 3	92		192	2,000 - 3,000		3 4	0.67	3 4	0 67	
Buffalo-Springfield Company Division of Koehring Company Springfield, Ohio	Buffalo-Springfield KX-25EV	3	15-20	48 x 54	60 x 54	48 x 54	180	383	217	2,000 to 2,100 for best results	0.080*	5 0	1.1	5.0	1 1	*Amplitude designated is the eccentricity of the eccentric axle.
Douglas Motors Corporation Milwaukee, Wisconsin	Western 2T-VR	2	1.2-1 77	24 x 36	20 x 28	24 x 36	-	-	-	1,150 - 1,500						Impact force = 8 tons dead weight
Littleford Bros , Inc., Cincinnati, Ohio	125-V	2	1-8	24-28		24-32	870		2,330	2,000	None fixed	1¾	1¾	1¾	1¾	
Rosco Manufacturing Company Minneapolis, Minn	Rosco Vibrapac	2	1¼-1¾	20 x 30		22 x 36*	37		69*	1,000 - 1,450	⅛ - ¼	1.7	0	1 7	0	*Also drive roll
Tampo Manufacturing Company San Antonio, Texas	VP-4	2	3¼	7.50x15 tires	39x42½	39x42½		125	125	1,100 - 2,200		3.5	1.75	3 5	1 75	Drive roll same as vibration roll (Centrifugal force = 6,800 lb)
Vibro-Plus Products, Inc , Stanhope, New Jersey	"Terrapac" CG10	2	1	19¾x19¾	29½x37½	29⅛x27⅛				1,500 - 2,000	1/32	1 8		1.8		

[1] Maximum ballasted weight if weight of roller is variable

[2] Amplitude varies with soil type, density, etc., and if resonance occurs. These values indicate range under average working conditions.

TABLE 68

MANUFACTURERS SPECIFICATIONS FOR COMBINATION PNEUMATIC-TIRED AND SMOOTH-WHEEL ROLLERS—SELF-PROPELLED AND TOWED TYPES

		Gross Weight (lb)				Compaction Per Lin. In. of Roller Width (lb)			Tire Size and Inflation Pressure Data			No. of Wheels		Wheel Loads (lb) Weight Per Wheel (lb)[1]			Range of Speed of Travel (mph)	
										Recommended Tire Pressure								
Manufacturer	Make and Model	Empty	With Water Ballast	With Wet Sand Ballast	Rolling Width (in)	Empty	With Water Ballast	With Wet Sand Ballast	Tire Size and Ply (standard)	Max (psi)	Min. (psi)	Front	Rear	With Roller Empty	With Water Ballast	With Wet Sand Ballast	Forward	Reverse
Seaman-Gunnison Corp., Milwaukee, Wis.	Seaman-Gunnison Self-propelled Duo-Pactor (combination rubber and steel) 7-20 DTR[1]	14,000	-	40,000	86	100	-	520	(rear) 7.50x15x10 (front) 15 x 26 x 10	105 30	35 12	2	8	1,040	-	4,180	¾ - 20	¾ - 5
	9-27 DTR[2]	18,000	-	54,000	86	100	-	595	(rear) 7.50x15x10 (front) 18.00x26x10	105 30	35 12	2	8	1,040	-	4,750	¾ - 20	¾ - 5
	10-30 RD[2]	20,000	-	60,000	89	115	-	700	(rear) 7 50x15x10 (front) 18 00x26x10	105 30	35 12	2	8	940	-	5,600	¾ - 20	¾ - 5
	Seaman-Gunnison Tow type compactor PT-86	4,000	-	28,000	86	62	-	430	7.50x15x10	105	35	Single axle	8	500	-	3,500	Tow type	

[1] Wheel load is weight divided by number of wheels.

[2] Operator controlled wheel loading by hydraulically variable wheel base

TABLE 69

MANUFACTURERS SPECIFICATIONS FOR COMBINATION OF 3-WHEEL-TYPE ROLLER AND MULTIPLE-UNIT PAN-TYPE[1] VIBRATORY AND IMPACT COMPACTORS[2]

Manufacturer	Make and Model	Over-All Width of Compacted Strip (in.)	Characteristics of Compacting Units: Number of Compacting Units	Weight of Individual Unit (lb)	Dimensions (in.) Width	Dimensions (in.) Depth	Frequency or Range of Frequency (cpm)	Range of Working Speed (fpm)	Range of Working Speed (mph)	Remarks
Austin-Western Aurora, Illinois	A-W RV-20	78	3	450	25½	26	2200 VPM	-	1	The RV-20 and RV-24 compactor units are attachments for our 3-wheel rollers—102 or 122 models—or any 3-wheel roller with hydraulic steering. Recommended working speed 1 mph but speed can be varied according to job.
	A-W RV-24	82¾	3	450	2-27⅞ 1-25½	26 26	2200 VPM	-	1	
The Galion Iron Works and Manufacturing Company Galion, Ohio	Galion 3-wheel roller with Jackson electric vibrator	85	3	400	28	24	4200	44 to 132	½ to 1½	
	Galion 503 motor grader with Jackson electric vibrator	121	4	400	30	24	4200	do	do	

[1] Also known in different geographical regions by the terms vibrating base-plate type, vibrating shoe type, vibrating pad type and vibrating sled type.

[2] Machines of variable frequency when operated at low frequencies are sometimes known as impact-type compactors.

TABLE 70

MANUFACTURERS SPECIFICATIONS FOR COMBINATION SELF-PROPELLED SMOOTH-WHEEL, STEEL, PNEUMATIC-TIRED AND VIBRATORY ROLLER

Manufacturer	Make and Model	Gross Weight of Roller Empty (lb)	Gross Weight of Roller Ballasted (lb)	Over-All Rolling Width (in.)	Steel Roll Unit: Dimensions Diam. (in.)	Dimensions Width (in.)	Maximum Compression (lb per in. of width of roll) Empty	Maximum Compression Ballasted	Pneumatic-Tired Unit: No. of Wheels	Tire Size (in.)	Range of Inflation Pressure Max (psi)	Range of Inflation Pressure Min. (psi)	Maximum Wheel Load (lb) Empty	Maximum Wheel Load (lb) Ballasted	Vibratory Unit: Frequency or Range of Frequency (cpm)	Range[1] of Amplitude (in.)	Range of Speed (mph)
Bros, Inc., Minneapolis, Minn.	SP-54B-CR	8,700	29,000	61¼	35¼	61¼	100	310	9	15	36	25	666	2,675	Non vibrating		
Seaman-Gunnison Corp., Milwaukee, Wisconsin	Seaman-Gunnison self-propelled "Tri-Pactor" 8-20DTRV	14,000	40,000	86	31	72	90	375	8	7.50x15 x10	105	35	1,050	4,180	800 - 1,400	¼ - 2	¾ - 20
	10-27 DTRV	20,000	54,000	86	31	72	100	475	8	7.50x15 x10	105	35	1,475	4,750	800 - 1,400	¼ - 2	¾ - 20

*Operator controlled wheel loading by hydraulically variable wheel base.

[1] Amplitude varies with soil type and condition and if resonance occurs. These values indicate range under average working conditions.

TABLE 71

MANUFACTURERS SPECIFICATIONS FOR PNEUMATIC-TIRED VIBRATORY ROLLER—TOWED TYPE

Manufacturer	Make and Model	Gross Weight Empty (lb)	Gross Weight Fully Ballasted (lb)	Rolling Width (in.)	Compaction per lin. in. of Roller Width Empty (lb)	Compaction per lin. in. of Roller Width Fully Ballasted (lb)	Tire Size and Inflation Pressure Data: Tire Size and Ply Rating (in.)	Recommended Tire Inflation Pressures Max. (psi)	Recommended Tire Inflation Pressures Min. (psi)	No. of Wheels Front	No. of Wheels Rear	Wheel Loads (weight per wheel) Empty (lb)	Wheel Loads (weight per wheel) Fully Ballasted (lb)	Vibration Characteristics: Frequency or Range of Frequency (cpm)	Range of Amplitude (in.)	Range of Speed of Travel (mph)
Iowa Manufacturing Company Cedar Rapids, Iowa	Cedarapids "60" Compactor	30,000	60,000	48	-[1]	-[1]	24:00 x 33 36 ply	110	40	2	-	15,000	30,000	900-1,400	-[2]	2-15 Normal 2-4
	Cedarapids "25" Compactor	12,500	25,000	48	-[1]	-[1]	12·00 x 20 14 ply	110	40	4	-	3,125	6,250	900-1,400	-[2]	2-15 Normal 2-4

[1] Variable—depends on tire pressure and the amount of energy being delivered by the vibrating unit.

[2] Variable—depends on resistance of material being compacted and the speed of vibrating unit.

TABLE 72

MANUFACTURERS SPECIFICATIONS FOR SINGLE-UNIT, SELF-PROPELLED, MANUALLY-GUIDED[1] PAN[2]-TYPE VIBRATORY COMPACTORS

Manufacturer	Make and Model	Characteristics of Compacting Unit: Dimensions (in.) Width (of strip compacted)	Dimensions (in.) Depth	Weight (lb)	Frequency or Range of Frequency (cycles per min.)	Range of[3] Amplitude (in.)	Range of Working Speed (ft per min)	Range of Working Speed (mph)	Remarks
Allgemeine Baumaschinen-Gesellschaft (Combined Agencies Corp) Bosingfeld, Germany	All ABG								
	PV 400	15.7	15.7	310	2,500 - 3,350		20 - 40	0.22 - 0.45	
	PV 600	20	23.5	398	2,500 - 3,000		20 - 40	0.22 - 0.45	
	SPV (heated pan)	20	20	463	3,000 - 3,600		20 - 40	0.22 - 0.45	
	PV 2	23.5	26.3	607	2,500 - 3,000		20 - 40	0.22 - 0.45	
	PV25	23.5	31.5	990	2,500 - 3,000		33 - 66	0 37 - 0.74	
	PV 40	27.5	35.5	1,540	2,400 - 2,800		33 - 66	0.37 - 0.74	
	Up to three of Models PV 25 and PV 40 can be coupled to work abreast, being controlled by one operator								
Barco Manufacturing Co., Barrington, Ill.	Barco Vibra-Tamp Model B	27	Up to 24	225	2,950	¼ - ½	Up to 60	App. 1	Presently designing an entirely new machine with many improvements over the current.
Jackson Vibrators, Inc. Ludington, Michigan	Jackson Hand Compactor CP410A	26	4⅜	350	3,600 - 4,500	1/16 - ⅜	40 average		
Jay Company Columbus, Ohio	Jay model J-13	13 to 24 depending on tamping plate used.	6 - 10	255	2,500	¼	50 - 75		
	Jay model J-18	18 to 30 depending on tamping plate used.	6 - 10	335	2,500	¼	60 - 80		
	Jay model J-36	24 to 36 depending on tamping plate used.	6 - 10	440	1,866	½	70 - 100		
Maginniss Power Tool Co., Mansfield, Ohio	Maginniss PP-18	18 (basic plate) 24 (with 2-3" extensions) 30 (with 2-6" extensions)	6	250	3,500 - 7,000	5/16 - 5/32	30 - 70		
Vibro-Plus Products, Inc. Stanhope, New Jersey	"Terrapac" CM15	13½	6 - 12	242	To 2,500 VPM	3/64	60		
	"Terrapac" CM20	20	To 24	950	To 2,000 VPM	9/64	75		Only unit on market which compacts most clays as well as granular material.

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[1]By walking operator. [2]Also known in different geographical regions by the terms vibrating base-plate type, vibrating shoe type, vibrating pad type and vibrating sled type. [3]Amplitude varies with soil type, density, etc., and if resonance occurs. These values indicate range under average working conditions.

TABLE 73

MANUFACTURERS SPECIFICATIONS FOR MULTIPLE-UNIT SELF-PROPELLED AND TOWED TYPES OF PAN-TYPE[1] VIBRATORY AND IMPACT COMPACTORS[2]

Manufacturer	Make and Model	Over-All Width of Compacted Strip (in.)	Number of Compacting Units	Characteristics of Compacting Units: Weight of Individual Unit (lb)	Dimensions (in.) Width	Dimensions (in.) Depth	Vibration Characteristics: Frequency or Range of Frequency (cpm)	Vibration Characteristics: Range of Amplitude (in.)	Range of Working Speed (fpm)	Range of Working Speed (mph)	Remarks
Baldwin-Lima-Hamilton Corp., Lima, Ohio	Lima Model D Roadpacker	157	6	437	25⅛	26	1,500-2,200	⅛ - ¼	20-90	0 23-1 02 *	Compacting units hydraulically powered. 4 shoe working width = 8 ft 9 in 5 shoe working width = 11 ft 0 in 6 shoe working width = 13 ft 1 in Gasoline or diesel power mounted on rubber tires *Highway travel speeds to 30 mph
	Lima Super Roadpacker	180	12	450	29⅛	26	1,500-2,200	⅛ - ¼	22-268	0.25-2.82 **	Compacting units hydraulically powered. Two sets of 6 shoes each in tandem. 4 shoe working width = 10 ft 0 in. 5 shoe working width = 12 ft 5 in. 6 shoe working width = 15 ft 0 in Gasoline or diesel power. Mounted on Rubber tires. **Highway travel speeds to 26 mph
Note Baldwin-Lima-Hamilton Corporation has always referred to their equipment as "vibrating shoe type."											
Jackson Vibrators, Inc. Ludington, Michigan	Jackson multiple compactor No MC525A	158 5	6	350	26	4⅜	3,600-4,500	1/16 - ⅜	20-90	Travel speed 10 mph	Self-propelled
	CT-106A	Variable to 158.5	6	350	26	4⅜	3,600-4,500	1/16 - ⅜	20-90	30 mph	Towed type

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[1]Also known in different geographical regions by the terms vibrating base-plate type, vibrating shoe type, vibrating pad type and vibrating sled type.
[2]Machines of variable frequency when operated at low frequencies are sometimes known as impact type compactors.

TABLE 74

MANUFACTURERS SPECIFICATIONS FOR SELF-PROPELLED MANUALLY-GUIDED[1] VIBRATORY ROLLERS

Manufacturer	Make and Model	Weight (lb)	Dimensions of Roll Diam. (in.)	Dimensions of Roll Width (in.)	Vibration Characteristics Frequency or Range of Frequency (cpm)	Vibration Characteristics Range of Amplitude (in.)	Range of Speed of Travel (mph) Forward	Range of Speed of Travel (mph) Reverse	Remarks
Essick Manufacturing Company Los Angeles, California	Essick Model VR-13-W	630	22½	13	4,500	-	1	1	-
	Essick Model VR-28-W	865	22½	28	4,500	-	60 - 115	60 - 115	
Vibro-Plus Products, Inc. Stanhope, New Jersey	"Terrapac" Model CL21	1,000	24½	30	to 3,000 VPM	to 1/32	100	100	With transp. hooks 1,100 lb

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[1] By walking operator.

TABLE 75

MANUFACTURERS SPECIFICATIONS FOR SINGLE-DRUM VIBRATORY AND IMPACT[2] ROLLERS—TOWED AND SELF-PROPELLED TYPES

Manufacturer	Make and Model	Dimensions of Vibrating Roll (in.) Diameter	Dimensions of Vibrating Roll (in.) Width	Weight (lb)	Vibration Characteristics Frequency or Range of Frequency (cycles per min.)	Vibration Characteristics Range of[1] Amplitude (in.)	Range of Recommended Speeds (ft per min.)	Range of Recommended Speeds (mph)	Remarks
Allgemeine Baumaschinen-Gesellschaft (Combined Agencies Corporation) Bosingfeld, Germany	ABG Model AW25	43.3	55.1	7,250	1,600 to 2,000	-	40 to 70	½ to 7	
	ABG Model SAW	63	79	17,500	1,500 to 1,800	-	40 to 70	½ to 7	(Depending on type of material and height of lift) With Model SAW, silty sandy gravel has been compacted to 100% Proctor at a depth of 5 ft, in four passes, although the moisture content was three to four percent above optimum.
Bros, Incorporated Minneapolis, Minnesota	Bros, VP-9D	48	66	9,950	1,100 to 1,300	¼	Dependent on Soil Conditions 88 to 440	1 to 5	A compactive effort of 30,450 lb.
Douglas Motors Corporation Milwaukee, Wisconsin	Douglas Motors Western Vibrated 4T	47	65	8,000	1,400 to 1,600	-	-	-	Compression per lin. in. of drum width 475 - 560 lb. Impact force 16 tons.
	2T VT	31	60	3,800	1,400 to 1,600	-	-	-	Compression per lineal inch of drum width 340 lb. Impact force 8 - 10 tons.
Essick Manufacturing Company Los Angeles, California	Essick VR-54-TE	30	54	3,237	3,600	-	132 - 176	1½ - 2	-
	Essick VR-72-TEC	51	72	8,100	2,320	-	132 - 176	1½ - 2	-
Rosco Manufacturing Company Minneapolis, Minnesota	Rosco Vibrator	30	60	6,600	1,000 to 1,450	⅛ - ¼	117	1⅓	-
Seaman Gunnison Corporation Milwaukee, Wisconsin	Seaman-Gunnison Impactor VR-72	31	72	5,000	800 to 1,400	¼ - 2	45 - 350	½ - 4	25,000-lb dynamic impact directed vertically. External vibratory element twin counter rotating eccentrics.
Tampo Manufacturing Company San Antonio, Texas	Tampo VC40	43	51	7,400	1,100 to 1,600	-	-	to 5	Centr. force 9,700 lb.
	VC80	48	60	7,000	1,100 to 1,600	-	-	to 5	Centr. force 15,000 lb.
Vibro-Plus Products, Inc. Stanhope, New Jersey	"Terrapac" CK10	29½	55	3,100	to 2,400 VPH	3/64	-	2 - 4	-
	"Terrapac" CH31	48	57	8,000	1,400 to 1,600 VPH	5/64	-	2 - 4	-

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[1] Amplitude varies with soil type, density, etc., and if resonance occurs. These values indicate range under average working conditions.

[2] Vibrators with lower frequency, and higher amplitude productive of higher impact force are sometimes referred to as impactors.

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Appendix A

DEFINITIONS

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" (119, 121), 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 these references. Terms not included therein and terms believed in need of further explanation are defined according to use and the source reference is given where appropriate.

Absolute Maximum Density (Dry Unit Weight)—The greatest unit weight that can be at-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 (118) is in progress aimed toward the development of a standard test procedure for absolute maximum unit weight.

Apparent Specific Gravity—See "Specific Gravity, Apparent."

Apparent Cohesion—See "Cohesion, Apparent."

Backfill—All material behind a wall (or above and adjacent to a conduit) whether undisturbed ground or fill, that contributes to the pressure against the wall or the conduit (in part from 107).

Base (Base Course)—The layer used in a pavement system to reinforce and protect the subgrade or subbase.

Basement Soil—See "Subgrade Soil."

Bearing Capacity—See "Ultimate Bearing Capacity."

Bulk Specific Gravity—See "Specific Gravity, Bulk."

California Bearing Ratio (CBR)—The ratio of (1) the force per unit area required to penetrate a "soil" mass with a 3-sq in. circular piston (approximately 2 in. in diameter) at the rate of 0.05 in. per min. to (2) that required for corresponding penetration of a standard material. The ratio is usually determined at 0.1-in. penetration, although other penetrations are sometimes used. Original California procedures required determination of the ratio at 0.1-in. intervals to 0.5 in. Corps of Engineers' procedures require determination of the ratio at 0.1 in. and 0.2 in. Where the ratio at 0.2 in. is consistently higher than at 0.1 in., the ratio at 0.2 in. is used.

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 which 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, since there is ample evidence that from an engineering standpoint the properties described in the above 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.")

Coefficient of Permeability, k, (Permeability)—The rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions (usually 20 C).

Cohesion, c—The portion of the "shear strength" of a "soil" indicated by the term c in Coulomb's equation, $s = c + \tan$.

Cohesion Apparent—Cohesion in granular "soils" due to capillary forces.

Cohesionless Soil—A "soil" that when unconfined has little or no strength when air-dried, and that has little or no "cohesion" when submerged.

Cohesive Soil—A "soil" that when unconfined has considerable strength when air-dried, and that has significant "cohesion" when submerged.

Compaction—The densification of a "soil" gy 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 dimension 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—This term can apply 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.

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.)

Consolidation Test—A test in which the specimen is laterally confined in a ring and is compressed between porous plates.

Contact Area—A rating factor for soil compactors.

(1) For smooth-wheel static force type rollers and for vibratory type rollers this factor is not used; the unit load is expressed in lb per lineal inch of width of roll.
(2) For sheepsfoot rollers the contact area is the total area of the tamper foot faces in one row of tamper feet in contact with the ground surface.
(3) For pneumatic-tire rollers the contact area is the area in contact with an unyielding plane surface. On treaded tires the contact area may sometimes be considered as the total area of tread and area between treads.
(4) For vibratory base-plate-type compactors, the contact area is the surface area of the base-plate.

Contact Pressure—For all types of compactors it is the total load divided by the contact area (authors' definition).

Coverage—One coverage consists of one application of either a wheel of a rubber-tired roller or a foot of a sheepsfoot roller (or a drum of a smooth-wheel roller or the plate of a vibratory base-plate-type compactor) over each point in the area being compacted (44).

Degree of Saturation—See"Percent Saturation."

Density—See"Unit Weight." (Note: 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 (53). Also, compaction by blows of a pneumatic-type or explosion-type tamper.

Effective Pressure—See "Stress, Effective."

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 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.

Internal Friction—The portion of the shearing strength of a soil indicated by the terms $p \tan \phi$ in Coulomb's equation $s = c + p \tan \phi$. It is usually considered to be due to the interlocking of the soil grains and the resistance to sliding between grains.

Maximum Density (Maximum Unit Weight)—See "Unit Weight."

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 (118).

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 (53, 111). See text for further explanation regarding use of this term.

Moisture Content (Water Content), w—The ratio, expressed as a percentage, of (1) the weight of water in a given soil mass to (2) the weight of solid particles (119). 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.

Pass—One movement of a given type compactor over the area being compacted. Pass should not be confused with coverage (authors' definition).

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 second.

Penetration Resistance Curve (Proctor Penetration Curve)—The curve showing the relationship between (1) the penetration resistance and (2) the water content.

Percent Compaction (Relative Compaction)—The ratio, expressed as a percentage, of (1) dry unit weight of a soil to (2) 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 (1) the volume of water in a given soil mass to (2) the total volume of intergranular space (voids).

Permeability—See "Coefficient of Permeability."

Pore Pressure (Pore Water Pressure)—See "Stress, Neutral."

Pore Water Pressure—See "Stress, Neutral."

Porosity, n—The ratio, usually expressed as a percentage, of (1) the volume of voids of a given soil mass to (2) the total volume of the soil mass.

Proctor Penetration Curve—See "Penetration Resistance Curve."

Relative Compaction—See "Percent Compaction."

Relative Density, D_d—The ratio of (1) the difference between the void ratio of a "cohesionless soil" in the loosest state and any given void ratio to (2) the difference between its void ratios in the loosest and densest states.

Roller Compaction Curve—Curve of dry unit weight vs moisture content produced in testing a compactor under controlled conditions to determine the maximum dry unit weight and the optimum moisture content that result (authors' definition).

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."

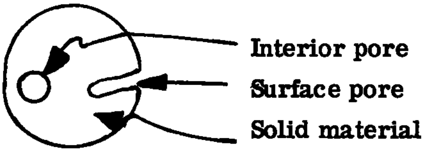
Settlement of Embankment—Decrease in elevation of the surface of an embankment due to the consolidation of the soil in the embankment due to its own weight over a period of time following construction. Localized settlements may result from increase in unit weight resulting from traffic loadings (63).

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[1]—Ratio of (1) the weight of any volume of a substance to (2) the weight of an equal volume of water (at the same temperature). Note: Since the volume of displaced water in milliliters (cc) equals its weight in grams, this ratio, for all practical purposes, can be written as follows:

$$\text{Specific Gravity} = \frac{\text{Weight}^{2}}{\text{Volume}}$$

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 below in terms of the weight:volume ratio above and the sketch below 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, gm, 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, gm, 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, gm, and
Volume = volume of solid material plus volume of interior pores, cc.

Specific Gravity (Soil) G_s—The ratio of (1) the oven-dry weight (in grams) of the sample to (2) 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

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[1] General definition, in part from 253B (93, 121) and in part by authors.

[2] This equation is correct if weights and volumes are expressed in grams and cubic centimeters (cc), respectively.

method and results obtained under designations AASHO T 99 and ASTM D 698 before the adoption of the 1957 (AASHO) and 1958 (ASTM) revisions.

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.

Stress, Neutral, u, u_w (Pore Pressure) (Pore Water Pressure)—Stress transmitted through the pore water (water filling the voids of the soil).

Subbase—The layer used in the pavement system between the subgrade and base course. Also, according to usage, the layer between the subgrade and portland cement concrete pavement.

Subgrade (Basement Soil) (Subgrade Soil)—The prepared and compacted soil below the pavement system.

Subgrade Surface—The surface of the earth or rock prepared to support a structure or a pavement system.

Subsidence of Embankment—Decrease in the elevation of the surface of an embankment due to the consolidation or lateral displacement of the foundation soil during or following construction (63).

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).

Ultimate Bearing Capacity—The average load per unit of area required to produce failure by rupture of a supporting soil mass.

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 which, 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 (1) the volume of void space to (2) 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.

Appendix B

TABLE A

UNIT WEIGHT—TOTAL SOLIDS CONVERSION TABLE
(For Various Specific Gravities)

Total Solids, Percent by Volume	Pounds Per Cubic Foot															
	2.55	2.56	2 57	2.58	2.59	2.60	2.61	2.62	2.63	2.64	2.65	2.66	2.67	2.68	2.69	2.70
78	124.2	124.7	125.1	125.6	126.1	126.6	127.1	127.6	128.1	128.6	129.0	129.5	130.0	130.5	131.0	131.5
77	122.6	123.1	123.5	124.0	124.5	125.0	125.5	125.9	126.4	126.9	127.4	127.9	128.3	128.8	129.3	129.8
76	121.0	121.5	121.9	122.4	122.9	123.4	123.8	124.3	124.8	125.3	125.7	126.2	126.7	127.2	127.6	128.1
75	119.4	119.9	120.3	120.8	121.3	121.7	122.2	122.7	123.1	123.6	124.1	124.5	125.0	125.5	126.0	126.4
74	117.8	118.3	118.7	119.2	119.7	120.1	120.6	121.0	121.5	122.0	122.4	122.9	123.3	123.8	124.3	124.7
73	116.2	116.7	117.1	117.6	118.0	118.5	118.9	119.4	119.9	120.3	120.8	121.2	121 7	122.1	122.6	123.0
72	114.6	115.1	115.5	116.0	116.4	116.9	117.3	117.8	118.2	118.7	119.1	119.6	120.0	120.5	120.9	121.4
71	113 0	113.5	113.9	114.4	114.8	115.2	115.7	116.1	116.6	117.0	117.5	117.9	118.3	118.8	119.2	119.7
70	111.4	111.9	112.3	112.7	113.2	113.6	114.1	114.5	114.9	115 4	115.8	116.2	116.7	117.1	117.6	118.0
69	109.8	110.3	110.7	111.1	111.6	112.0	112.4	112.9	113.3	113.7	114.2	114.6	115.0	115.4	115.9	116.3
68	108.3	108.7	109.1	109.5	110.0	110.4	110.8	111 2	111.6	112.1	112 5	112.9	113.3	113.8	114.2	114.6
67.5	107.5	107.9	108.3	108.7	109.1	109.6	110.0	110.4	110.8	111.3	111.7	112.1	112.5	112.9	113.4	113.8
67	106.7	107.1	107.5	107.9	108.3	108.8	109.2	109.6	110.0	110.4	110.8	111.3	111.7	112.1	112.5	112.9
66.5	105.9	106.3	106.7	107.1	107.5	107.9	108.4	108.8	109.2	109.6	110.0	110.4	110.8	111.3	111.7	112.1
66	105.1	105.5	105.9	106.3	106.7	107.1	107.5	108.0	108.4	108.8	109.2	109.6	110.0	110.4	110.8	111.3
65.5	104.3	104.7	105.1	105.5	105.9	106.3	106.7	107.1	107.5	108.0	108.4	108.8	109.2	109.6	110.0	110.4
65	103.5	103.9	104.3	104.7	105.1	105.5	105.9	106.3	106.7	107.1	107.5	107.9	108.3	108.8	109.2	109.6
64.5	102.7	103.1	103.5	103.9	104.3	104.7	105.1	105.5	105.9	106.3	106.7	107.1	107.5	107.9	108.3	108.7
64	101.9	102.3	102.7	103.1	103.5	103.9	104.3	104.7	105.1	105.5	105.9	106.3	106.7	107.1	107.5	107.9
63.5	101 1	101.5	101.9	102.3	102.7	103.1	103.5	103.9	104.3	104.7	105.1	105.5	105 8	106.2	106 6	107.0
63	100.3	100.7	101.1	101 5	101.9	102.3	102.7	103.0	103.4	103.8	104.2	104.6	105.0	105.4	105.8	106.2
62.5	99.5	99.9	100.3	100.7	101.1	101.4	101.8	102.2	102.6	103.0	103.4	103.8	104.2	104.6	105.0	105.4
62	98.7	99.1	99.5	99.9	100.3	100.6	101.0	101.4	101.8	102.2	102.6	103.0	103.3	103.7	104.1	104.5
61.5	97.9	98.3	98.7	99.1	99.4	99.8	100.2	100.6	101.4	101.4	101.7	102.1	102.5	102.9	103.3	103.7
61	97.1	97.5	97.9	98.2	98.6	99.0	99.4	99.8	100.2	100.5	100.9	101.3	101.7	102.1	102.4	102.8
60.5	96.3	96.7	97.1	97.4	97.8	98.2	98.6	99.0	99.3	99.7	100.1	100.5	100.8	101.2	101.6	102.0
60	95.5	95.9	96.3	96.6	97.0	97.4	97.8	98.1	98.5	98.9	99.3	99.6	100.0	100.4	100.8	101.1
59.5	94.7	95.1	95.5	95.8	96.2	96.6	97.0	97.3	97.7	98.1	98.4	98.8	99.2	99.6	99.9	100.3
59	93.9	94.3	94.7	95.0	95 4	95.8	96.1	96.5	96.9	97.2	97.6	98.0	98.3	98.7	99.1	99.5
58.5	93.1	93.5	93.9	94.2	94.6	95.0	95.3	95.7	96.1	96.4	96.8	97.1	97.5	97.9	98.2	98.6
58	92.3	92.7	93.1	93.4	93.8	94.1	94.5	94.9	95.2	95.6	96.0	96.3	96.7	97.0	97.4	97.8
57.5	91.5	91.9	92.3	92.6	93.0	93.3	93.7	94.1	94.4	94 8	95.1	95.5	95.8	96.2	96.7	96.9
57	90.7	91.1	91.5	91.8	92.2	92.5	92.9	93.2	93.6	93.9	94.3	94.7	95.0	95.4	95.7	96.1
56.5	89.9	90.3	90.7	91.0	91.4	91.7	92.1	92.4	92.8	93.1	93.5	93.8	94.2	94.5	94.9	95.2
56	89.2	89.5	89.8	90.2	90.5	90.9	91.2	91.6	91.9	92.3	92.6	93.0	93.3	93.7	94.0	94.4
55.5	88.4	88.7	89.0	89.4	89.7	90.1	90.4	90.8	91.1	91.5	91.8	92.2	92.5	92.9	93.2	93.6
55	87.6	87.9	88.2	88.6	88.9	89.3	89.6	90.0	90.3	90.6	91.0	91.3	91.7	92.0	92.4	92.7
54.5	86.8	87.1	87.4	87.8	88.1	88.5	88.8	89.1	89.5	89.8	90.2	90.5	90.8	91.2	91.5	91.9
54	86.0	86.3	86.6	87.0	87.3	87.7	88.0	88.3	88.7	89.0	89.3	89.7	90.0	90.3	90.7	91.0
53.5	85.2	85.5	85.8	86.2	86.5	86.8	87.2	87.5	87.8	88.2	88.5	88.8	89.2	89.5	89.8	90.2
53	84 4	84.7	85.0	85.4	85.7	86.0	86.4	86.7	87.0	87.4	87.7	88.0	88.3	88.7	89.0	89.3
52.5	83.6	83.9	84.2	84.6	84.9	85.2	85.5	85.9	86.2	86 5	86.9	87.2	87.5	87.8	88.2	88.5
52	82.8	83.1	83.4	83.8	84.1	84.4	84.7	85.1	85.4	85.7	86.0	86.4	86.7	87.0	87.3	87.7
51.5	82.0	82.3	82.6	83.0	83.3	83.6	83.9	84.2	84.6	84.9	85.2	85.5	85.8	86.2	86.5	86.8
51	81.2	81.5	81.8	82.1	82.5	82.8	83.1	83.4	83.7	84.1	84.4	84.7	85.0	85.3	85.6	86.0
50.5	80.4	80.7	81.0	81.3	81.7	82.0	82.3	82.6	82.9	83.2	83.5	83 9	84.2	84.5	84.8	85.1
50	79.6	79.9	80.2	80.5	80.8	81.2	81.5	81.8	82.1	82.4	82.7	83.0	83.3	83.7	84.0	84.3
49.5	78.8	79.1	79.4	79.7	80.0	80.3	80.7	81.0	81.3	81.6	81.9	82.2	82.5	82.8	83.1	83.4
49	78.0	78.3	78.6	78.9	79.2	79.5	79.8	80.1	80.5	80.8	81.1	81.4	81.7	82.0	82.3	82.6

Wt. per cu ft $= \frac{(100-n) \times G_s \times 62.43}{100}$

Example Find wt. per cu ft for porosity (n) = 35 when G_s = 2 57

Wt. per cu ft $= \frac{(100 - 35) \times 2.57 \times 62.43}{100} = \frac{65 \times 160.45}{100} = 104.3$ pcf

TABLE B

DETERMINATION OF ZERO AIR VOIDS CURVE

γ_d (pcf)	Grams per c.c.	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: $w = \left(\frac{62.43}{\gamma_d} - \frac{1}{G_s}\right) \times 100.$

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