HIGHWAY RESEARCH BOARD

Bulletin 58

Compaction of Embankments, Subgrades, and Bases

National Academy of Sciences—
National Research Council

publication 240

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Compaction of Embankments, Subgrades, and Bases

1952

Washington, D. C.

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Preface

● THE ORIGINAL Wartime Road Problems No. 11 "Compaction of Subgrades and Embankments" was published in August 1945 during World War II. It presented information on the mechanics of compaction, on moisture-density relationships, soil classification, suitability of soils for embankments, methods for controlling moisture content and density during compaction, and maximum limiting slopes for embankment construction. It also presented a review of practices current in 1945 and gave a list of selected references on compaction and allied subject matter.

During and following the war, highways were subjected to a larger number of heavier wheel loads than prior to the publication of Wartime Road Problems No. 11. That increase in heavy vehicles has emphasized the need for compaction of subgrades and bases for pavements. Also, since that time more information has been developed on the amount of compaction needed in highway and airport subgrades and bases and the relative permanence of moisture content and density. Recent data are available from carefully controlled experiments in field rolling which throw some light on the practicable limits of field compaction for different types and weights of equipment. Some investigations have been completed and others are in progress to determine the feasibility of using vibration as a means of compacting soils, especially soils of a granular nature.

During the war, attention was given to the use of sheepsfoot rollers having high tamping-foot contact pressures. Also, efforts were made to use heavy pneumatic-tire wheel loads for compacting subgrades and bases on some airfields. The result of some of those efforts has been a trend toward the manufacture of heavier compaction equipment, both in the sheepsfoot and rubber-tired types on the premise that they offer possibilities for greater densities or compaction to greater depths.

This bulletin is the result of efforts by the Committee to list practices pertaining to compaction equipment and its use and specifications which govern compaction of embankments, subgrade soils, and bases. In addition, this bulletin attempts to present latest developments in the technology of soil compaction with special reference to the use of equipment heavier than that discussed in Wartime Road Problems No. 11.

Contents

Compaction of Embankments, Subgrades, and Bases

● THIS BULLETIN discusses fundamentals of compaction, the purpose for which the compaction is intended, and the amount needed for various soils in different parts of the road structure in the light of how compaction is affected by climatic, load, and road conditions. From those considerations, suggestions are made on recommended practice for compacting embankments, subgrades, and granular bases and for the control of compaction.

Soils work for highways may be classified broadly into four categories: (1) selection of soil as to quality; (2) prediction and control of behavior of soil under load; (3) protection of soils against effects of climate; and (4) improvement of bearing value of soil by drainage, incorporation of admixtures, or compaction.

There is no other single treatment which can be applied to natural soils which produces so marked a change in their physical properties at so low a cost as does compaction, when it is controlled to meet the desired needs. The bearing value of some soils may be increased several times by increase in density of the order 3 to 5 pcf. Because compaction has great influence on the manner in which soils behave, it is worthwhile presenting not only a discussion of factors which influence compaction and how compaction is obtained but also how it influences the nature of soils and how it is affected once it is obtained. The committee believes this broad perspective of compaction is necessary if it is to be used to the fullest advantage in the preparation of embankments, subgrade materials and bases for pavements.

DEFINITIONS OF TERMS

The terms embankment, embankment foundation, subgrade materials, bases, and subbases, as used here, comply with the definitions set forth in Standard Definitions of Terms Relating to Subgrade, Soil Aggregate, and Fill Materials, AASHO Designation: M 146-49, except as noted.

Settlement of Embankment. Decrease in elevation of the surface of an embankment due to consolidation of the soil in the embankment due to its own weight and the effect of traffic, over a period of time following construction.

Subsidence of Embankment. Decrease in the elevation of the surface of an embankment due to consolidation or displacement of the foundation soil over a period of time during or following construction.

Embankment Foundation. The material on which an embankment is placed.

Embankment (Fill). A raised structure of soil, soil-aggregate, or rock.

Subgrade Material (Basement Soil). The material in excavation (cuts), embankment (fills), and embankment foundations immediately below the first layer of subbase, base, or pavement and to such depth as may affect the structural design.

Subbase. Specified or selected material of planned thickness placed as a foundation for a base.

Base. Specified or selected material of planned thickness placed as foundation for a pavement.

Compaction. The practice of artificially densifying and incorporating definite density into the soil mass by rolling, tamping, or other means.

Consolidation. The decrease in the volume of voids, or the increase in density, for the most part inelastic, which is caused by the stresses imposed in the supporting soils by permanent foundation loads, or by the repeated passage of highway or airplane traffic under actual service conditions.

Bearing Value. The unit load $\left(\frac{P}{A}\right)$ for a specified amount of settlement (Δ) and a specified loaded area (A).

Bearing Capacity. That unit pressure greater than which progressive settlement will occur leading to failure.

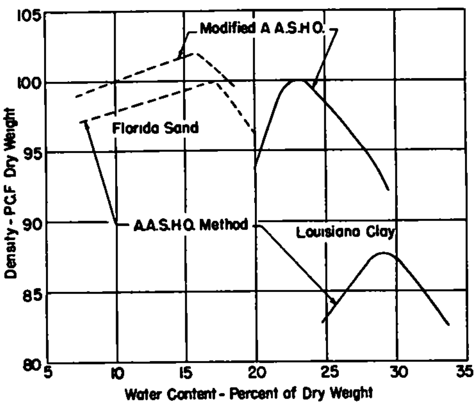


Figure 1. Effect of two compactive efforts on the densities of two soils.

FUNDAMENTALS OF COMPACTION

The term "compaction" refers to the act of artificially densifying the soil. It means the pressing of soil particles together into a closer state of contact and in so doing expelling air or water from the soil mass. The density of soil is measured in terms of its volume-weight and is usually expressed as pounds of wet soil or dry soil per cubic foot (or as porosity in percent of total volume). Those volume weights are expressed as wet density and dry density, respectively.

The term "consolidation," by usage, refers to closer particle contact obtained in the time-consolidation process whereby a superimposed load causes closer packing by expelling water and/or air from the soil mass.

Factors Influencing Density

There are several factors which influence the value of density obtained by compaction. The most important of these are: (1) the moisture content of the soil; (2) the nature of the soil, that is, its grain size distribution and its physical properties; and (3) the nature (including both type and amount) of the compactive effort used.

The following two factors influence density but are of less significance than the factors given above: (1) The temperature of the soil and (2) The amount of manipulation given the soil during the compacting process (this includes addition and mixing in of water or removal of water by aëration).

In addition to the above factors there are the natural effects of "curing," which may increase the density of the soil.

Influence of Soil Moisture Content. If a soil is compacted under a given compactive effort at each of several moisture contents, there results a moisture-density relationship of the nature shown for the Louisiana clay in the lower right-hand part of Figure 1. There is developed, for each soil, a maximum dry density at an optimum moisture content for the compactive effort used. The optimum moisture content, at which maximum dry density is obtained, is the moisture condition at which the soil has become sufficiently workable under the compactive effort used to cause it to become packed so closely as to expel most of the air. At moisture contents less than optimum, the soil (except for cohesionless sands) becomes increasingly more difficult to work and thus to compress. As moisture contents are increased above optimum, most soils become increasingly more workable. However, a closer packing is prevented when the water fills the soil pores. Thus the moisture-density relationship established in the test is indicative of the relative workability of the soil at various moisture contents under the compactive effort used. The moisture-density relationships hold for the laboratory compaction test and for field compaction by rolling. Available data from carefully controlled field studies of rolling show moisture-density relationships almost identical with those developed from laboratory tests. These are described later.

Influence of Soil Type. The nature of the soil has great influence on the value of density obtained under a given compactive effort. Soils ranging from lightweight volcanic and diatomaceous soils and heavy clays to well-graded sandy and gravelly soils may, when subjected to identical compaction procedures, yield values of maximum density ranging from 60 pcf. or less for the volcanic and diatomaceous soils, about 90 to 100 pcf. for the clays and up to about 135 pcf. or

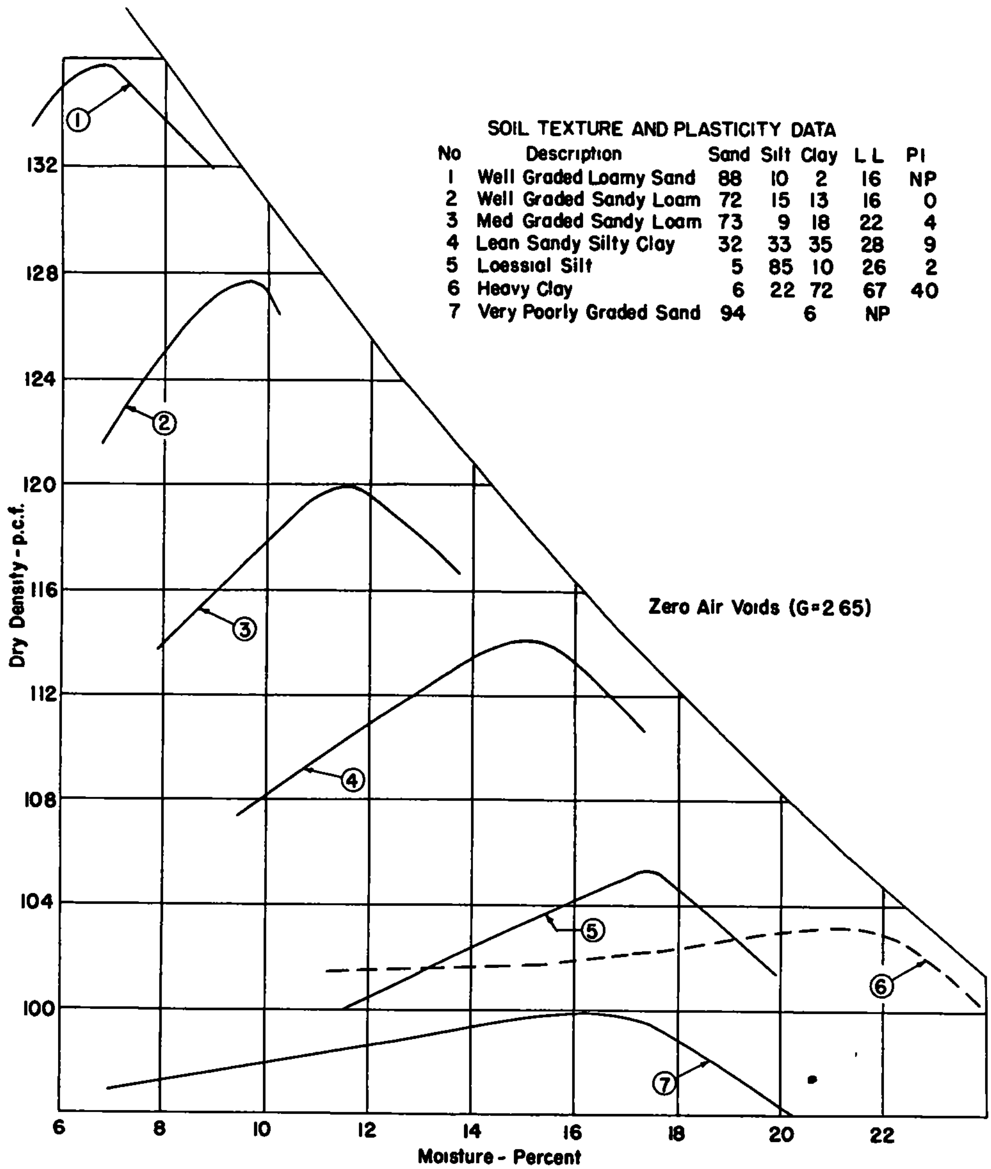


Figure 2. Moisture-density relationships for seven soils compacted according to AASHO Method AASHO T99 (in part after "Public Roads").

more for the better-graded, coarse granular soils.

Examples illustrative of the differences in soil densities obtained under a given compactive effort (AASHO Method T 99) on seven different soils ranging in texture from clays to sands are shown in Figure 2. It may be seen from the moisture-density relationships in Figure 2 that the different soils reflect not only differences in optimum moisture content and maximum density, but also differences in how the soils react to the given compactive effort at moisture contents less than optimum. This is illustrated by the curve for the heavy clay[1]

[1] A "heavy" clay is a clayey soil which is difficult to manipulate. It usually contains more than 50 percent of particles smaller than 0.005 mm. in diameter

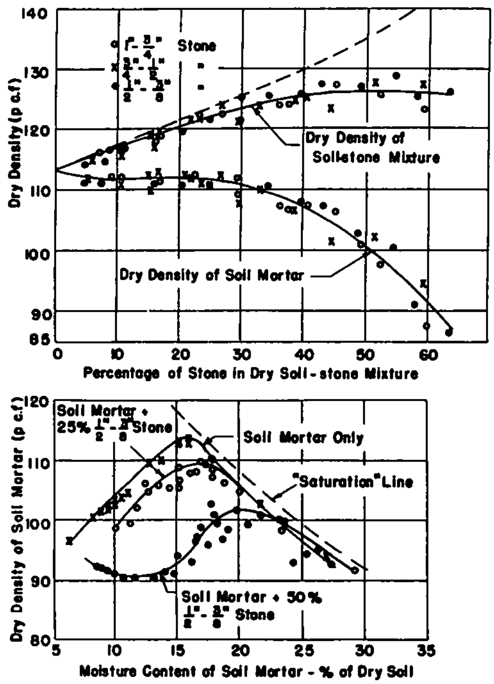


Figure 3. Effect of addition of coarse aggregate on density of soil.

(No. 6). Moisture content is less critical for heavy clays than for the feebly plastic soils in which sand and silt grain sizes predominate. Heavy clays may be compacted through a relatively wide range of moisture content below optimum with relatively small changes in density. In contrast, the more granular and better-graded soils, which produce high densities under the same compactive effort, react sharply to small changes in moisture content, producing marked changes in density, as shown by the curves for Soils 1 and 2 in Figure 2. Relatively clean, poorly graded, nonplastic sands of the type indicated by Soil 7 in Figure 2 having small silt and clay content are relatively insensitive to moisture changes.

The gravel content in a soil also has an influence on the compaction characteristics of that soil. The effect of increasing the proportion of coarse material on the density of the soil mortar and on the density of the total mix is illustrated in Figure 3. Increasing the content of coarse material above 25 percent causes a small decrease in density of the soil mortar, while increasing coarse materials to more than about 35 percent causes a marked decrease in density of the soil mortar and yields no significant increase in density of the total mixture.

Influence of Compactive Effort. The results of compaction at different compactive efforts on each of several soils gives evidence of the comparative effect of soil moisture content and soil type on the degree of compaction obtained. For each compactive effort applied in compacting a soil, there is a corresponding optimum moisture content and maximum density. The maximum density increases and the optimum moisture content decreases with increase in compactive effort. That is illustrated in Figure 1 which shows moisture-density relationships for the AASHO standard method T 99 (25 blows of a $5\frac{1}{2}$-lb. hammer with 2 sq. in. of striking face dropping 12 in. on each of three layers in a 1/30-cu.-ft. mold) and the Corps of Engineers modification of the AASHO method (25 blows of 10-lb. hammer with 2 sq. in. striking face dropping 18 in. on each of five layers in a 1/30-cu.-ft. mold). Moisture-density relationship curves for each of the two compactive efforts on a Louisiana clay soil are shown

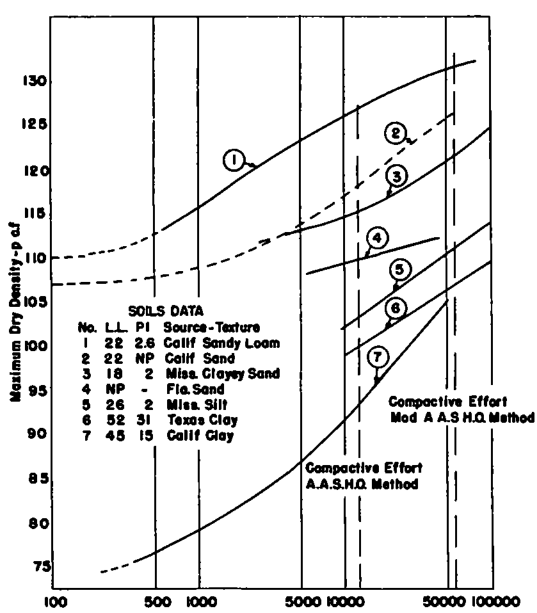


Figure 4. Relationship between compactive effort and maximum dry density.

in solid lines in the right-hand side of Figure 1. Similar curves for a poorly graded, fine Florida sand are shown in the left of Figure 1. These graphs show that the optimum moisture content for the clay soil is decreased 6 percent (29 to 23) and the maximum density is increased 12 pcf. (88 to 100) while for the Florida sand the corresponding changes are only 1 percent and 2 pcf. respectively.

If laboratory compaction tests are made at each of several different compactive efforts, there is developed for each soil a relationship between maximum density and compactive effort. Similar determinations for each of several soils make it possible to compare the relative effects of compactive effort on the different types of soil. The relationships between maximum density (for each compactive effort) and compactive effort are shown in Figure 4.

The curves in Figure 4 show that there is, within the range of compactive efforts normally used, an almost straight-line relationship between effort and density and that there is a marked difference in the slope of the lines for different types of soils. For example, the Florida sand shows a small gain in density with increase in effort while the California clay (No. 7) shows that increase in effort materially increases the density.

Knowledge of the compaction characteristics of different soils is of particular value to the engineer who prepares specifications and to the inspector who must interpret the results of density tests. For example, the California sand (No. 2) in Figure 4 has a maximum density of 118.1 pcf. at the compactive effort of the AASHO Method T 99 (12,375 ft.-lb. per cu. ft.). The compactive effort necessary to obtain 95 percent of maximum density is 3500 ft.-lb. per cu. ft. which is about 28 percent of the compactive effort of AASHO Method T 99. However, the sand can be poured into place with but little if any compactive effort to obtain a density of 106.5 pcf. which value is slightly greater than 90 percent of maximum density. Applying the same analysis to the clay (No. 7) it may be seen that 95 percent of maximum density (AASHO T 99) is obtained at about 57-percent compactive effort and 90 percent of maximum density at about 24-percent compactive effort. Thus twice as much compactive effort is required to compact the clay to 95 percent as is needed to compact the sand to the same percentage of maximum density.

The effect of compactive effort is as evident and equally as significant in field rolling as in the laboratory compaction test. In rolling, the effort applied is a product of the drawbar pull (which reflects the weight) and the number of passes for the width and the depth of the rolled area compacted. Increasing the weight or the number of passes increases the compactive effort applied. The significance of size of tamping foot, contact pressure, and lift thickness as related to compactive effort is discussed later.

The density-measurement method is the only procedure available which gives a direct quantitative measure of the degree of densification (expressed in terms of porosity, or in terms of weight per unit volume). It should be understood however, that the relationship between density and compactive effort is not linear and specifying a percentage of density does not infer that a compactive effort of similar proportions will be necessary for compaction. There is however, a relation between wheel load and compactive effort, and hence between compactive effort and bearing capacity. A knowledge of the significance of the relationship between density, compactive effort, and bearing capacity is helpful in the preparation of specifications for compaction, whether it be for subgrades, bases, or embankments.

Other Factors Which Influence Soil Density. There are several factors which influence the density obtained by compaction but do so in a small degree. Soil temperature has an effect, particularly on soils high in clay content. Hogentogler found from laboratory compaction tests on a clayey soil that density (under AASHO T 99 test procedure) was increased 3 pcf. and the optimum moisture content decreased 3 percentage units when the temperature of the soil was increased from 35 F to 115 F.

Compaction tests on some clayey soils show that they are quite sensitive to manipulation, that is, the more they are

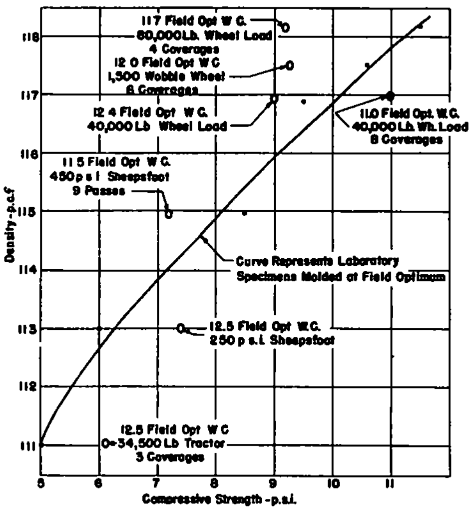


Figure 5. Unconfined compressive strength of field-compacted clayey sand compared with strength of laboratory specimens having approximately similar densities (after Corps of Engineers).

worked, the lower the density for a given compactive effort. Manipulation has little effect on the degree of compaction on soils which are dominantly silty or sandy.

Curing, that is, a drying following compaction, is not a factor which influences the mechanical process of compaction, but it may affect an increase in the density of subgrade and base material, especially if those materials contain cohesive materials. Density may increase on drying as much as 3 to 4 pcf.

INFLUENCE OF DENSIFICATION ON PHYSICAL PROPERTIES OF SOILS

The behavior of a soil in a compact state differs from the behavior of the same soil in a loose state. Compaction under controlled moisture content influences all of the physical properties of the soil mass related to performance of embankments, subgrades, and bases in highways. These major properties are bearing value, water movement (capillarity, water-retention capacity, and permeability), volume change (shrinkage and swell), and resistance to frost action.

Compaction does not improve all soils for all uses in different parts of the road structure in the same degree. Therefore, the engineer should not use compaction to improve bearing capacity without considering the effect which degree of densification has on volume change and other properties.

One of the prime purposes of compaction is to prevent settlement within embankments. Because compaction and settlement each bring about a closer arrangement of soil particles, it is obvious that artificial densification by compaction will prevent later natural consolidation and settlement of an embankment under its own weight.

Increasing the density by compaction increases the resistance to shear deformation and makes densification by compaction a useful tool in designing and building stable slopes of high embankments, which if not compacted, would not be stable.

Other conditions being equal, the bearing value of a soil increases with increase in density. A great many laboratory studies have shown how soil density and soil moisture content influence bearing capacity. Only recently (1, 2) have large-scale efforts been made to develop comparable data on the relationship between bearing value and soil density under both field and laboratory conditions.

Figure 5 shows unconfined compressive strengths of a clayey sand compacted to various densities at optimum moisture content in the laboratory. Figure 5 also shows unconfined compressive strengths of undisturbed cylinders cut from field-compacted lifts. The field lifts were compacted with different numbers of passes or coverages of different types of rolling equipment and represent a range of field compaction. It may be seen that compressive strengths are approximately doubled by compaction, yet the greatest density shown is not beyond the limits obtainable in highway construction.

Increasing the density reduces both the total porosity and the sizes of the pore spaces of soils which contain sufficient fines to make them compressible. It is that phenomenon, plus the increased friction developed, which increases bearing capacity and resistance to shear deformation and decreases elastic deformations. The reduction in pore spaces re-

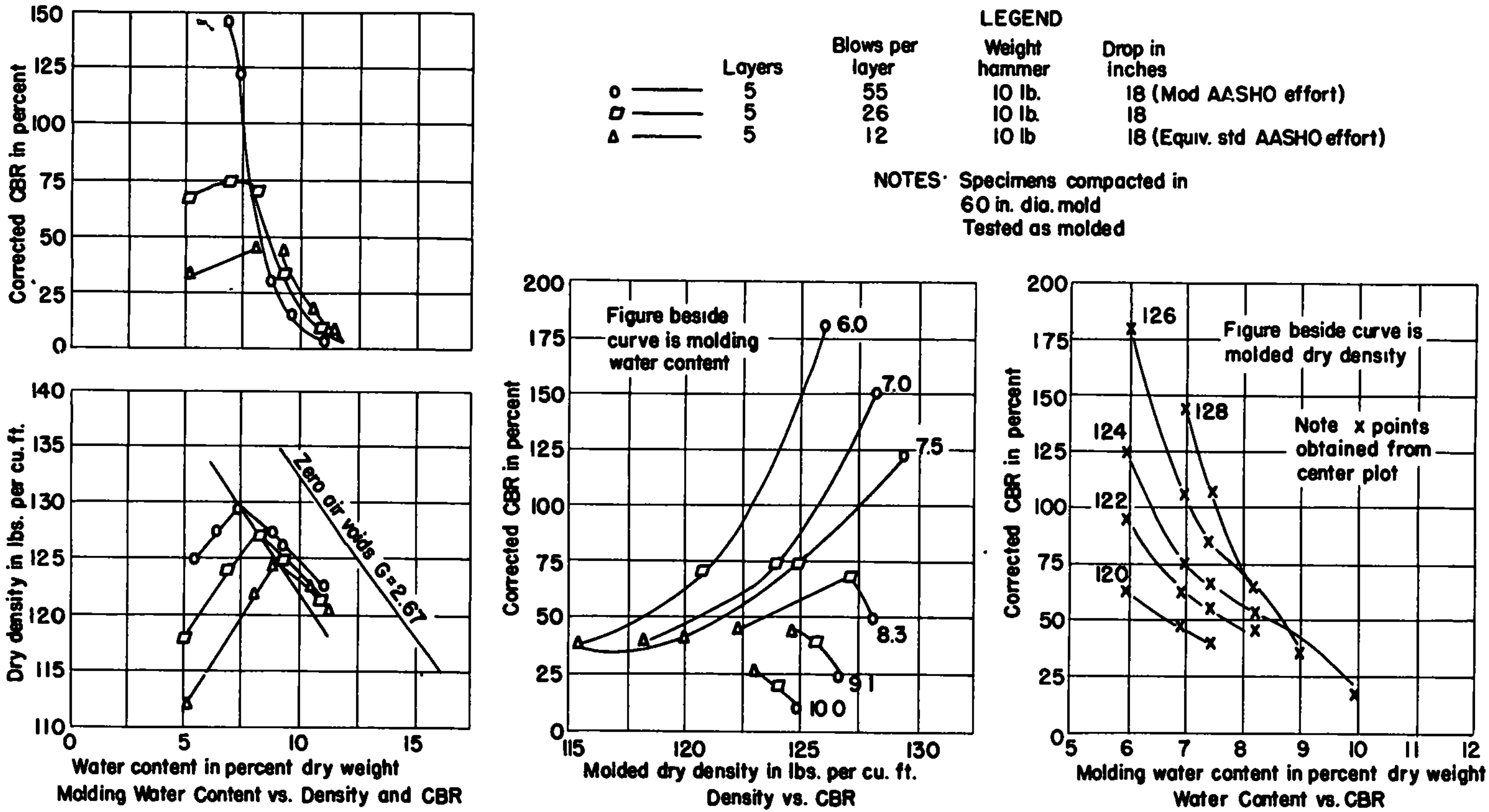


Figure 6. Relationship between CBR values and density and moisture. Tests were made on specimens at the as-moulded moisture content (after Corps of Engineers).

duces permeability, thus restricting percolation of water. When compaction is accomplished with proper moisture control for the particular soil, it restricts capillary movements, making the soil less susceptible to increase in moisture by absorption, and thus restricts changes in bearing capacity.

The importance of reducing the porosity in finely grained soils and its relation to bearing capacity may be seen by comparing porosities with the porosity at the plastic limit. The plastic limit is a critical moisture content affecting the bearing capacity of fine-grain soils which are characterized by becoming plastic when wet. At or slightly above the plastic limit, small increases in load yield large increases in deformation. It is practically possible to compact nearly all soils to densities having porosities less than the porosity at the plastic limit. Compactive efforts equal to 100 percent or more of standard (AASHO Method T 99) may be required to reduce the porosity below that which holds for the plastic limit for very heavy clays. That may not be desirable for subgrades for high-swelling clay soils. Volume change (shrink and swell) is an important soil property which affects the behavior of subgrade materials. Soils which exhibit volume change may swell nonuniformly on absorbing water and suffer a reduction in bearing capacity. In swelling they may become the cause of rough riding pavements. They may also shrink nonuniformly and cause uneven settlement and contribute to fractures in pavements.

Compaction has a marked influence on the volume change of clay soils. Density influences volume change, the greater the density the greater the potential swell, unless the soil is restrained by force. An expansive clay soil should be compacted at a water content and to a density at which swelling will be a minimum. Likewise, it should be compacted so shrinkage will be a minimum. Although the two conditions may not be the same, a soil exhibiting volume change can be compacted at a moisture content to a density where both swell and shrink will be near a minimum for any given condition of exposure.

Many investigations have been made, both in the field and in the laboratory, to determine the desirable range of moisture-density control to hold volume change to a minimum. The work of Allen and Johnson (3), McDowell (4), Russell (5), and the Corps of Engineers (6) is indicative of the nature of work done.

Swell or shrinkage and its relation to initial density and moisture content is easily determined by direct swell and shrinkage tests. Normal soils (not including micaceous, diatomaceous, and other soils having certain constituents) show a good relationship between swell and plasticity index (when correction is made for plus No. 4 mesh sieve content). The fact that swell is so important has caused most investigators to test soils for bearing capacity[2] in an expanded condition by fabricating specimens in a wet condition for testing or testing specimens after they have had an opportunity to absorb water and swell. The work of Turnbull and McRae (8) shown in Figure 6, indicates the relationship between moisture content, density, and bearing capacity as expressed by the California Bearing Ratio (CBR) for a given soil. The work of Benkelman and Olmstead (7), shown in Figure 7 and 8, indicates the relationship between soil strength, as determined by the triaxial testing apparatus, and soil density and moisture content.

The relationship between soil-density-moisture-content and volume change is, in itself, a broad subject. Space does not permit complete coverage here. The best results may be obtained by recognizing the influence of compaction and moisture control on the related properties of volume change and bearing capacity and compacting subgrade soils so that the range of shrinkage and swell will be a minimum.

Increasing recognition is being given to the influence of moisture and density control on the susceptibility of soils to cause segregation of ice on freezing and subsequent reduction in bearing capacity during the frost-melting period. Reliable data on the influence of controlled compaction on damage due to freezing are yet too meager from which to draw con-

[2] Whether interpreted through bearing tests, compression or shear tests

clusions on which to base a recommended practice.

FACTORS INFLUENCING PERMANENCE OF DENSIFICATION

There are several factors which tend to change soil density. The two primary factors are climate and traffic. Others are of a secondary nature, as for example, condition of pavement surface and nature of base and subbase or shoulders which influence the degree of exposure.

There is no evidence that the main body of an ordinary embankment suffers any decrease in density due to swelling of clay soils, unless it is subject to prolonged inundation. The surface slopes may increase in porosity with time, but for most cases only surface softening will result. Likewise, there is no evidence that it continues to settle in detrimental amounts for some period following adequate and uniform compaction, either as a result of climatic or traffic conditions. For practical purposes normal embankments retain their degree of compaction, except in the upper and outer portions subject to seasonal wetting and drying and frost action: The item of permanence is significant for compacted embankments only when they are subjected to unusual conditions.

Subgrade materials, subbases, and bases are subject to more severe exposure to climatic changes and traffic than embankments. Climatic conditions may bring about permanent or seasonal reduction or gain in soil moisture and, as a result, may decrease or increase soil density and cause distortion of the road surface.

In considering the permanence of compaction, the engineer needs to take into account two stages in the life of the road. The first concerns the period during which the road adjusts itself to its environment, that is, from the "as-built" to the "in-service" condition. The second concerns changes in density of the subgrade materials which result from seasonal or long-time changes in climatic conditions after the road has been in service for some time. If the soil is compacted too little or too much, too wet or too dry, there will be a change as it adjusts itself to the new conditions under the pavement.

High-volume-change soils, if compacted at moisture contents less than optimum, may gain in moisture, swell, and suffer a reduction in density and bearing capacity from the as-built condition. Contrariwise, if compacted too wet they may lose moisture and shrink in a degree sufficient to crack the pavement. The studies made by several highway departments (9) showed clearly the need for control of moisture content and density to approach a condition of least swell and least shrinkage if damaging effects of moisture and density changes on high-volume-change clays from the as-built to the in-service condition are to be held to a minimum.

Granular soils retain a large measure of their compaction. The clayey-sands, sandy clays, and the silty soils are affected in a lesser degree and need to be compacted in accordance with the degree of protection offered by the type thickness and cross-section of the pavement used and other conditions which prevail locally. Seasonal changes which affect swell and shrinkage are the most severe in areas near and bordering semi-arid regions where long, hot dry periods may occur. Even more-severe seasonal changes may occur in humid regions where deep freezing occurs.

The freezing of wet soils results in the formation and often the segregation of ice, which on thawing, may cause a reduction in soil density. Upon the redistribution of the thaw water in the soil, there is a regain in soil density. There is evidence that some reduction occurs in the density of fine-grained soils, if they are in a saturated condition prior to freezing.

The incidence of a greater number of near-legal-axle weights in recent years and the experience on airfields give evidence that traffic has an influence on the permanence of compaction in bases and subbases. Heavy traffic may bring about an increase in density over that obtained during construction, causing a rutting of a flexible-type pavement or subsidence of a rigid pavement. Although there are a few factual data, it is quite generally believed that even relatively clean, coarse granular bases suffer some

TABLE 1

RECOMMENDED MINIMUM REQUIREMENTS FOR COMPACTION OF EMBANKMENTS

CONDITION OF EXPOSURE

Class of Soil (AASHO M 145-49	CONDITION 1 (Not Subject to Inundation)			CONDITION 2 (Subject to Periods of Inundation)		
	Height of Fill (ft.)	Slope	Compaction (% of AASHO Max. D.)	Height of Fill (ft.)	Slope	Compaction (% of AASHO Max. D)
A-1	Not Critical	1½ to 1	95+	Not Critical	2 to 1	95
A-3	Not Critical	1½ to 1	100+	Not Critical	2 to 1	100+
A-2-4	Less than 50	2 to 1	95+	Less than 10	3 to 1	95
A-2-5	Less than 50			10 to 50		95 to 100
A-4	Less than 50	2 to 1	95+	Less than 50	3 to 1	95 to 100
A-5	Less than 50					
A-6 A-7	Less than 50	2 to 1	90-95[a]	Less than 50	3 to 1	95 to 100

REMARKS

Recommendations for Condition 2 depends upon height of fills. Higher fills of the order of 35 to 50 ft. should be compacted to 100 percent, at least for part of fills subject to periods of inundation. Unusual soils which have low resistance to shear deformation should be analyzed by soil-mechanics methods to determine permissible slopes and minimum compacted densities.

[a]The lower values of minimum requirements will hold only for low fills of the order of 10 to 15 ft. or less and for roads not subject to inundation nor carrying large volumes of very heavy loads

reduction in density in frost areas, and that traffic will recompact such granular bases after the frost leaves the ground. It is now generally accepted that only that compaction can be "maintained" which will be regained by traffic.

The extent to which the original degree of compaction is preserved depends on the protection the soil receives. Full width, impervious pavements or pavements with surfaced shoulders provide more protection against infiltration of surface water than normal-width pavements with shoulders built of average soils which shrink and swell seasonally. The use of shoulders made of select, dense, low-volume-change material, the maintenance of tight joints, and the provision of good surface drainage all contribute toward maintaining density in subgrade materials.

DEGREE OF DENSIFICATION NEEDED

The purpose of compaction in the different parts of the road structure may be itemized as follows:

Part of Road Structure	Purpose of Densification
Embankments	To prevent detrimental settlement To aid in providing stable slopes
Subgrade Materials	To provide bearing capacity To control volume change To provide uniformity
Bases and Subbases	To provide uniform high bearing capacity

It should be the aim of the engineer to obtain, as nearly as possible, the densities necessary to satisfy the needs for the conditions involved.

Embankments

The minimum densities necessary in the construction of embankments[3] depend on the soil type, the height of the embank-

[3] The term "embankment," as used here, refers to that part of the raised structure below the depth of the subgrade materials influenced by traffic loads and effects of climate.

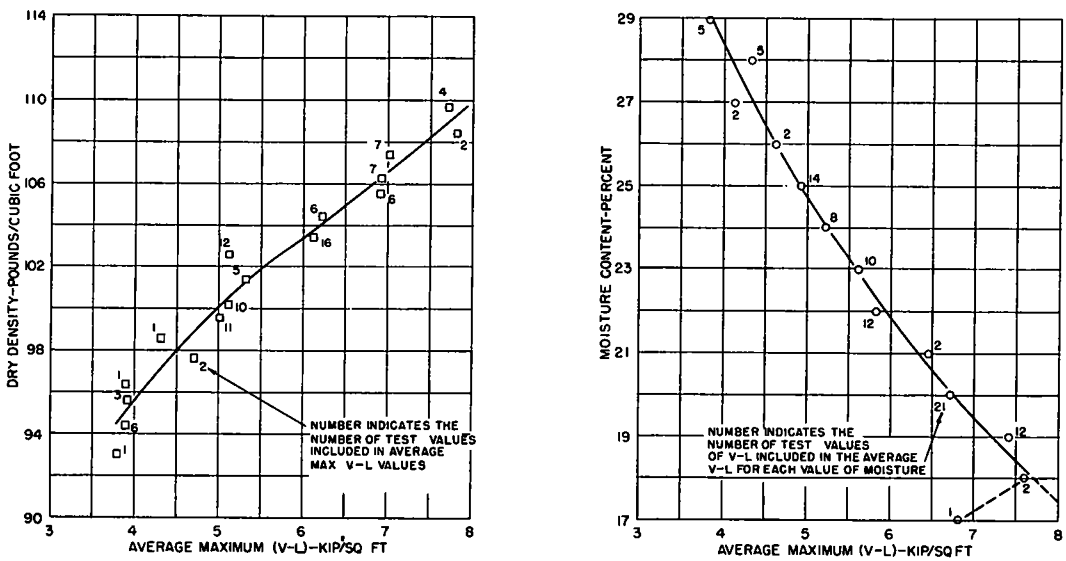
ment, the design slopes, and the condition of exposure. The necessary minimum requirements for compaction should be determined by consideration of all those factors and should not be based upon a single requirement. Sandy and gravelly soils of the A-1, A-2, and A-3 groups (13) can be compacted to relatively high densities. Some of the very-sandy soils exist in the dry, uncompacted state at densities of the order of 90 percent of AASHO maximum densities and attain densities of that magnitude or higher under normal construction procedures without benefit of rolling and have stable slopes at those densities. When they are placed where they are not subjected to wetting, there is little danger of excessive settlement. However, if subjected to saturation, they may settle in detrimental amount unless compacted to about 95 percent of maximum density. The relatively clean granular soils retain their stability when saturated.

The friable soils of the A-2, A-4, and A-5 groups can also be compacted with relative ease but require relatively high densities if stable slopes are to be built. They are more subject to reduction in shear strength on saturation and require higher densities to produce stable slopes. Normally, 95 percent compaction will produce adequate results. However, under conditions of saturation by inundation it is advisable to increase compaction to about 100 percent for high fills of the order of 35 to 50 ft.

The plastic soils (A-6 and A-7) show the greatest improvement from compaction. They should be compacted to relatively high densities (low porosities) if stable slopes are to result for the higher fills. Recommended minimum requirements for compaction of embankments are given in Table 1.

Because of their need for greater resistance to softening, reduction in strength, and erosion, embankments subject to flooding require better compaction than those not subject to inundation. Experience has shown that well-compacted soils offer much-greater resistance to stream erosion during overflows than uncompacted or poorly compacted soils. Clay soils are greatly improved in that respect.

Rigid control of moisture for soils dryer than optimum is not necessary for embankments not to be subjected to flooding. The moisture content may be within the range below optimum which permits obtaining the desired density with the compaction equipment available. Sheepsfoot-type rollers which produce high unit pressures and other types of rollers which



Figures 7 and 8. Relation of maximum V-L (triaxial shear) with density and moisture.

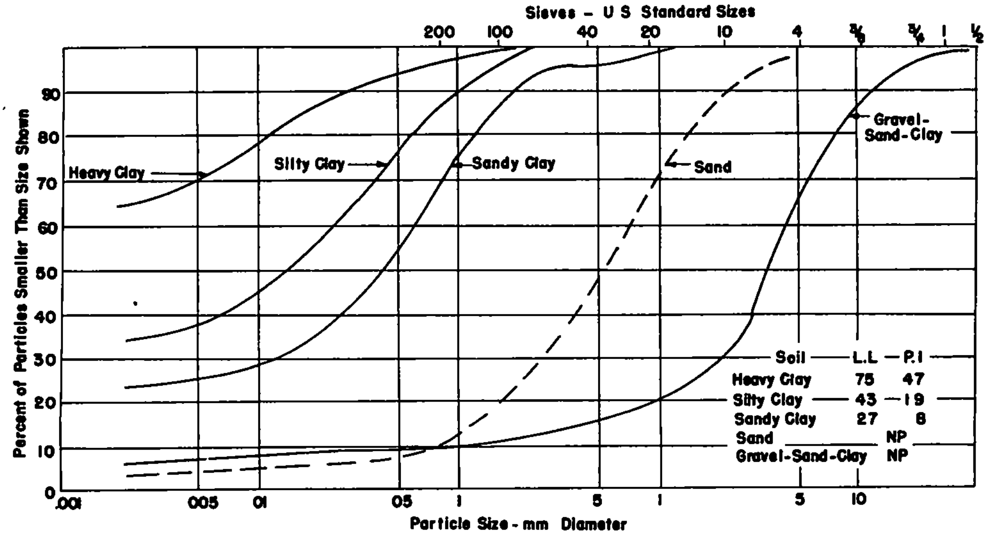


Figure 9. Grain-size distribution and Atterberg limits of soils used in British field-compaction experiments (after Williams).

produce heavy wheel loads and high unit pressures permit securing desired densities at low moisture content. Moderately plastic soils in Groups A-4 through A-7 should be compacted at moisture contents not greater than 2 or 3 percentage points over optimum to insure uniform density and to avoid the unsatisfactory construction condition of low stability and rutting under heavy construction equipment. High-silt-content soils of low plasticity in Groups A-4 and A-5 and sandy silts of Group A-4 should be compacted at moisture contents not in excess of optimum to insure uniform density and to avoid the instability and rutting under heavy construction equipment which occurs when these soils are placed at moisture contents which exceed optimum.

Soils compacted at optimum moisture content have lower permeability and a greater resistance to softening than dry soils at equal densities. Therefore, fills or portions of fills subject to inundation or scour should be compacted at moisture contents as near optimum as is practicable and economical for these conditions.

Subgrades, Subbases, and Bases

The term subgrade material (basement soil) is intended to include soil to the depth which may affect structural design or the depth to which climate affects the soil, whichever is the greater depth. Because of the effect of climate on bearing capacity and on the permanence and effectiveness of compaction, more careful consideration need be given compaction of various types of subgrade materials for different climatic conditions than is necessary for embankments. The needed density and moisture content for adequate bearing capacity may not be ideal for holding volume change within desired limits.

Several state highway departments recognize, in their methods for designing flexible type surfaces (11), that the bearing capacity of the soil must be based on a degree of saturation which occurs under service conditions. If compaction can be controlled to approximate that condition, insofar as is practical under construction methods used, there will result a minimum change in moisture content and density from the as-built to the in-service condition. Because the chief function of a subgrade is to carry loads, that function must be considered with respect to the relative permanence of the densification. The smoothness of the riding surface depends on the uniformity of compaction, hence any factor which influences uniformity also needs consideration.

Obviously the highest density obtainable consistent with a moisture content less than optimum provides the greatest bearing capacity. Nonplastic, granular soils and subbase and base materials have little or no volume change and retain a high degree of their compaction. Thus, it is advantageous from all considerations to compact those soils to high densities.

The less-plastic soils of the silty and clayey groups, which have low volume changes, decrease in bearing capacity as the degree of saturation is increased. Those soils should be compacted to moderately high densities. A reduction in density and an accompanying increase in moisture and reduction in bearing capacity occur on soils having high volume change. Thus, unless temporary advantage of high bearing capacity during the early life of the road is desired, and volume change (and road smoothness) is not a prime factor, those soils should be compacted to densities and at moisture contents which constitute the best compromise between need and permanence. Because granular soils retain compaction except in areas of severe frost and because high densities are desirable, knowledge of the practicable maximum field limits of compaction is important. Hence, recommended procedures for selecting the best densities are given later in this bulletin.

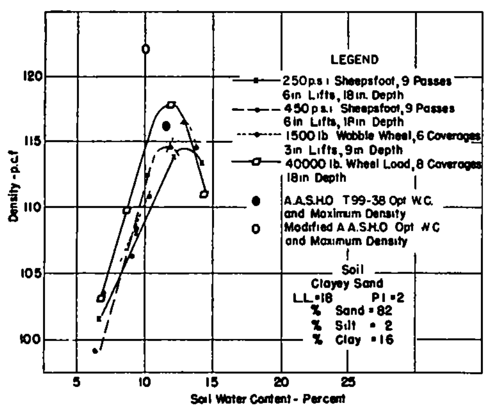


Figure 10. Typical moisture-density data from construction lifts on sandy soil (after Corps of Engineers).

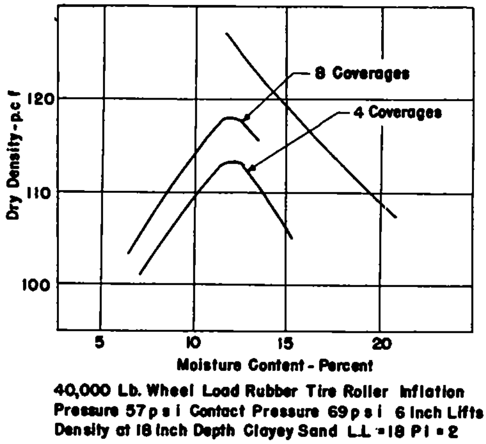


Figure 11. Typical moisture-density data from construction lifts on sandy soil (after Corps of Engineers).

Practicable Limits of Densification

The graphs in Figure 4, which illustrate the relationship between density and compactive effort from laboratory tests, indicate no decrease in rate of density gain with increase in compactive effort for the greatest compactive efforts shown. Undoubtedly that is due to compacting soils in a mold whose side-wall friction makes that possible. However, for field compaction there is a practicable maximum limit of density which can be obtained with reasonable economy for each combination of soil and compacting equipment. Specifications for bringing about the best results obtainable consistent with the desired economy cannot be arrived at without a foreknowledge of the practicable limits for various types of equipment on different types of soils.

The recent trend towards the use of higher contact pressures and heavier equipment has made possible the attainment of higher densities on well-graded, granular soils and on the more-compressible clayey soils. Their use has not increased materially the densities obtainable on very-sandy materials nor on very-friable silty soils. Data from three investigations and from several years of compaction practice make it possible to predict with reasonable accuracy the highest degree of compaction practicable with present equipment.

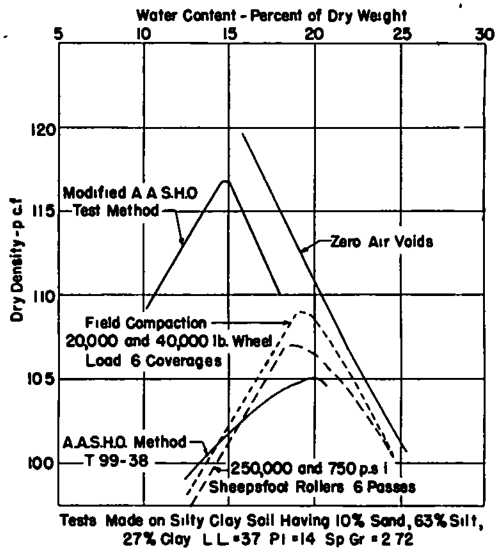


Figure 12. Results of field and laboratory compaction on silty clay soil (after Corps of Engineers).

The first of the investigations referred to were two experimental fill construction projects (12) constructed in 1938, one in Delaware County, Ohio, and the other in Gibson County, Indiana. The results of the two experiments are summarized as follows:

Rollers Used (Indiana and Ohio)

Sheepsfoot Type. Dual-drum oscillating Type 40 and 44-in. -diameter drums 48 in. wide, 88 to 112 tamping ft. per drum in rows of 4. Tamping-foot areas 5.25 and 5.5 sq. in. Tamping-foot pressures, Indiana, 209 and 290 psi.; Ohio, 223 and 290 psi.

3-Wheel Type. 10-ton, 325 and 350 lb. per inch of width of rear rolls.

Pneumatic-Tire Type. 9-Wheel, 35 psi. tire pressure, 225 lb. per inch of tire width in contact with ground.

RESULTS

Indiana

Soils. Silts and silty clay loams, P. I. range 8 to 17.

Moisture Content. Approximately optimum as determined by AASHO Method T 99.

Density, Lift Thickness, and Number of Passes.

Sheepsfoot Type. 95 to 96 percent of AASHO maximum dry density on 6-in. loose lifts in 5 to 6 passes.

3-Wheel Type. 97 to 100 percent of AASHO maximum dry density on 6-in. loose lifts in 1 or 2 coverages. 101 to 104 percent of AASHO maximum dry density on 9-in. loose lifts in 2 to 2½ coverages. 100 percent of AASHO maximum dry density in 12-in. loose lifts in 2 coverages.

Pneumatic Type. 99 percent of AASHO maximum dry density on 6-in. loose lifts in 2 coverages. 97 percent of AASHO maximum dry density on 9-in. loose lifts in 3 coverages. 97 percent of AASHO maximum dry density on 12-in. loose lifts in 4 coverages.

TABLE 2

SUMMARY OF BRITISH FIELD AND LABORATORY COMPACTION STUDIES ON FIVE SOILS

SOIL TYPE	BRITISH* STANDARD		MODIFIED AASHO		MAXIMUM FIELD COMPACTION (pcf.) AND OPTIMUM MOISTURE CONTENT (Percent) FOR DIFFERENT ROLLERS			
							SHEEPSFOOT ROLLERS	
	Density (pcf.)	Opt. M.C. (Percent)	Density (pcf.)	Opt. M.C. (Percent)	8-Ton 3-Wheel	Pneumatic Roller	"Clubfoot" (115 psi.)	"Taper Foot" (249 psi.)
Gravel-sand-clay	129	9	138	7	138-7	126-7	129-6	128-5
Sand	121	11	130	9	132-8	127-11	- -	- -
Sandy-Clay	115	14	128	11	116-14	108-19	119-12	120-12
Silty-Clay	104	21	120	14	111-16	104-20	116-14	115-14
Heavy-Clay	97	26	113	17	104-20	98-25	107-16	107-15

*British Standard Test does not differ greatly from AASHO Method T 99.

TABLE 3

BRITISH STANDARD COMPACTION ON 5 SOILS BY 4 ROLLERS

Roller	Gravel-Sand-Clay %	Sand %	Sandy Clay %	Silty Clay %	Heavy Clay %
8-ton, 3-wheel	107	109	101	106	107
Pneumatic	97	105	94	100	101
Club-foot	100	---	103	111	110
Taper-foot	99	---	104	110	110

Ohio

Soils. Approximately equal percentages of sand, silt, and clay. Majority of soils in P. I. range of 15 to 25.

Moisture Control. Majority within 1 percent of optimum.

Density, Lift Thickness, and Number of Passes.

Sheepsfoot Type. 97 to 101 percent of AASHO maximum dry density on 6-in. loose lifts in 6 to 9 passes. 97 percent of AASHO maximum dry density on 9-in. loose lifts in 6 passes.

3-Wheel Type. 101 to 105 percent of AASHO maximum dry density on 6-in. loose lifts in 2.5 to 3.3 coverages. 104 percent of AASHO maximum dry density on 9-in. loose lifts in 6 coverages.

The British Road Research laboratory (13) released results in 1950 of rolling experiments on five different soils ranging from a gravel-sand-clay to a heavy clay. The characteristics of the five soils are indicated in Figure 9. The British studies included (among others) the following types and weights of rollers:

Sheepsfoot Type. "Club-foot," fixed-frame, dual-drum type. 42-in.-diameter by 48-in. drums having 64 tamping feet per drum in rows of four with 4 in. by 3 in. (12 sq. in.) contact area, and ballasted tamping-foot pressure of 115 psi. "Taper-foot," dual-drum, oscillating type 42-in.-diameter by 48-in. drums having 88 ft. per drum in rows of four with $2^1/_4$ by $2^1/_4$ in. ($5^1/_{16}$ sq. in.) contact area and ballasted contact pressure of 249 psi.

3-Wheel Type. 8 ton, 186 lb. per in. of width of front roll 311 lb. per in. of width of rear rolls.

Pneumatic-Tired Type (with pairs of wheels on oscillating axles). 9 wheel. 36-psi. inflation pressure 39 psi. contact pressure, 3,000 lb. per wheel.

The British studies were unique in two respects. They made all tests on one thickness of lift. They obtained maximum compaction for each roller, each soil being "fully compacted" at each moisture content to enable finding maximum field density and optimum moisture content for each soil for each roller. From 4 to 16 passes were required for full compaction with pneumatic and 3-wheel rollers and from 16 to 64 with sheepsfoot types. The results bring out some interesting relationships between maximum field density and field optimum moisture content and soil type and equipment. The results of the British investigations are shown in Table 2.

Tables 3 and 4 show the relative percentages of British standard compaction and modified AASHO compaction obtained by the different types of rollers on the five soils.

TABLE 4

MODIFIED AASHO COMPACTION ON 5 SOILS BY 4 ROLLERS

Roller	Gravel-Sand-Clay %	Sand %	Sandy Clay %	Silty Clay %	Heavy Clay %
8-ton, 3-wheel	100	101	91	92	92
Pneumatic	91	98	84	87	87
Club-foot	93	---	93	97	95
Taper-foot	93	---	94	96	95

TABLE 5

STANDARD AASHO AND MODIFIED AASHO COMPACTION OBTAINED ON A CLAYEY SAND IN FIELD ROLLING EXPERIMENTS (AFTER CORPS OF ENGINEERS)

Equipment	Passes No.	Compacted Lift Thickness in.	Modified AASHO Density %	Standard AASHO Density %
250-psi. Sheepsfoot	9	6	94	98
450-psi. Sheepsfoot	9	6	93-95	97-99
1500-lb. Wobble-Wheel Pneumatic Tire	6	3	94-95	98-99
20,000-lb. Wheel-Load Pneumatic Tire	4	6	95	99
40,000-lb. Wheel-Load Pneumatic Tire	4	6	94-96	98-100
40,000-lb. Wheel-Load Pneumatic Tire	8	6	95-97	99-102

Laboratory Standard Optimum moisture content was 11.5 percent. Field optimum moisture contents ranged from 11.5 to 12.2 percent.

TABLE 6

STANDARD AASHO AND MODIFIED AASHO COMPACTION OBTAINED ON A SILTY CLAY IN FIELD ROLLING EXPERIMENTS (AFTER CORPS OF ENGINEERS)

Equipment	Passes No.	Compacted Lift Thickness in.	Modified AASHO Density %	Standard AASHO Density %
250 psi. Sheepsfoot	6	6	92	102
500 psi. Sheepsfoot	6	6	91-92	102
750 psi. Sheepsfoot	6	6	91-92	102-104
10,000 lb. Wheel Load Pneumatic Tire	6	6	92-94	103-104
20,000 lb. Wheel Load Pneumatic Tire	6	6	92-93	102-103
40,000 lb. Wheel Load Pneumatic Tire	6	6	93-94	103-104

Laboratory Standard AASHO optimum moisture content was 17.9 percent. Field optimum moisture contents ranged from 18.5 to 19.5 percent.

TABLE 7
AVERAGE DENSITIES OF
HIGHWAY SUBGRADE MATERIALS

Type of Subgrade Material	Densities	
	AASHO %	Modified AASHO %
Bases	100.5	96.5
Granular Materials	101.2	96.7
Silt-Clay Materials	96.8	88.8

The Corps of Engineers (14, 15) have conducted field-compaction experiments under conditions of close control of moisture content and rolling. The tests were made on two types of soils. One soil was a clayey sand having a plasticity index of 2. The other was a silty clay having a plasticity index of 14. A significant feature of the tests was that the effectiveness of the different rollers was compared on the basis of the number of passes which might be used normally on a construction project.

The field and laboratory moisture-density relationships obtained on the clayey sand are shown in Figures 10 and 11. The equipment used, number of passes, lift thickness, and relative densities at field optimum moisture content expressed as percentages of AASHO maximum density (T 99) and modified AASHO maximum density are shown in Table 5.

Field and laboratory moisture-density relationships for the silty clay soil are shown in Figure 12. The equipment used, and relative densities at field optimum moisture content expressed as percentages of standard AASHO and modified AASHO maximum densities are shown in Table 6.

The three rolling experiments showed that densities of 95 percent or more of Standard AASHO maximum density were obtained with relative ease. Five to six passes of sheepsfoot rollers having medium contact pressures (200 to 250 psi.); one to two coverages of 10-ton, 3-wheel-type rollers and two to three coverages of pneumatic-type rollers gave 95 percent or more of standard compaction on most soils on lift thicknesses of the order of 6 to 9 in. of loose depth (approximately 4 to 7 in. of compacted depth.) Increasing the contact pressures of the tamping feet on sheepsfoot-type rollers without some increase in the contact area brought only a small gain in compaction. The higher contact pressures were only partly effective because the bearing capacity of the soils in the loose state could not withstand the pressures and the rollers sank deeper into the soil until the effective contact pressure equalled the bearing capacity of the soil. Thus, the benefit of higher contact pressures cannot be realized unless the contact area also is adequate for the soil.

The experiments showed that 100 percent, or more, of standard (AASHO T-99) compaction was obtained by increasing the number of passes. Thus it is practicable to specify 100-percent compaction for special conditions where densities of that order are desirable. Also, some rollers are more effective on some soils than on others and some soils attain a high degree of compaction with less compactive effort than others.

Correlation of Need, Practicable Densification Limits, and Permanence

The data presented are too meager from which to develop firm rules for the

TABLE 8
DENSITIES OF SUBGRADE MATERIALS UNDER RIGID PAVEMENTS IN KANSAS

Description of Soil Group	Average Field Dry Density for Group pcf.	Average AASHO Standard Density for Group pcf.	Relative Compaction (AASHO T 99) %
Soils found under pumping slabs (all soils had less than 50% sand and gravel)	98.9	104.3	94.8
Soils having less than 50% sand and gravel from under non pumping slabs	99.8	106.8	93.5
Soils having more than 50% sand and gravel	115.5	117.6	98.3

TABLE 9
MOISTURE CONTENTS OF SUBGRADE MATERIALS UNDER FLEXIBLE PAVEMENTS
(After Kersten)

State	Textural Soil group	Saturation %	Plastic Limit %	Optimum M.C. %
Minnesota	Sandy Loam	78	75	101
Kansas	Sandy Loam	65	73	82
Arkansas	Sandy Loam	59	72	73
Minnesota	Clay	83	91	105
Kansas	Clay	92	103	112
Arkansas	Clay	92	105	109

TABLE 10
AVERAGE MOISTURE CONTENTS FOUND IN THE SUBGRADE GROUPS (after Hicks)

Class of Soil (AASHO M 145-49) group	AASHO T99 Optimum %	Plastic Limit %	Saturation %
A-1-b	82.5	36.4	69.0
A-2-4	75.5	43.7	62.9
A-2-6	104.3	62.3	85.3
A-4	106.1	65.0	82.6
A-5	114.7	54.0	89.8
A-6	109.1	75.2	85.4
A-7-5	118.9	68.2	91.2
A-7-6	109.4	70.9	90.9

selection of the most desirable limits of densification for different types of soils. However, the data do indicate trends which can be used as a broad basis for applying compaction to a good advantage. This requires a correlation between compaction needs, the limits of compaction which can be obtained practicably and the relative permanence of the compaction under the conditions of exposure expected. Through such correlation it is possible to select the range of densities and moisture contents which will result in the 'best' bearing capacity for the service life of the part of the structure in question.

Embankments. Because of the wide difference in the range of values indicative of the measures of various soil properties, hard-and-fast limiting values of densities for compaction cannot be drawn. Discussion under "Degree of Densification Needed" and the range of values in Table 1 relate need with design of slopes under the two conditions of (1) inundation and (2) not subject to inundation. The values of relative density (percent of standard AASHO) are all less than the maximum practicable limits. Hence no compromise need be made due to construction limitations. Such compromise may need to be made for very high fills indicating high compaction requirements. That must then be done by flattening slopes or using selected soils. An analysis of conditions for high fills should be made by soil mechanics methods which are beyond the scope of this report.

Subgrade Materials and Bases. The selection of the best density range for subgrade soils varies widely because of the difference in the behavior of soils under service conditions. It is entirely possible that the compaction which is deemed best from the designers point of view is not practicable for construction and contrary, that deemed best from the construction point of view may not provide the desired subgrade condition.

It is not possible to present in tabular form recommended compaction limits for subgrade materials for all types of pavements, loadings, soil types and climatic conditions. The best that can be done here is to consider need, permanence, and practical limits and set forth a method of analysis for arriving at the best density range.

Hicks (16) found from his field survey of moisture contents and densities in road subgrade materials and bases under flexible type pavements that heavy vehicles will cause a higher degree of densification than will light vehicles and

TABLE 11
INFLUENCE OF COMPACTION ON MOISTURE CONTENTS OF GRANULAR BASES (after Hicks)

Average Density %	Standard Optimum Moisture Content %	Plastic Limit %	Saturation %
	(For Densities Under 100%)		
98.5	75.0	43.8	60.3
	(For Densities 100% and Above)		
101.1	73.1	40.6	61.1

a large volume of traffic will bring about density equilibrium quicker than will a small volume of traffic. Thus traffic is an important consideration. He found that traffic will maintain densities greater than 100 percent of AASHO maximum density in granular subgrade material but densities in silt-clay subgrade material were much lower. Average values from his survey are given in Table 7.

Some of the recent studies of pumping of rigid type pavements yielded data on relative densities of subgrade soils under pavements which had been in service several years. The results from the Kansas Investigation (17) which was limited largely to the eastern one-half of the State show average values of density for each of three broad soil groups for that locality. The results are shown in Table 8.

The densities found in granular soils under rigid type pavements in service were found higher than those of the finer grained soils.

Kersten's (18, 19) study of the moisture contents of soils under flexible pavements and the reports of the Highway Research Board Committees on Warping (20) and Pumping (21) of Concrete Pavements provide evidence of the range of moisture contents which exist in subgrade materials under pavements. The average values obtained in three States from Kersten's work indicate the range of soil moisture found under flexible pavements in those localities. The values are given in Table 9 for only two different types of soils to show the difference in soil moisture content for sandy loam soils and clay soils.

Hicks' 1948 report of seasonal measurements of subgrade soil moisture contents under flexible type pavements also showed that soil moisture is related to soil texture. The relationship expressed in terms of average moisture contents found in the various Subgrade Soil Groups, (Soil Classification Method AASHO M 145-49) is shown in Table 10.

Generally the soil moisture increased during the fall and winter, reached a maximum during the month of April and receded to a minimum during late summer or early fall.

Hicks also reported on the relationship between densities and average moisture contents of granular bases. The average densities (expressed as percentages of AASHO T 99 maximum densities) and moisture contents are given in Table 11.

Studies in Tennessee showed average moisture contents of 23 percent compared to an average plastic limit of 19 for fine grained plastic subgrade soils (having less than 50 percent sand and gravel) under rigid type pavements. The corresponding values for Kansas were 24.8 and 19.4 respectively. Moisture contents of the more granular soils (having more than 50% sand and gravel) were 17.7 and 13.6 and their plastic limits were 15 and 14.1 respectively. Moisture contents in Illinois subgrade soils underlying granular bases averaged 22.5 percent and corresponded to an average plastic limit of 21.3 percent. Thus the fine grain subgrade soils existed at a condition near saturation while the granular soils existed at a condition of about 83 percent saturation.

It is recognized that the values given will not hold for all climatic conditions. They do however, point out that there is a range for density and for moisture content which can be maintained for each type of soil and type of pavement for a given locality. It follows that the least volume change will occur if compaction is aimed at the range which is most apt to "stay put" in the subgrade material. The range of desirable moisture content can be obtained for any locality by a survey of field conditions on pavements which have been in service for some time. It should be kept in mind that they reflect in some degree the initial moisture contents and densities at which they were compacted.

In arriving at the best ranges of moisture content and density, it is desirable to make an analysis of the needs for the conditions and correlate those needs with other factors. One way of making such analysis consists of stating design and construction requirements and the corresponding ranges of moisture content and density. The desirable values for one may not coincide with that for the other, necessitating a compromise to obtain the best practicable values. Examples 1 and 2 illustrate that approach for determining the best range of values.

EXAMPLE 1

Conditions: A rigid pavement, a subgrade soil exhibiting high-volume change overlaid by a 4- to 6-in. granular base.

DESIRABLE DESIGN REQUIREMENTS

Description of Requirements	Corresponding Approximate Range of	
	Density (% of AASHO Maximum Den.)	Moisture Content (% of Optimum)
Maximum bearing values consistent with minimum swelling or shrinking from as-built to in-service condition and from season to season for maintenance of smooth riding surface.		
1. Due to soil swell or shrink	90-95	100-115
2. Due to freezing and thawing	90-95	less than 65[a]

CONSTRUCTION REQUIREMENTS AND LIMITATIONS

Adequate Bearing Capacity		
a. For hauling purposes when subgrade is subject to construction traffic	95-100	95-100
b. When paver and trucks do not use area to be paved	No construction requirements. The density and moisture values may be as desired within reasonable limits.	

[a]The effect of density on frost action is not well established. Meager data show that, for certain conditions, heaving increases with increases in density to a maximum, then decreases. The effect of moisture content is known to be great. No significant heaving and accompanying softening occurs at moisture contents below the value given.

EXAMPLE 2

Conditions: A densely-graded, granular base of nonplastic materials of considerable depth for a flexible pavement carrying a large volume of heavy traffic.

DESIRABLE DESIGN REQUIREMENTS

Description of Requirements	Corresponding Approximate Range of	
	Density (% of AASHO Maximum Den.)	Moisture Content (% of Optimum)
Maximum bearing capacity which can be maintained under the traffic carried	105-115[a]	95-100

CONSTRUCTION REQUIREMENTS AND LIMITATIONS

Maximum practicable density obtainable with heavy rollers is only construction limitation	105-110[a]	95+

[a]These values vary with type of materials. It is assumed in this statement that the thickness of the base course is adequate to carry such loads without overstressing the subgrade.

The best compromise value for the clay soil will depend on the exact properties of the soil and conditions under which it must serve. Except for a very-high-volume-change soil or for semiarid or subhumid conditions, a range of density centering about 95 percent of AASHO T 99 is adequate. For semiarid and subhumid conditions on the very heavy clay, a value of 90 percent or less may be necessary. Subgrades for intermediate soils of low volume change may well be compacted to densities of 95 to 100 percent.

The compromise on the granular base material is entirely that of obtaining the maximum density practicable. That may require the use of relatively heavy rollers or the use of thin lifts and close control of moisture content to obtain the high degree of compaction which is desirable for bases.

A suggested range of densities for subgrade soils and base materials is given in Table 12. It is recognized that a desirable range of density and moisture content for a semiarid or subhumid climate may differ from that of humid climate. Likewise, small differences may be desirable in southern compared to northern climes, especially on soils whose susceptibility to freeze damage bears a strong relationship to degree of densification.

Shoulder Materials. Because of the severe exposure of shoulder materials to the climatic elements, it is poor economy to compact fine-grain clayey soils in road shoulders to high densities. If compacted to high densities they will swell and prevent good surface drainage. Moisture contents for compaction are not critical and need be only sufficient to obtain good bonding, or knitting, of the soil to minimize erosion. The following tabulation suggests desirable ranges of compaction limits for shoulder materials.

TYPE OF SOIL	DENSITY RANGE (% of AASHO T 99 Max. D.)	MOISTURE CONTENT RANGE (% of Optimum)
Fine-grained clay	85-90	75-100
Silts and sands	90-95	85-100
Granular material	Roll in a moist condition with smooth-wheel or rubber-tire roller.	

METHODS OF SPECIFYING COMPACTION REQUIREMENTS

There are three methods in use for stating minimum requirements for compaction: (1) controlling soil density, (2) controlling compactive effort, and (3) a combination of 1 and 2.

Each of the methods can be made to produce satisfactory compaction if it controls soil moisture content and is properly applied to the existing conditions. Each has some advantages as well as disadvantages. It is the purpose here to point out the advantages and disadvantages of the methods.

Control of Density

The problem of compaction is basically one of controlling the amount and size of pore spaces of the soil. When the specific gravity of the soil is relatively uniform, controlling the dry weight per cubic foot gives close control of porosity. A large majority of agencies specifying control of compaction do so through the medium of controlling dry weight per cubic foot and also stating maximum and minimum limiting values of moisture content. In most instances the AASHO T 99 maximum density and optimum moisture content form the basis for the specification as, for example, specifying a minimum compaction of 95 percent of AASHO maximum density and a moisture content range of 90 to 110 percent of optimum moisture content.

Some of the advantages and disadvantages of that method may be stated briefly as follows:

Advantages

1. Because soils seldom differ greatly in specific gravity, it constitutes a definite means for measuring the degree of densification obtained.

2. Unless encumbered with other restrictions it gives the constructor a wide range in latitude of equipment and methods to acquire the desired compaction.

Disadvantages

1. It does not tell the constructor

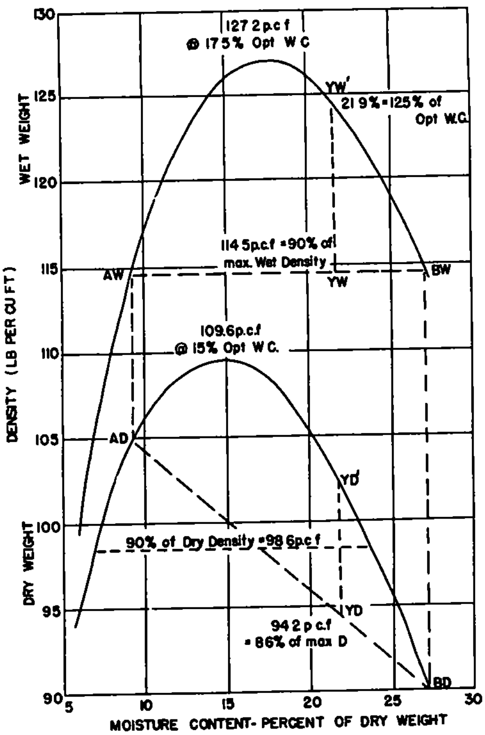


Figure 13. Interrelationships between specified values based on wet- and dry-volume weights.

which equipment is best suited, nor how much rolling is necessary to obtain the specified density.

2. It requires field testing equipment and personnel.

3. It requires some time, depending on equipment and method and skill of the inspector, to measure the dry density.

4. In unusual cases where specific gravities are not known and may differ markedly, it does not reflect the true densification of the soil.

5. There is sometimes danger that a soil may be improperly identified and an improper laboratory density value assigned. Care is needed to compare field and laboratory values for similar materials.

The degree of compaction may also be controlled by specifying limits of wet weight per cubic foot. This method has the advantage in that wet weight per cubic foot can be determined rather quickly in field testing. However, if it is accompanied by control of moisture it has no advantage over the dry density method and has even greater disadvantages. Figure 13 shows a typical dry weight-moisture content relationship and the corresponding relationship between wet weight per cubic foot and moisture content. Density and optimum moisture content values are: maximum dry density 109.6 per cu. ft., maximum wet density 127.2 per cu. ft., optimum moisture content 15 percent, optimum moisture content 17.5 percent.

If for example, a minimum wet weight of 90 percent of maximum is specified (114.5 per cubic foot wet weight) that wet weight will require a minimum dry weight of 104.9 per cubic foot (equal to 95.7 percent of maximum dry weight) at 9.2 percent moisture content. If no maximum moisture content is specified and the field moisture-density relationship is similar to the wet weight curve, a dry density 90 pcf. (equal to about 82 percent of maximum dry weight) is permitted at the moisture content approaching saturation. If for example, the moisture content is limited to a maximum of 125 percent of optimum[4] (wet weight per cubic foot) or 21.9 percent, the density requirement of 90 percent of maximum wet weight will permit a dry weight of 94.2 pcf. which is equal to 86 percent of maximum dry weight. Thus, if the specification is stated as a percentage of maximum wet weight, it permits a decrease in dry weight (and a marked decrease in bearing capacity) with increase in moisture content. That should be taken into consideration and accounted for in determining specification limits based on wet weight per cubic foot.

Control of Compactive Effort

There are two methods of specifying control of compaction by specifying requirements controlling the compactive effort used. One method which is used by many agencies is that of specifying types and weights of rollers, and by controlling

[4] Normally too wet for ease in handling

lift thickness and the amount of rolling. The amount of rolling is governed by specifying the number of passes or coverages or by including roller hours as a bidding item and placing control of the total effort used under the immediate supervision of the project engineer. This method of control usually includes control of soil moisture content. Often this method also includes specification requirements relating the number of compaction units to the rate of earth moving or requires a maximum output per compaction unit.

A second method which has been proposed by some engineers differs from the present density-control method only in the manner in which it is put to use. It consists of specifying a given compactive effort for the material to be compacted, if it be embankment, subgrade, or base. For example, it is indicated that some base materials can be compacted in the field to the density obtained in the laboratory under two AASHO T 99 compactive efforts (2 times 12,375 ft.-lb. per cu. ft.). That compactive effort then forms the basic requirement and the maximum density obtained at the compactive effort is the density to be obtained in the field. The compactive effort can be applied to the identical sample removed from the base in the in-place density test, and used to determine the sufficiency of field compaction. If, for example, it is found that a density less than that of Standard AASHO Method T 99 is required for a clay subgrade soil, specifications might be based on compactive effort equal to 80 percent of standard effort (9,900 ft.-lb. per cu. ft.) which would be equivalent to 20 blows of a 5½-lb. hammer dropping 1 ft. on each of three layers.

The first method given above has the advantage of keeping control in the hands of the engineer. The effectiveness and economy of the method depend in a large degree on the care with which the quantities are set up and the resourcefulness of the project engineer and his knowledge of soils and the use of equipment for compaction. It has the disadvantage of preventing resourceful contractors from developing and using better equipment and methods for compacting soil to arrive at a lower construction cost.

The second method has not yet been developed. It has the obvious advantages of the density method without the disadvantage of present methods which specify some percentage, usually less than 100 percent, of the density obtained under standard compactive effort.

Most specifications for compaction combine density control with control over equipment, giving minimum requirements for equipment (as to size, weight, and ratio of units to rate of earth moving), lift thickness, and control of moisture content.

SELECTION AND USE OF EQUIPMENT

The success, that is, the economy and ease, of obtaining compaction depends in large measure on the methods and on the type and weight of equipment used for rolling. It also depends on the equipment and methods used in placing and preparing the soil for rolling.

Dumping and Spreading

Compaction depends on the size of the loaded area, the pressure exerted on the loaded area, and on the lift thickness. Lift thickness is an important factor governing the degree of compaction obtained. Many of the difficulties of obtaining the desired compaction can be traced to lift thickness in excess of that which can be handled by the rolling equipment used. It varies for different types of soils for a given piece of rolling equipment.

Proper spreading is largely a matter of attention to the job. It can be done directly by adjusting scrapers during dumping. Proper spacing of dumps from wagons makes a simple job of bulldozing or blading of the loose soil to proper lift thickness. Close attention to the effectiveness of the roller in early trial runs will soon indicate the best lift thickness for the various types of soils.

It is not possible to predict the exact lift thickness which results in the most economical rolling for all soils and types and weights of equipment. However, some general rules can be laid down. Generally, the heavier the equipment the greater the lift thickness which can be handled. The rule does not hold in the

TABLE 12

SUGGESTED RANGE OF DENSITIES FOR SUBGRADE SOILS AND BASE MATERIALS IN CONSTRUCTION

TYPE OF SOIL	TYPE OF PAVEMENT		MINIMUM DENSITY RANGE (PERCENT OF AASHO MAXIMUM DENSITY)	MOISTURE CONTENT RANGE (PERCENT OF AASHO OPTIMUM)	REMARKS
Moderate to high volume change predominantly clayey soils	Flexible		95-100	95-100	
	Rigid	Condition 1	90-95	100-110	When construction traffic does not use prepared subgrade.
		Condition 2	95+	<100	When construction traffic hauls over prepared subgrade.
Predominantly silty and sandy soils having little or no volume change	Flexible		100±3	95-100	
	Rigid		100±3	95-100	
Good quality granular materials suitable for base and subbase construction.	Flexible		100-110	95-100	Maximum practicable density varies with type and grading of material. A maximum range can be selected according to material.
	Rigid		100-105	95-100	For condition 1 above[a]
			100-110	95-100	For condition 2 above

[a]The lower range of densities and higher range of permissible moisture contents for Condition 1 may make it difficult to obtain high densities in base materials.

TABLE 13

EQUIPMENT AND METHODS FOR ADDING WATER PRIOR TO COMPACTION

TYPE OF SOIL	EQUIPMENT AND METHODS FOR INCORPORATING WATER WITH SOIL
Heavy Clays	Difficult to work and to incorporate water uniformly. Best results usually obtained by sprinkling followed by mixing on grade. Heavy disc harrows are needed to break dry clods and to aid in cutting in water, followed by heavy-duty cultivators and rotary speed mixers. Lift thickness in excess of 6 in. loose measure are difficult to work. Time is needed to obtain uniform moisture distribution.
Medium Clayey Soils	Can be worked in pit or on grade as convenience and water hauling conditions dictate. Best results are obtained by sprinkling followed by mixing with cultivators and rotary speed mixers. Can be mixed in lifts up to 8 in. or more loose depth.
Friable Silty and Sandy Soils	These soils take water readily. They can often be handled economically by diking and ponding or cutting contour furrows in pit and flooding until the desired depth of moisture penetration has taken place. That method requires watering a few days to 2 or 3 weeks in advance of rolling (depending on the texture and compactness of the soils) to obtain uniform moisture distribution. These soils can also be handled by sprinkling and mixing, either in-pit or on-grade, and require relatively little mixing. Mixing can be done with cultivators and rotary speed mixers to depths of 8 to 10 in. or more without difficulty.
Granular Base and Subbase Materials	These materials take water readily. Best results are obtained by sprinkling and mixing on the grade. Any good mixing equipment is adequate.

same proportion for sheepsfoot rollers as for other types, because some stock models have about the same length of tamping foot regardless of the contact pressure and size of tamping feet. In any instance, the maximum lift thickness which can be compacted in different soils should be determined during the early stages of rolling on a project. Small differences in soil moisture may make the job values differ markedly.

Adding Water to Soil

It is often necessary to increase the moisture content of embankment soils, subgrade materials, and base materials to make it possible to obtain the desired degree of compaction and the uniformity. Due to the variable conditions encountered, there can be no single method nor piece of equipment which is always superior. The soil can be watered on the grade or in the pit. Although sprinkling is most commonly used, there are instances where watering can be done most economically by flooding the pit, provided that the water soaks in readily to adequate depths. There are also some differences in the relative efficiency of various pieces of mixing equipment on different soils. Table 13 summarizes some rules which have been found to be useful in incorporating water into soils and base materials.

Handling Excessively Wet Soil

When the soil moisture content markedly exceeds that needed to obtain the required density, the moisture content must be reduced or the soil must be relegated to a use where the excessive moisture content is not detrimental. Drying great quantities of soil from highway cuts is at best a slow and costly process. It has been done successfully by the use of aggregate-drying kilns similar to those used in asphalt plants. However, most drying has been air drying, which relies on aeration and exposure to the sun's rays to remove excess moisture. In drying by aeration, the object is to manipulate and expose the wet soil to the air and sun and to keep mixing and reexposing wet soil to promote the fastest drying practicable. Manipulation can be done by the use of plows, cultivators, or rotary mixers. Rotary speed mixers, with their tail-hood sections raised, permit good aeration and constitute one of the best methods of facilitating soil drying.

Where wet soils must be used and where dry soils are also available, the mixing of the two has proved a good way to reduce the excess moisture content in the wet soil. Rapid mixing can be accomplished with the use of rotary speed mixers. Another method which has been used is alternate-layer construction, where a layer of wet soil about a foot deep is covered with a layer of dry, stable soil. The thickness of the layer of dry soil is adjusted to that necessary to permit hauling equipment to be carried, so both layers can be compacted sufficiently to provide a stable embankment.

If wet soils are encountered in only the surface soils, the simplest method is to blade off or otherwise remove the excessively wet topsoils. That will in many cases permit construction to proceed using the subsoils.

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 being covered with a second layer of wet material, should the quantity of wet material make that necessary.

Sheepsfoot-Type Rollers

The weight of the roller, the area and shape of the feet, and the spacing of the feet are variables in the sheepsfoot roller which influence compaction. Other variables include soil type, moisture content, initial density, and thickness of lift. The existence of so many variables makes it difficult to present specific recommendations on the selection and use of that type of roller without many reservations. The best that can be done at this time is to discuss the effect of the variables and then make recommendations based on the trends which have developed to date.

The contact pressure should be as large as possible without greatly exceeding the bearing capacity of the soil. If that is exceeded, the roller will sink deeper until greater contact area reduces

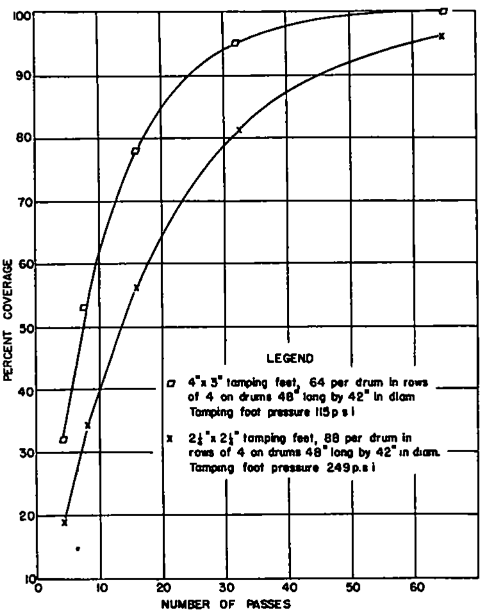


Figure 14. Relationship between number of passes of sheepsfoot rollers and percent coverage which may be expected from random rolling (after Williams and Maclean).

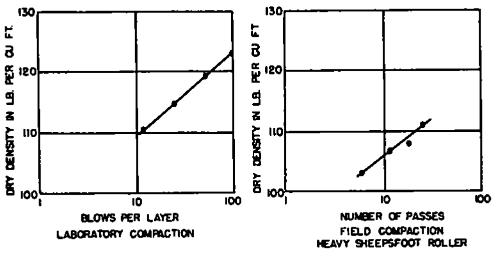


Figure 15. Relationship between compactive effort and dry density (after Corps of Engineers).

the contact pressure to that which the soil will carry, even if it must sink so far the drum makes contact with the soil. The bearing capacity increases with increase in density, which explains why a sheepsfoot roller "walks up" when contact pressure is not too great (22).

The bearing capacity decreases with decrease in size of loaded area for granular soils, which depend on their frictional qualities for bearing capacity. Increasing the size of the loaded area increases not only the total but also the unit-contact pressures which can be used effectively. Excessive pressures and small contact areas will shear the soil. Although nominal tamping-foot areas seldom exceed 7 sq. in., there is ample experience to indicate that greater areas are desirable for the friable soils, which are dominantly silty or sandy in nature.

There is little evidence to indicate that increasing the length of tamping feet will permit more efficient compaction by permitting greater thickness of lift. Some increase in lift thickness is gained by increasing contact pressures on the larger feet, but the inherent character of the sheepsfoot roller is such that stock models can seldom compact efficiently to depths greater than 10 to 12 in. of compacted thickness.

TABLE 14

CONTACT PRESSURES AND SIZES OF TAMPING FEET BEST SUITED FOR COMPACTING DIFFERENT SOILS WITH SHEEPSFOOT ROLLERS

SOIL TYPE	CONTACT AREA (sq. in.)	CONTACT PRESSURE (p.s.i.)	REMARKS
Friable silty and clayey sandy soils which depend largely on their frictional qualities for developing bearing capacity.	7-12	75-125	These groupings are based on stock models for use in compacting to densities of about 95% AASHO T 99 maximum density at moisture contents at or slightly below optimum when 6- to 9- in. compacted lift thicknesses are developed. It is also based on the experience that rollers are most easily towed when their weight allows them to begin to "walk up" as rolling progresses. It is realized that much heavier contact pressures may be more desirable if contact areas are increased and that such increases are necessary if higher field densities are to be produced.
Intermediate group of clayey silts, clayey sands and lean clay soils which have low plasticity.	6-10	100-200	
Medium to heavy clays.	5-8	150-300	

The spacing of the feet has a bearing on contact pressures and percent coverage, that is, the actual area of tamping feet in contact with the ground in one pass divided by the area passed over. Other things being equal, the greater the tamping-foot area, the fewer passes required to compact the soil. It has been shown in actual rolling tests (23) that random rolling will give 32 percent coverage in 4 passes and 53 percent coverage in 8 passes of a roller having 64 3-by-4-in. tamping feet per drum (42 in. diameter by 48 in. long) and corresponding values of 19 and 34 for a roller having similar size drum but having 88 $2^1/_4$-by-$2^1/_4$-in. feet per drum ($5^1/_{16}$ sq. in.). The relationship between percent coverage and number of passes is shown by the two curves in Figure 14. The values given for the two rollers will serve to indicate comparable values for other rollers.

The number of passes has large influence on the degree of densification obtained. It has been found that the relationship between density and number of passes is approximately a straight line when plotted on semilogarithmic paper, as is the relationship found in the laboratory between number of blows and the density obtained in the laboratory compaction test. However, rolling beyond a given number of passes is uneconomical. Comparable relationships are shown in Figure 15.

An additional factor influencing selection of the proper sheepsfoot roller is the rolling radius, because it determines in some degree the force required for towing as well as its maneuverability. The smaller the rolling diameter (diameter of drum plus feet) for a given weight, the greater is the drawbar pull both in the straight-away and in turning.

The factors to be considered in the selection of a roller which will compact the soil to the desired density in the least amount of time are: (1) select the maximum contact pressure which the soil can carry without shear failure as evidenced by failure of the soil to compact under rolling, and (2) select the roller which satisfies No. 1 and which also gives the greatest coverage per pass.

Table 14 may be used as a guide in the selection of rollers for three broad groups of soils. It must be borne in mind that unit contact pressures far in excess of those shown are being used and are giving good results. However, those rollers are settling to a depth which adjusts the contact pressure to that of the soil, hence do not walk up and require greater drawbar pull for towing. It should also be borne in mind that plastic soils at moisture contents well below optimum require much greater contact pressures if adequate densities are to be obtained.

Methods of Rolling. When commencing compaction on a project, even though operators and inspectors are experienced, it is well worth while to conduct tests on trial lifts to determine the best rolling procedure. Assuming there is no choice of equipment (as to size of tamping feet), then test rolling is limited to determining the best lift thickness which can be compacted, the number of passes required for the major soil types encountered, and the need for increasing or decreasing foot pressures. Such test rollings should include a minimum of variables, and the soil should be at optimum moisture content. Usually three lifts are sufficient to show minimum rolling necessary to produce the required density. For example, loose lifts of 6, 9, and 12 in. are spread and strips of each are rolled 4, 7, and 10 passes of the roller. Density tests will indicate the most effective combination. If the roller walks up too fast and densities are inadequate, the lift thickness may need to be reduced or the foot pressure increased, or both; contrariwise, if the roller does not walk up or sinks deeper with increasing number of passes, the shear strength of the soil is being exceeded and the foot pressures need be decreased by removing ballast from the roller. In either instance the moisture content may need adjustment.

The length of the rolled area, while otherwise not significant, may have large influence on densities in hot summer months when evaporation is high. Quick handling of soils on the grade often means the difference between adequate densities with few passes and the addition of and mixing in of water. Routing construction equipment so its compacting effect is well distributed may decrease materially the rolling required. Roller speed, within the range normally used in towing

TABLE 15

RANGE OF COMPRESSION OF 3-WHEEL ROLLERS

Weight Group	Range of Compression of Drive Rolls
Light (5 to 6 tons)	150 to 225 lb. per lin. in. of width of drive rolls
Medium (7 to 9 tons)	225 to 300 lb. per lin. in. of width of drive rolls
Heavy (10 to 12 tons)	300 to 400 lb. per lin. in. of width of drive rolls

sheepsfoot rollers behind tractors, has little influence on effectiveness.

The proper balance between earth-moving equipment and compaction equipment is necessary if compaction is to be adequate and economical. Productive capacity of a given group of trucks, wagons, or scrapers can be estimated for any given group by the number of units of each size delivered to the dump. The roller capacity of sheepsfoot rollers in terms of cubic yards of compacted soil can also be determined with reasonable accuracy. The two values should balance as nearly as possible, with ample reserve

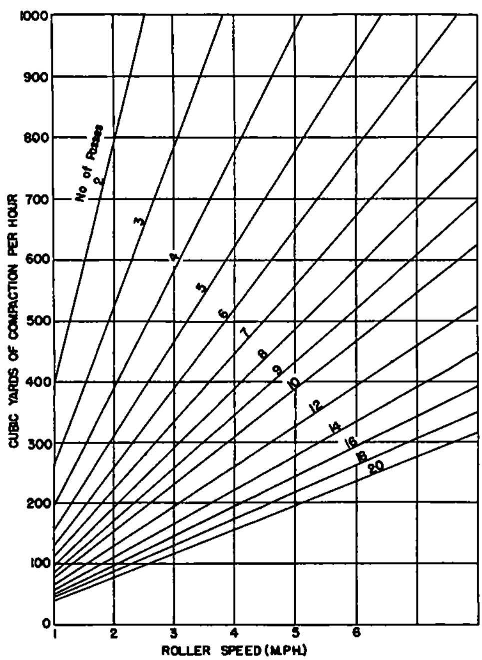


Figure 16. Maximum rolling capacity of sheepsfoot rollers (based on 6-in. compacted lift and 8-ft. compacted strip with no overlap; continuous operation).

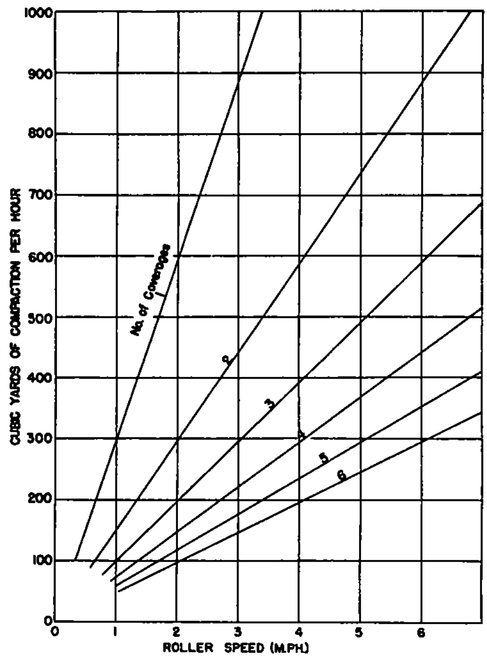


Figure 17. Maximum rolling capacity of 3-wheel roller. (Based on 10- to 12-ton nominal size having 20-in.-wide rear rolls spaced 36 in. apart providing 2-in. overlap and complete coverage by rear rolls, 6-in. compacted lift).

roller capacity available if conditions change from a soil which rolls with a minimum of rolling to one which requires greater effort.

Figure 16 shows graphically the maximum possible productive capacity of a given sheepsfoot roller (dual-drum type with 4-ft. drums) for different numbers of passes and different operating speeds when compacting a 6-in. compacted lift. Similar charts may be constructed for other thicknesses of lift.

Since increases in speed within reasonable limits do not change the effec-

TABLE 16

RANGE OF COMPRESSION OF 3-WHEEL ROLLERS OBTAINED BY BALLASTING

Weight Class	Compression Pressures in Lb. per Lin. In. of Width of Rolls: Guide Roll	Drive Roll
5-6	99-129	153-196
6-8	119-162	178-241
7½-10	136-177	218-284
9-12	157-212	236-317

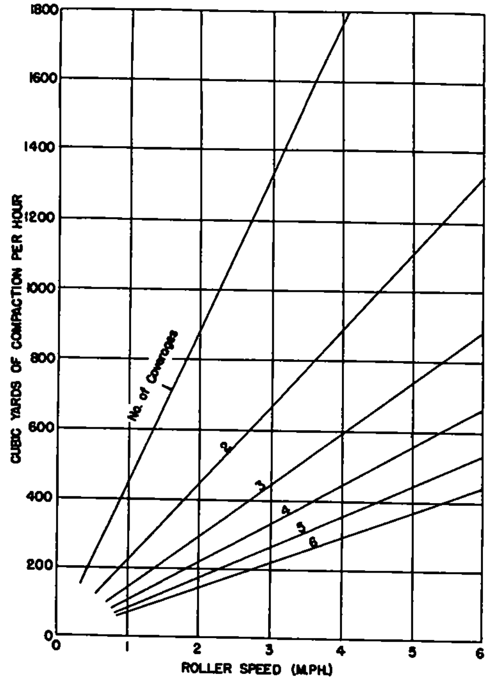


Figure 18. Maximum rolling capacity of 3-wheel roller (on same basis as Fig. 15, except 9-in. compacted lift).

tiveness of sheepsfoot rollers, it may be seen in Figure 16 that the productive capacity is directly proportional to the operating speed. This makes it worthwhile to consider speed when specifying roller hours.

Smooth-Wheel Power Rollers

Smooth-wheel steel rollers of 3-wheel type have long been used to obtain compaction of soils. Tandem-type rollers are not widely used for earth work but are used for final surface compaction of subgrades and bases. Normally the 3-wheel type is used in earthwork com-

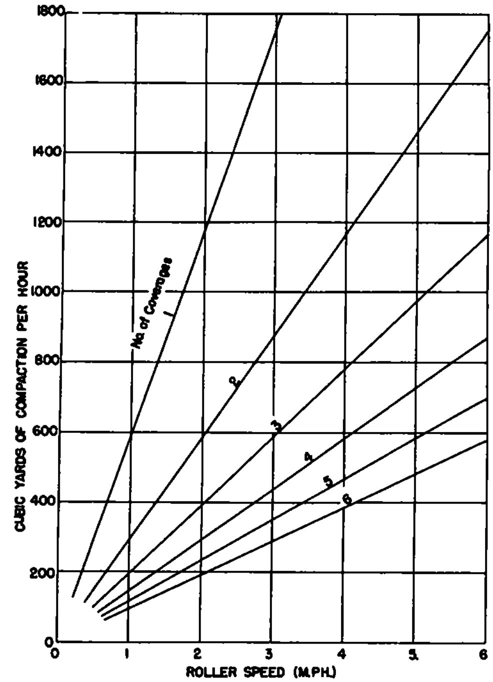


Figure 19. Maximum rolling capacity of 3-wheel roller (on same basis as Fig. 15, except 12-in. compacted lift).

TABLE 17
PRESSURE AND WEIGHT CLASSES OF 3-WHEEL ROLLERS SUITED FOR COMPACTING DIFFERENT SOILS

Soil Group	Weight Group and Pressure (Wt. per Lin. In. of Width of Rear Rolls)
Clean, well-graded sands, uniformly graded sands (one size), and some gravelly sands having little or no silt or clay	Cannot be rolled satisfactorily with 3-wheel type rollers
Friable-silt and clay-sand soils which depend largely on their frictional qualities for developing bearing capacity	5 to 6 tons, 150-225 lb.
Intermediate group of clayey silts and lean clayey soils of low plasticity (<10)	7 to 9 tons, 225-300 lb.
Well-graded sand-gravels containing sufficient fines to act as filler and binder	10 to 12 tons, 300-400 lb.
Medium to heavy clayey soils	10 to 12 tons, 300-400 lb.

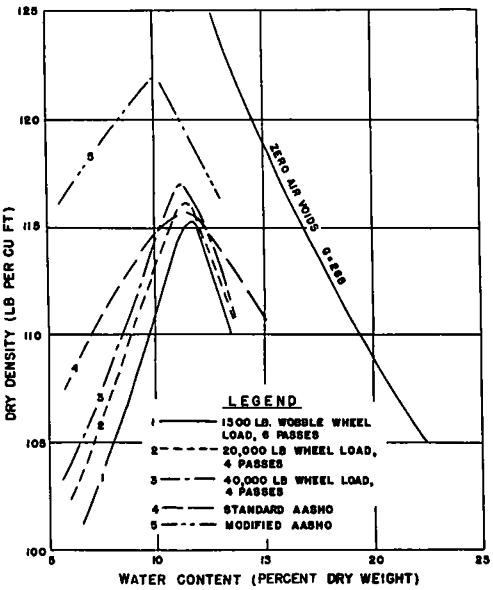


Figure 20. Comparison of field and laboratory compaction data for clayey sand (after Corps of Engineers).

paction, because of the greater pressure exerted by the rear (driving) rolls.

Rollers of the 3-wheel group may be obtained in a wide range of sizes and weights. The 3-wheel types may, for convenience, be divided into three weight classes. The weight classes and the approximate range of contact pressures, expressed in terms of pounds for linear in. of width of tire on the drive rolls, are given in Table 15.

Some manufacturers make no provision for ballasting 3-wheel-type rollers to provide a range of compression for a given weight. Others do, however, provide for ballasting to give a range between maximum and minimum pressure sufficiently great to be of value in adjusting a given weight class for best performance on different soils. An example of one manufacturer's specifications is given in Table 16 to illustrate the range of compression which may be obtained by ballasting.

The principles which govern the relationship between contact pressures and compaction apply to 3-wheel type rollers equally as well as to the sheepsfoot type; 3-wheel rollers adjust their contact pressures to the bearing capacity of the soil by simply sinking to that depth which provides adequate area to equalize the unit pressure.

The 3-wheel type has the advantage of giving complete coverage wherever the drive rolls pass. The passage of the guide roll often compacts the soil sufficiently to build up a bearing capacity adequate for the drive rolls. The heavier units of this type (10 to 12 tons or greater) can often compact lifts of 10 to 12 in. or greater in depth, especially on friable, fine-grained soils.

The proper balance between capacity of hauling equipment and roller capacity is important for 3-wheel rollers. If sheepsfoot rollers are towed by tractors having adequate capacity, they are more flexible in terms of capacity, because their towing speed can be increased or decreased. That range is not so great for 3-wheel rollers. The charts shown in Figure 17, 18, and 19 permit rapid estimate of the rolling capacity of 3-wheel rollers of 10-to-12-ton capacity for com-

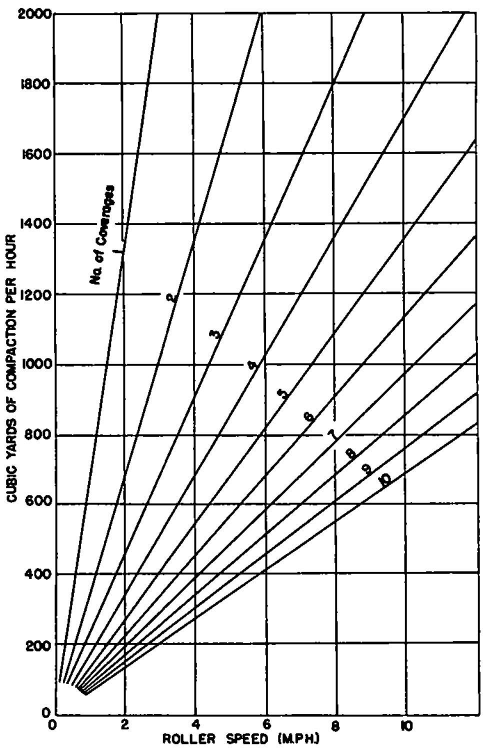


Figure 21. Maximum rolling capacity of pneumatic-tire roller (based on 2-axle, 13-wheel, type, rolling width, 84 in, no overlap, 6-in. compacted lift).

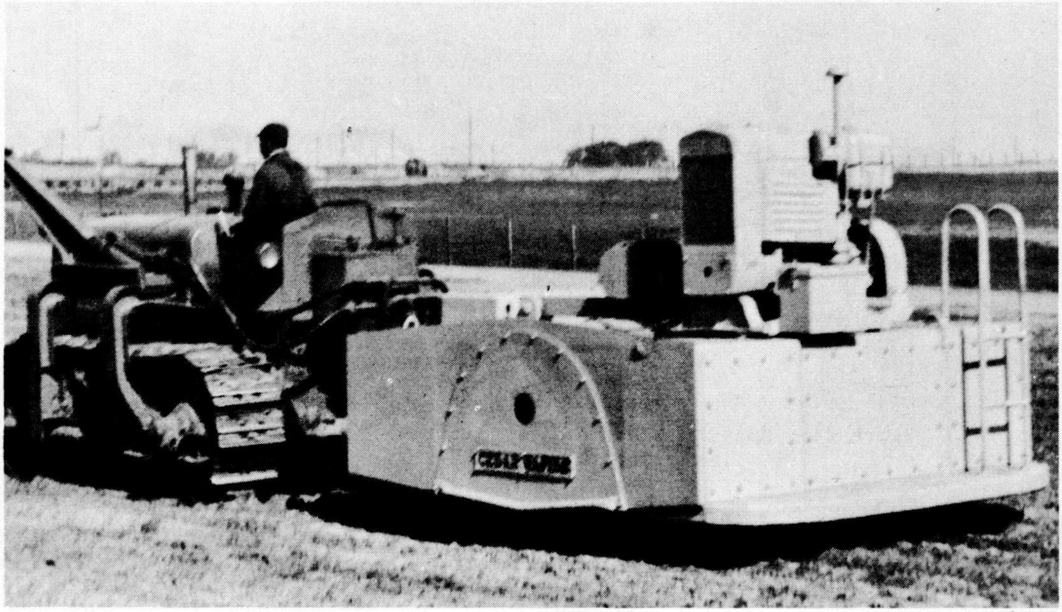


Figure 22. Heavy single-axle, multiple-wheel vibratory, pneumatic-tire compactor.

TABLE 18
CONTACT PRESSURE OF PNEUMATIC ROLLER SUITED FOR COMPACTING DIFFERENT SOILS

Soil Group	Contact Pressure
Clean sands and some gravelly sands.	20 to 40 psi. inflation pressure, the greater pressures with the large size tires.
Friable-silty and clayey sands which depend largely on their frictional qualities for developing bearing capacity.	40 to 65 psi. inflation pressure.
Clayey soils and very gravelly soils.	65 psi. and up inflation pressure.

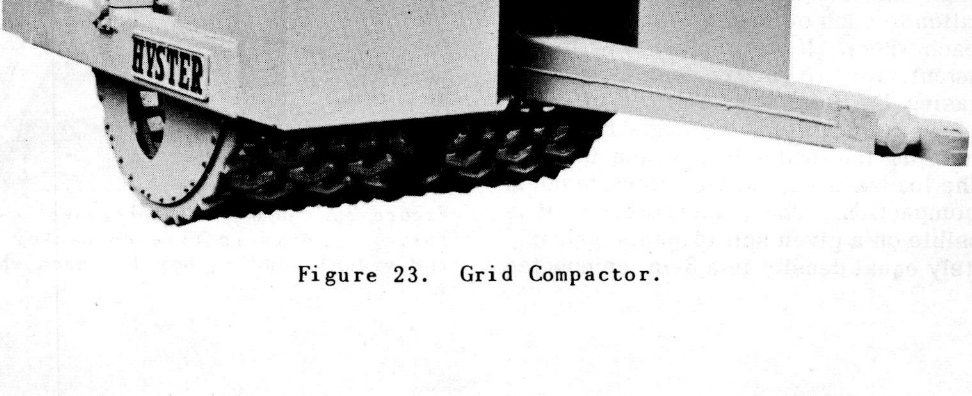


Figure 23. Grid Compactor.

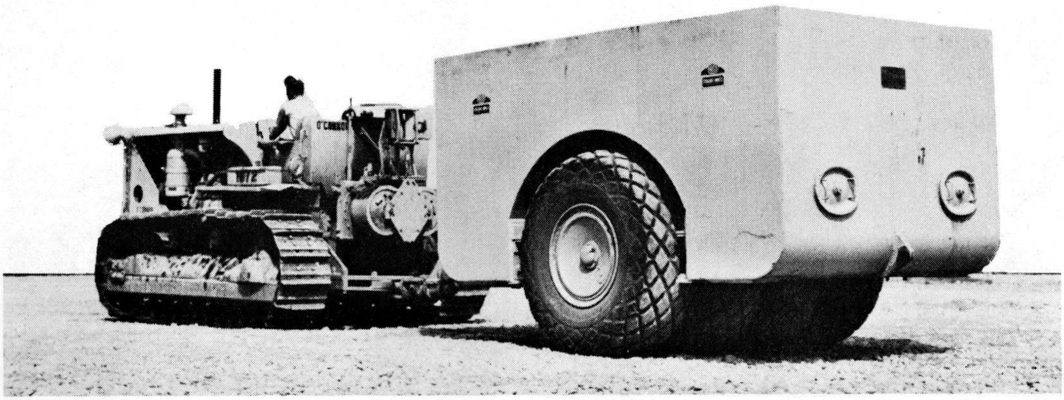


Figure 24. Heavy, oscillating multiple-wheel pneumatic-tire compactor.

pacted lift thicknesses of 6, 9, and 12 in.

The use of test strips to determine the best lift thickness is equally as worthwhile for the 3-wheel type as for the sheepsfoot type, if the most economical compaction is to result. Table 17 may be used as a general guide to estimate the range of lift thickness for the weight of the roller. Those values, however, do not hold if moisture contents differ materially from optimum.

Some 3-wheel rollers have little or no provision for ballasting; therefore, it is important to select the best weight for the prevailing conditions. Table 17 gives the approximate ranges of pressure and weight classes of 3-wheel rollers suited for compacting different soils.

Pneumatic-Tire Rollers

The pneumatic-tire roller, like the 3-wheel type, depends on area of contact pressure (the contact pressure is equal to the inflation pressure plus some pressure due to sidewall stiffness), number of coverages, and thickness of lift. The area of contact and the contact pressure bear a relation to each other and to the total load of each wheel. If the contact pressure is constant, for given tire equipment, increasing the total load will not increase the density obtained in rolling. However, increasing the load will increase the size of the loaded area and the effective depth of compaction. Thus, for example, it is possible on a given soil to obtain approximately equal density in a 3-in. compacted lift with a 1,500-lb. wheel load as is obtained in a 6-in. compacted lift with a 10,000-lb. wheel load. That does not hold equally true for cohesionless soils, which depend largely on their frictional quality for developing support. Here the larger the size of tire, the greater is the size of the loaded area and the greater the confining effect.

The experiments of the Corps of Engineers (24) furnish proof of the above statement. Figure 20 shows that the 1,500-lb. wobble-wheel roller and the 20,000 and 40,000-lb. wheel loads developed densities within about 2 lb. of each other. The data are not directly comparable because six passes of the 1,500-lb.-wheel-load roller were used, and the lift thicknesses may not have been proportional to the wheel load, but they do illustrate the relationships involved.

Thus, the contact pressure is a major factor in obtaining densities and the wheel load and number of passes are

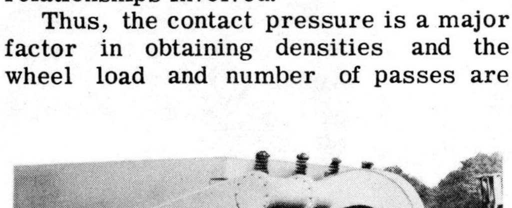


Figure 25. Heavy multiple-wheel oscillating, pneumatic-tire compactor with individual loading box for each wheel.

factors in determining the most economical lift thickness for a given roller. The data given in Table 18 may be used as a general guide for lift thicknesses which can be compacted with different contact pressures and wheel loads with ease and economy. The pneumatic-tire roller is quite flexible in that contact pressures can be changed by changing inflation pressures.

There is, for each soil (at its field optimum moisture content), a most desirable combination of inflation pressure and lift thickness for a given wheel load at optimum moisture content. Table 18 may be used as a guide for preliminary estimates of the approximate ranges of contact pressures for compacting different soils.

The chart in Figure 21 may be used as a guide for estimating roller capacity of a given size and weight of pneumatic roller based on a 6-in. compacted lift thickness.

Roller Performance on Different Types of Soil

An attempt has been made to show that the bearing capacity of the soil, when it is being compacted, limits the contact pressure which can be used in rolling. Therefore, in selecting a type and a weight of roller, the most economical roller is that which gives the best economy between contact pressure and lift thickness, when due consideration is given to size of loaded area.

Smooth-wheel rollers of the 3-wheel type give good results on all types of soils except clean, nonplastic sands. The maximum allowable compression is determined by the type of soil and the moisture content. The rollers are effective in compacting gravelly soils and clayey soils. In compacting clayey soils the thickness of the layer must be so compaction will be to full depth, otherwise, compaction is apt to be limited to a surface crust.

Sheepsfoot rollers are most efficient on fine-grained soils of the plastic groups and are least efficient on the very sandy and gravelley soils.

Pneumatic-tire rollers, as a type, are suited to compacting any type of soil, provided the values of contact pressure and wheel load are proper for the soil being compacted.

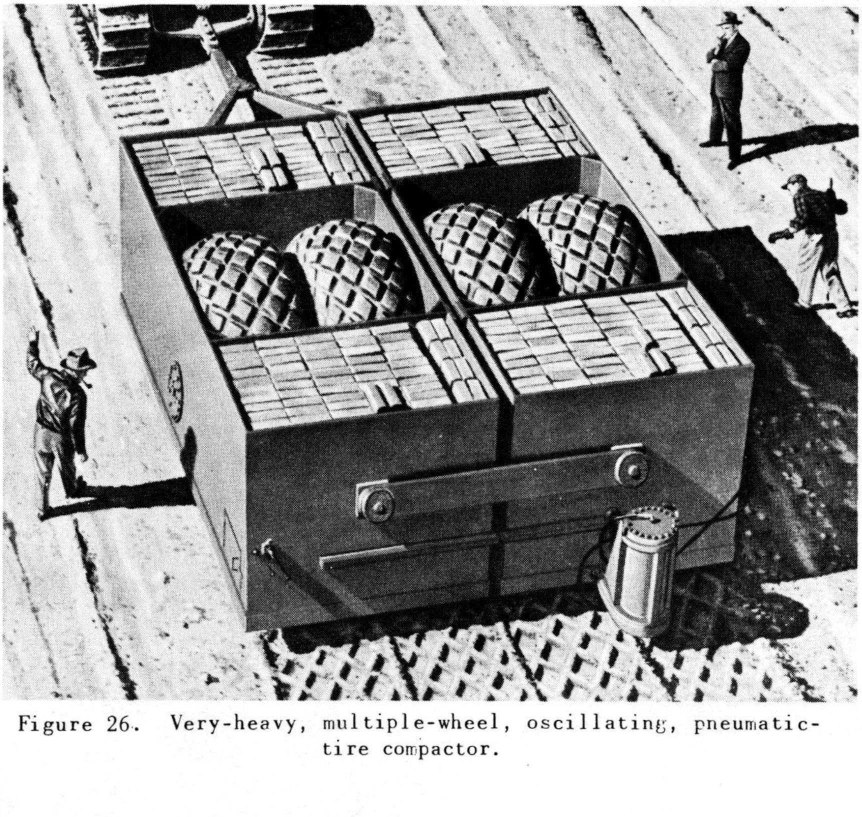


Figure 26. Very-heavy, multiple-wheel, oscillating, pneumatic-tire compactor.

Figure 27. Tandem roller with segmented guide roll.

NEW TYPES OF COMPACTION EQUIPMENT

Several new types of compacting equipment, some of which have shown promise of giving effective and economical compaction have recently come on the market:

Pneumatic-Tire Compactor with Vibratory Unit

This unit is built in two sizes, 30-ton and $12\frac{1}{2}$-ton. The 30-ton unit has two 24-by-33 tires (36 ply). The $12\frac{1}{2}$-ton unit has four 12-by-20 tires (14 ply). The unit consists of a heavily loaded framework superimposed on coil springs, supported by the axle, and held in place by flexibly mounted linkages; and a pair of unbalanced, weighted shafts which rotate and are timed with gears to produce a vertical vibrating force which will operate at speeds of 600 to 1,400 rpm. A photograph of one of the units is shown in Figure 2.

Heavy Pneumatic-Tire Rollers

Several manufacturers are now producing pneumatic-tire rollers of much greater weight than the multiple-wheel types which have been produced and in common use for many years. It is now possible to obtain heavy pneumatic-tire-roller units of 50-, 100-, 150-, and 200-

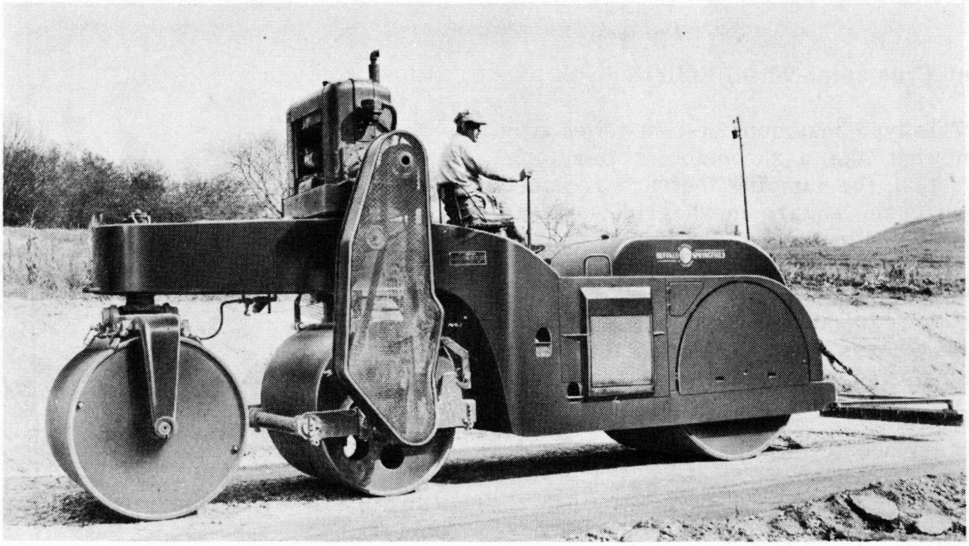


Figure 28. Tandem roller with vibratory intermediate roll.

ton gross weights with maximum wheel loads of 50 tons. Tire pressures range upwards to a maximum of about 150 psi. The units include single- and dual-axle types, oscillating units with two wheels per axle, and individually loaded wheel units. Examples of some of the heavy and very heavy pneumatic-tire roller

Figure 29. Small, hand-operated self-propelled, vibrating-baseplate compactor.

units are shown in Figures 24, 25, and 26.

Grid-Type Steel-Wheel Rollers

This type may consist of a towed type somewhat like a sheepsfoot roller, except that the tamping feet are replaced by an open, square-mesh grid work, as is indicated in Figure 23, or may consist of a 3-wheel roller in which the compression rolls are equipped with grids. The towed units, when equipped with ballast boxes, can be loaded toproduce compression pressures in excess of 300 lb. per lin. in. of drum width.

Three-Wheel Type with Scalloped Ribs on Rolls

A 16-ton, 3-wheel type of roller now comes equipped with a series of scalloped ribs on the wheels. Rear rolls have five scalloped ribs around the periphery of each wheel, the scallops being 4 in. high, 2 in. wide, and 13 in. long at the base and spaced $2\frac{1}{2}$ in. apart from one inside edge to the other ($4\frac{1}{2}$ in. center to center). The position of the scallops in each row is staggered, and the transverse angle (with the axle) of the scallops is reversed on the two wheels. The guide roll has 2-in. -high scallops about 8 in. long. The heavy weight (11,470 lb. per drive wheel) permits a wide range of compression pressures, depending on the area of scallops in contact with the ground.

Tandem Type with Segmented Front Roll

A conventional tandem roller has been built with the guide roll constructed in segments somewhat resembling a sheepsfoot roller with large rectangular tamping feet. This type is illustrated in Figure 27.

Tandem Type with Vibratory Intermediate Roll

The unit consists of a heavy-duty tandem-type roller in which the center roll is energized by a motor unit mounted directly above the center roll. Its principal use, to date, has been in the compaction of macadam bases (Fig. 28).

Figure 30. Large, hand-operated, self-propelled vibrating-baseplate compactor.

Vibrating-Base Compactors

This type consists of a vibratory unit mounted on a base plate. Previbration set up in the base plate is transmitted to the ground setting up a movement in the soil which has been found effective in compacting granular materials. One type of unit is a light-weight compactor similar to that illustrated in Figure 29. Another type is illustrated in Figure 30. This larger unit is constructed in different sizes ranging from small self-propelled units to large tractor-towed units. Figure 30 illustrates the self-propelled unit.

Tampers

Tamping of trench backfill has been done largely by hand tampers (see Current Practice) or by hand-manipulated mechanical tampers (largely pneumatic type). Recently a pneumatic-type pavement breaker has been used successfully in compacting trench backfill. Two adaptations of the pavement breaker for compacting backfill are illustrated in Figures 31 and 32. Figure 31 shows one of the smaller machines which straddles the trench. Figure 32 illustrates one of the larger machines capable of compacting backfill in wide, deep ditches.

A gasoline-driven, manually-operated rammer has been used in compacting backfill adjacent to structures, in trenches, and in restricted areas which cannot be reached by motor-driven equipment. This type is illustrated in Figure 33.

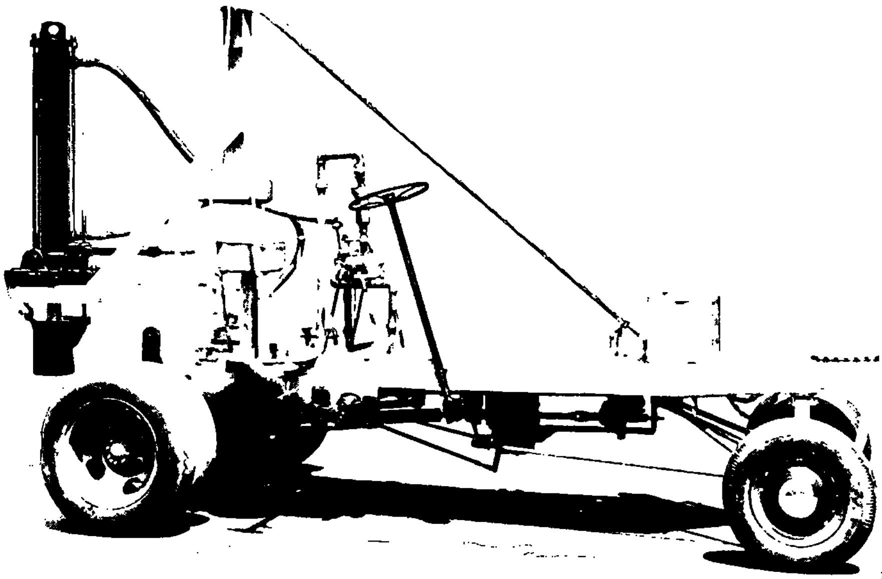


Figure 31. Pneumatic-driven pavement breaker adapted for compacting trench backfill.

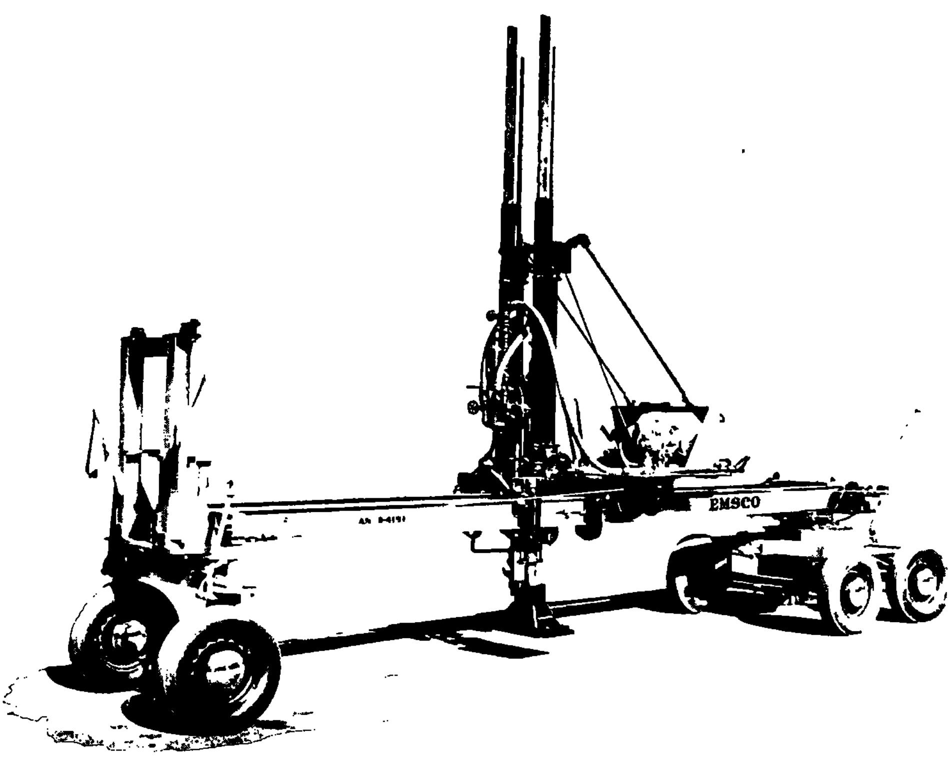


Figure 32. Pneumatic-driven pavement breaker fitted on unit for compacting backfill in wide trenches.

The rammer operates on regular grade gasoline. It makes 50 to 60 jumps per minute, the height of jumps being about 13 to 14 in. Productive capacity may range from about 150 to 250 cu. yd. per 8-hr. day, the rate depending on the nature of the soil and the degree of densification required.

FIELD CONTROL OF COMPACTION

The nature of the specifications determines, in large measure, the nature of methods of testing and inspection for the control of compaction. If specifications govern only the number of passes or coverages, control lies only in inspection by counting the number of passes actually made or, on a general basis, by balancing the equipment and inspecting to see that rolling is continuous as long as materials are moved. If provision is made for controlling the moisture content as well as the number of passes, or "rolling until thoroughly compacted," some control of density can be insured through control of moisture content to give the best results. Under conditions of control of moisture the standard AASHO compaction and field density tests can serve as useful guides for obtaining compaction.

Moisture Content and Density Control

Inspection and Test Methods. Inspection and testing for control of moisture content and density begin with determination of moisture-density relationships for the soils to be compacted. The procedure given for "Standard Method of Test for the Compaction and Density of Soils AASHO Designation: T 99-49" is recommended for use. The method "is also applicable for determining the moisture-density relations of soils compacted at other degrees of intensity produced by varying the weight of the rammer, the height of drop of the rammer, the num-

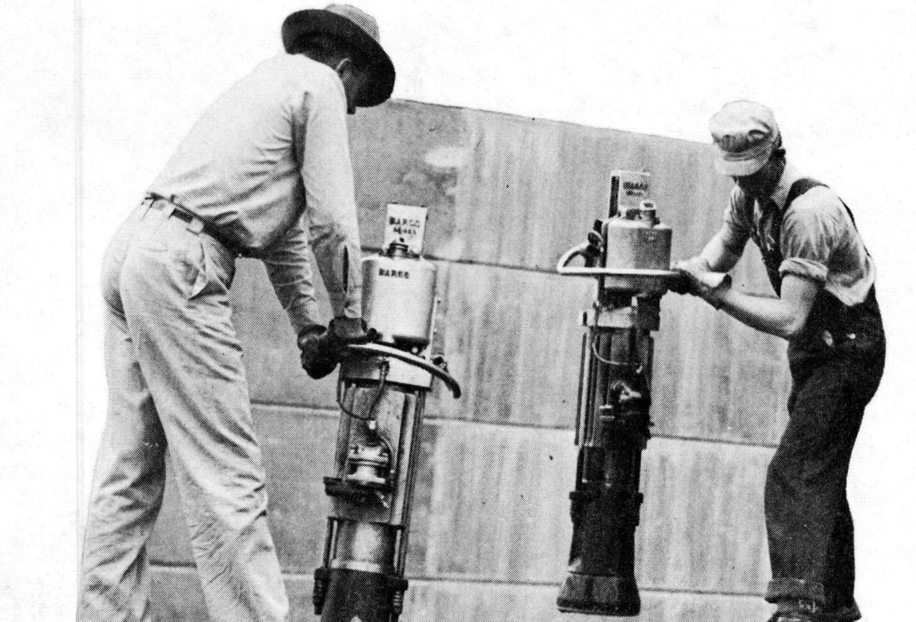


Figure 33. Gasoline-driven rammers for compacting soil in restricted areas.

ber of blows per layer, or the number of layers of soil compacted." That compactive effort which is necessary and practicable to produce the desired density should be used.

There are several factors which may influence the values of maximum density and optimum moisture content obtained in the test. Individually they seldom introduce serious errors, except in some types of soil. However, if the individual errors are added, the standard values may be difficult to use as a basis for interpreting the results of rolling. Some of those factors are: (1) initial moisture content of the soil (before increments are added in the test); (2) temperature used in drying to determine moisture content; (3) rigidity of the mold during compaction; (4) degradation of soft granular particles during preparation of sample and testing; (5) method of handling large proportions of plus-4 aggregates; and (6) amount of manipulation during the test.

Determinations of moisture content and density of rolled soils are often done under one overall test procedure. However, because there are several acceptable methods in use, they are described here separately. There is no one best way of determining moisture content, because the reliability and speed of any method depends, in a large measure, on the individual making the determination. The following methods are described:

Examination Methods. Experienced engineers, after they have become familiar with soils, can often judge moisture contents of soils very closely by examination. Friable soils contain sufficient moisture at optimum to permit forming a strong cast by compressing the soil in the hand. Some clay soils have optimum moisture contents (AASHO T 99) approximately equal to their plastic limits. Often the amount of moisture in those soils can be judged closely at those moisture contents at which a ribbon, thread, or cube can be formed of the sample. Standard rules have not been written for those means of appraising the amount of soil moisture. They can be learned only by practice and should be used by the experienced.

Proctor Penetration Needle. The Proctor penetrometer method of determining soil moisture is sufficiently accurate for most field purposes. It consists of determining the resistance to penetration when the point is forced steadily into the soil (when compacted in the mold under a standard procedure) at the rate of ½ in. per sec. to a depth of 3 in. (25). The penetration resistance must be measured in the mold and not in

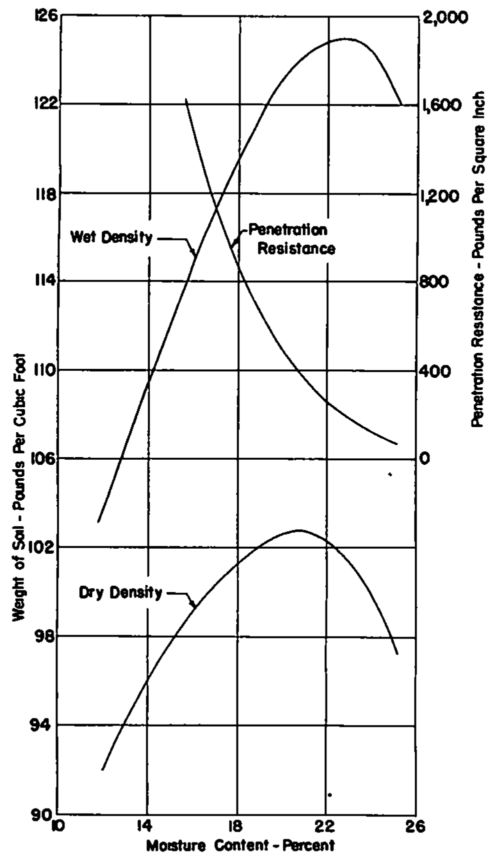


Figure 34. Density and penetration curves (after 'Public Roads").

the rolled material. It can be used in the rolled soil as an approximate means of estimating density, provided the operator has developed the experience necessary to interpret density by that means. Examples of density-moisture relations and relation between penetration resistance and moisture are shown in Figure 34.

Caution should be taken in the use of the penetrometer. If the soils contain

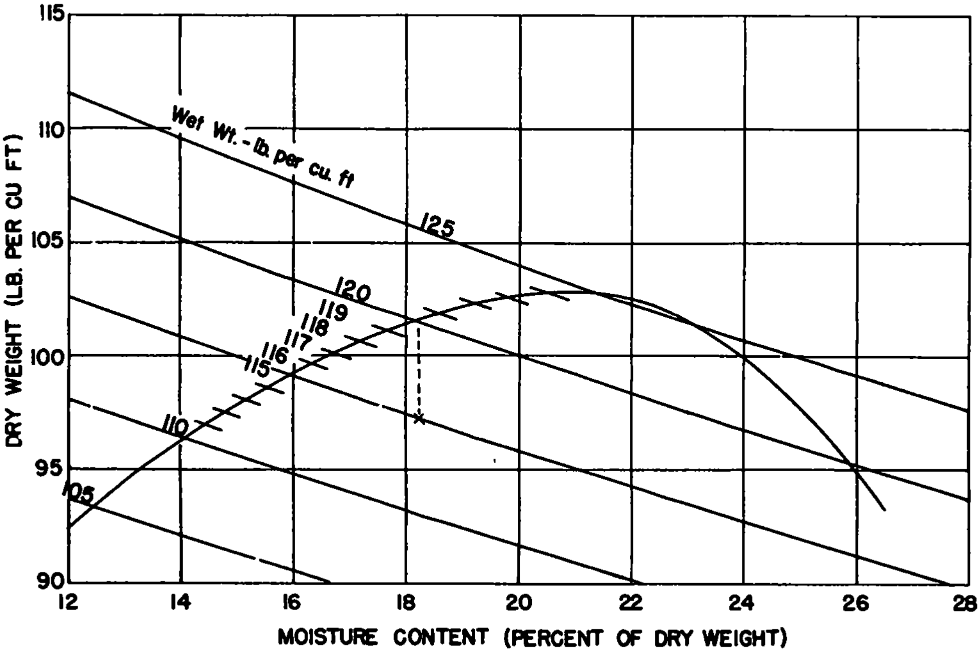


Figure 35. Wet-weight - dry-weight relationships for determining moisture content from in-place wet densities and laboratory moisture-density data (after Goldman).

gravel, the penetrometer is apt to give erroneous results. It may be seen from Figure 34 that the penetrometer becomes less and less sensitive to moisture change the wetter the soil becomes above optimum.

When laboratory moisture-to-density-relationship curves are available, the moisture content and dry density can be estimated with reasonable accuracy without the aid of the penetrometer by using the wet weight of the soil after recompacting it in the mold after obtaining the in-place wet density.

First, the lines showing the wet densities corresponding to various combinations of dry density and moisture content are drawn on the graph of the dry-density - moisture - content relationships as indicated in Figure 35. The following example will illustrate the method:

A soil sample from the rolled earthwork was found to have a wet density of 115 pcf. The same material taken from the rolled earthwork was recompacted in the compaction mold to determine the recompacted wet density. The recompacted wet density was found to be 120 pcf. That density line intersects the dry-density curve at 101. 5 pcf. (dry weight) and 18. 2 percent moisture. Since the samples were identical in moisture content, that of the rolled earth-work was also 18. 2 percent. The wet-rolled density of 115 pcf. corresponds to a dry density of 97. 3 pcf.

Drying to Constant Weight. The most-accurate method of determining moisture content is that of drying to constant weight in an oven at a temperature of 110 C (230 F,) - see AASHO T 99-49. It is not often that temperature-controlled ovens can be set up on construction projects. Small ovens which can be heated by gasoline stoves can be used. Another alternate is that of drying in an open pan over a stove. These methods can be handled satisfactorily only if the operator is cautious in keeping the temperature under control and does not overheat the soil.

Evaporating to dryness may be done in accordance with the following procedure:

1. Obtain a representative sample of

about 100 grams or less, the size to be convenient and within the accuracy of the scale used.

2. Weight sample and record weight.
3. Spread soil to uniform depth in a pan.
4. Place in oven or, if drying over burner, place in a second pan to aid in preventing burning.
5. Dry to constant weight at a temperature of 230 F. (110 C.). If over stove, stir often to prevent overheating.
6. Allow to cool sufficiently to handle.
7. Compute moisture content as follows:

$$\text{Percent moisture} = \frac{\text{wt. wet soil - wt. dry soil}}{\text{wt. dry soil}} \times 100$$

The alcohol-burning method may also be used to evaporate to dryness. That method consists of mixing damp soil with sufficient denatured grain alcohol to form a slurry in a perforated metal cup, igniting the alcohol, and allowing it to burn off. The alcohol method will produce results equivalent to those obtained under careful laboratory drying. A perforated metal cup (26) is used for drying the soil. The suggested procedure is as follows:

1. Weigh perforated cup with filter paper in place in bottom. Record weight.
2. Obtain representative sample of about 25 to 35 grams.
3. Place sample in cup and weigh sample and cup and record weight.
4. Place perforated cup in outside metal saucer 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 saucer and sample and burn off all alcohol.
6. Repeat the process three times, each time completely burning off the alcohol.
7. Weigh perforated cup and dry soil after third burning. The weight of dry soil equals this weight minus weight of cup and filter.
8. Calculate moisture content as shown under the previous method shown above.

There are other methods which can be used for field determination of soil moisture. One of these, proposed by Bouyoucos (27) and further developed by Bonar (28) consists of thoroughly dispersing the soil in alcohol and determining the amount of water removed from the soil by the alcohol by measuring the change in specific gravity of the alcohol by means of a hydrometer.

Another method (29) involves the use of a pressure-type volumeter which can be used to measure the volume of specimens and to determine the percentage of water in the soil by means of air pressure.

There are several other methods for determining soil moisture which are in the developmental stage but which have not been used sufficiently to test their reliability. Each of the methods described above is reliable. There is some difference in the relative accuracy of the methods. Drying to constant weight at a constant temperature of 110 C. is the most reliable. The alcohol method is equally reliable if at least three burnings are used. The penetrometer and the wet-density methods are reasonably quick ways of estimating moisture content and are not intended to yield values having the accuracy of the drying methods. They can, however, if used by experienced operators, be made to yield values within one or two percentage units of the correct value where care is taken in their use.

In-Place Density Measurement. There are a number of methods which are suitable, both in speed and reliability, for use in determining in-place wet and dry densities of soils. Standard methods of Test for the Field Determination of Density of Soil In-Place, AASHO Designation T 147-49, provides procedures for two general methods, namely; the undisturbed-sample method and the disturbed-sample method.

The undisturbed-sample method consists of removing a sample in as nearly as is practicable the undisturbed state. Properly designed sampling tubes will, in most instances, cause only very minor changes in soil moisture content and density. The method of obtaining a sample with a minimum of disturbance consists of removing the soil, by use of small, sharp hand tools (for example, a knife) from around a column of soil. The column of soil may then be coated with a known weight and volume of paraffin and the volume of the column deter-

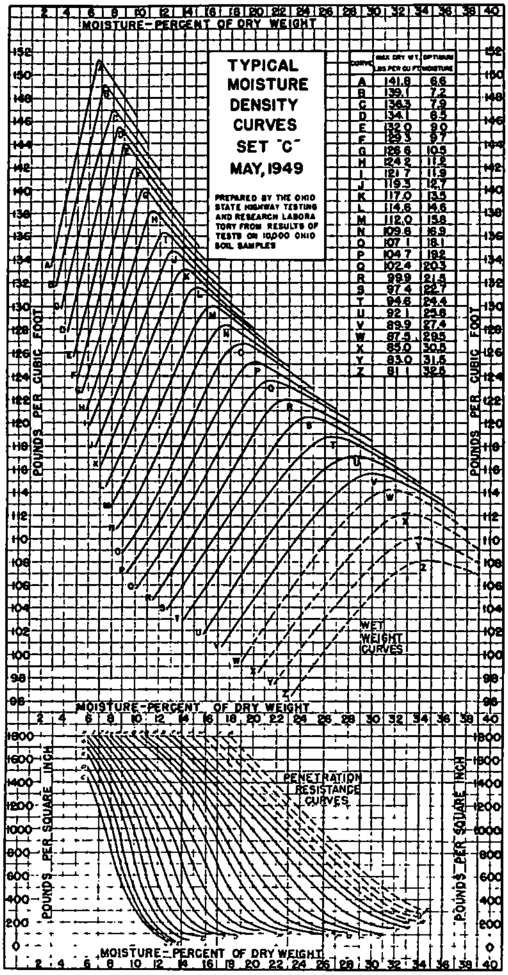


Figure 36. Typical moisture-density curves (prepared by Ohio State Highway Testing Laboratory from tests on 10,000 Ohio soil samples).

mined by means of a syphon-type overflow volumeter.

The disturbed sample method consists of digging a hole and removing the soil by means of an auger or small hand tools (for example, a spatula and a spoon), weighing the removed moist soil, and determining the moisture content and the dry weight of the soil thus removed. The volume of the hole represents the volume occupied by the soil. That volume may be determined by means of dry sand or oil of known volume-weight. The rubber-pouch method has also been used. The procedures for measuring volume and computing density from volume and weight measurements are generally similar for various methods and are not given here.

Nearly all methods have some weaknesses. Each method must be used with an understanding of its shortcomings. The sand method is reliable if:

1. The means of depositing the sand in the test hole is uniform from time to time for different operators. The cone method of depositing the sand has given good results.

2. The sand is calibrated frequently to determine its weight per cubic foot. That weight may vary some from hour to hour with changes in temperature and humidity.

3. The sand is uniform in size distribution and yields consistent results. Standard Ottawa sand has given good results. Some operators have found screened concrete sand (usually passing the No. 10 sieve) to deposit to a uniform density. Others use sand fractions, usually between No. 10 and No. 40 sieve. The important thing is to test for uniformity in deposition.

4. There are no large aggregates protruding from the edges of the hole which cannot be surrounded with sand or there are no large cavities which cannot be filled by the sand depositing to its natural angle of repose under the method of deposition used.

5. There is no jarring which will settle the sand, either in the test hole during measurement or in the container during calibration.

6. Care is taken to preclude soil from reused sand.

The oil method is not satisfactory in materials which are so porous that oil permeates into cavities adjacent the test hole. The rubber-balloon method is accurate only if sufficient air pressure is used to insure that the rubber membrane completely surrounds protruding aggregates and completely fills the test hole. The undisturbed-sample-overflow-volumeter method has no value in soils so friable they will not hold together. The drive-tube method, sometimes called the "undisturbed-core method," loses its value unless it produces a core of length equal to the depth of removed material.

Moisture-Density Relationship. De-

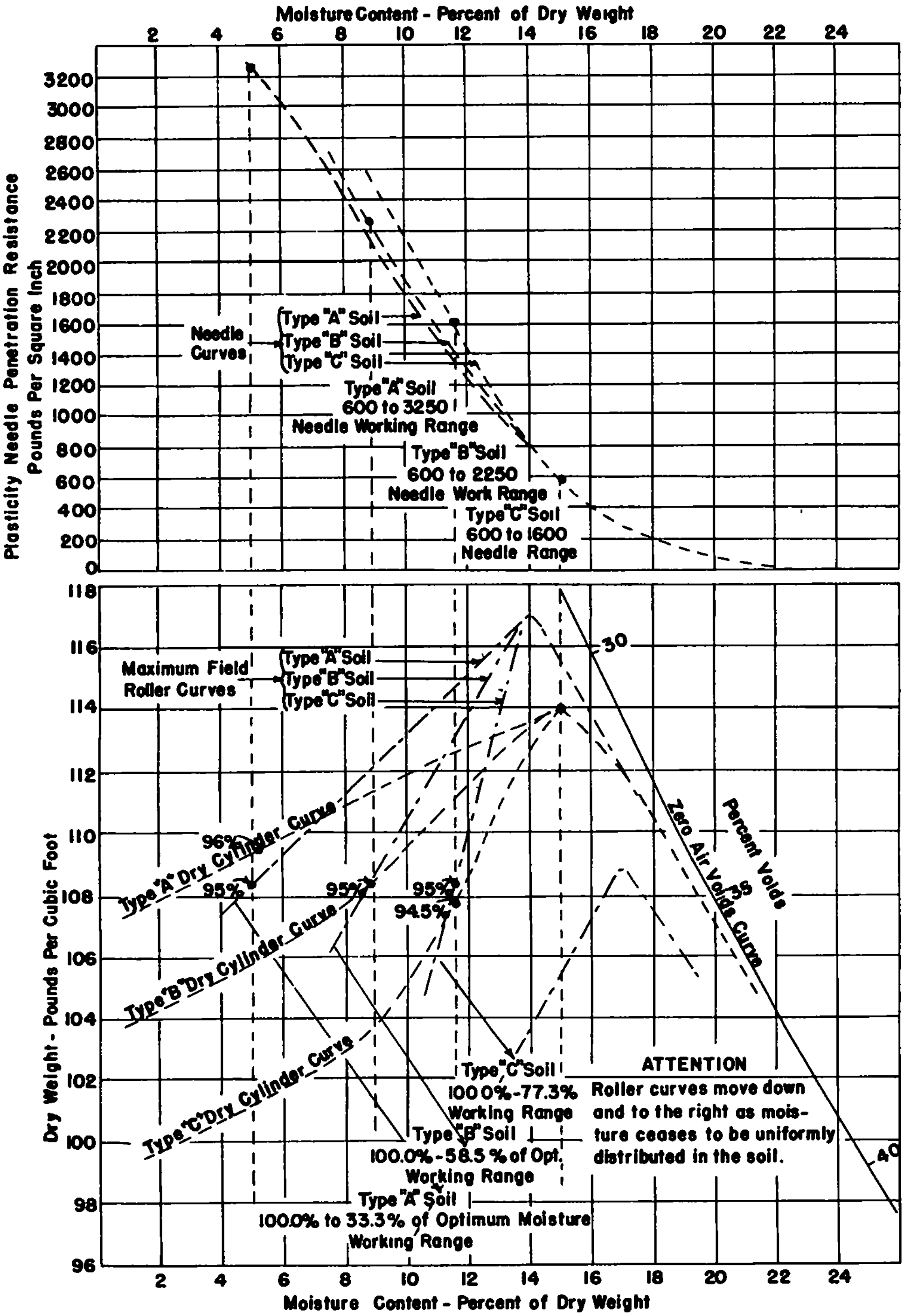


Figure 37. Sample embankment-control curves for typical curve chart, sets A, B, and C, November, 1941, (after "Wyoming Soils Manual," 1949).

termination of optimum moisture content and maximum density in accordance with AASHO Method T 99, or some modification thereof, can be determined by test in the field laboratory as well as in the central laboratory. However, it is often necessary to make determinations more rapidly than can be done by Method T 99 or some modification of it. One method for rapid determination of optimum moisture content and maximum density is that developed in Ohio by Woods and Litehiser (30). They found that moisture-density curves have characteristic shapes, the curves for the higher-weight materials assuming steeper slopes and their maximum densities occuring at lower optimum moisture contents. Most soils having similar maximum weight per cubic foot give identical moisture-density curves.

In the original set, based on 1,088 Ohio soil samples, 9 typical curves were used. The samples tested were placed in groups depending upon 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 36.

In determining the type of curve to use for the soil in question, two easily made steps of the field test for embankment control are required. The first consists of compacting the soil, for which the density curve is desired, into the density cylinder in the standard manner and calculating the wet weight per cubic foot. The second consists of determining the penetration resistance and then noting all possible typical curves in Figure 36 upon which the wet weight per cubic foot in the cylinder just obtained falls and the moisture content at these points. The moisture contents from the wet-weight and penetration curves which most nearly coincide designate the curve which most nearly approaches the true curve for the material.

Example

Let 122 pcf. equal the wet weight and 800 psi. equal the penetration resistance of the soil compacted in the density cylinder. Tabulating the moisture content at which the various wet-weight curves cross the 122 pcf. line and the 800 psi. penetration line in Figure 36 gives:

Curve	Moisture Content at 122 pcf.	Moisture Content at 800 psi.
P	17.5	18.4
Q	19.5	19.3
R	22.5	20.5

An examination of the above values indicates that a moisture content of 19.3 to 19.5 denotes Curve Q as the one which most nearly fits the soil in question.

Wyoming (31) adopted 20 curves and made some revisions. It found that the moisture content, as determined by drying, often was at variance with the moisture content indicated on the standard, typical curve chart at the point where the needle penetration readings and the wet weight per cubic foot would line up vertically on a needle-penetration curve and wet-weight curve of the same number. That indicated difference in moisture content would change the corresponding dry weight.

Soils having practically the same maximum dry 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 weight and optimum moisture content unless the penetration reading and wet-weight determinations were made at nearly optimum. Figure 37 indicates the typical different curve slopes on the dry side of optimum for soils which have similar maximum density and optimum moisture content. To correct for those differences, two additional sets of typical curves were prepared.[5] One of these had flatter-than-normal forward slopes (Type A in Fig. 37) and the other had steeper-than-normal (Type C in Fig. 37). The differences in moisture content were accounted for by a special moisture graph placed above the wet-weight and penetration-resistance curves.

After a sufficient number of four to six point curves has been determined by test to establish the type of curve (A, B, or C), the number of points may be re-

[5] Because of space required for the three sets of 20 typical curves, they are not reproduced here

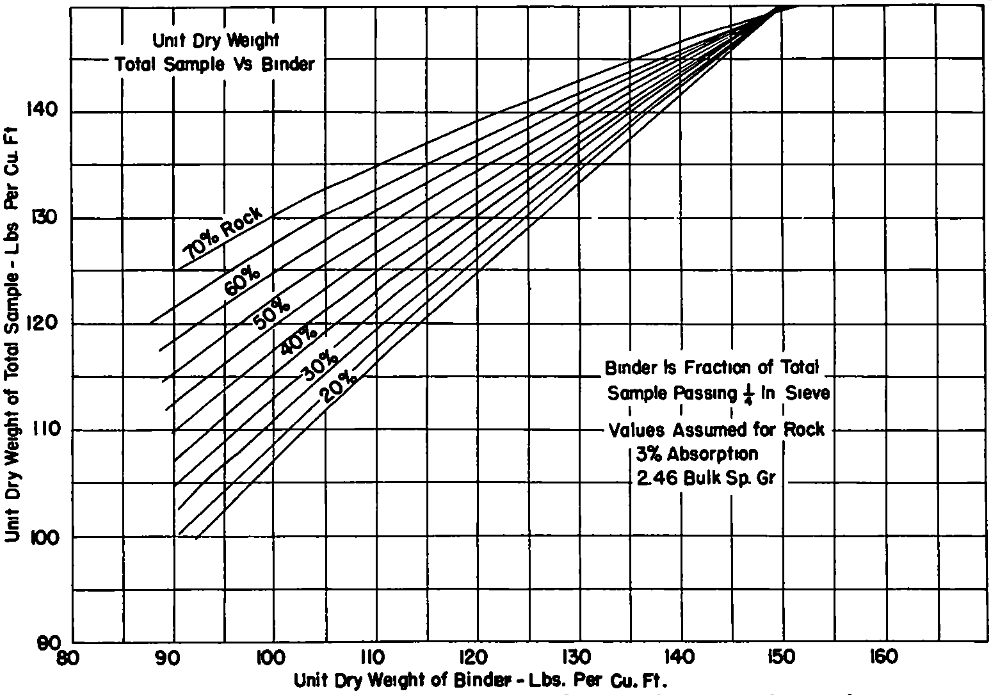


Figure 38. Chart for determining relation between dry-volume weights of minus No. 4 fraction and total sample (after Shockley).

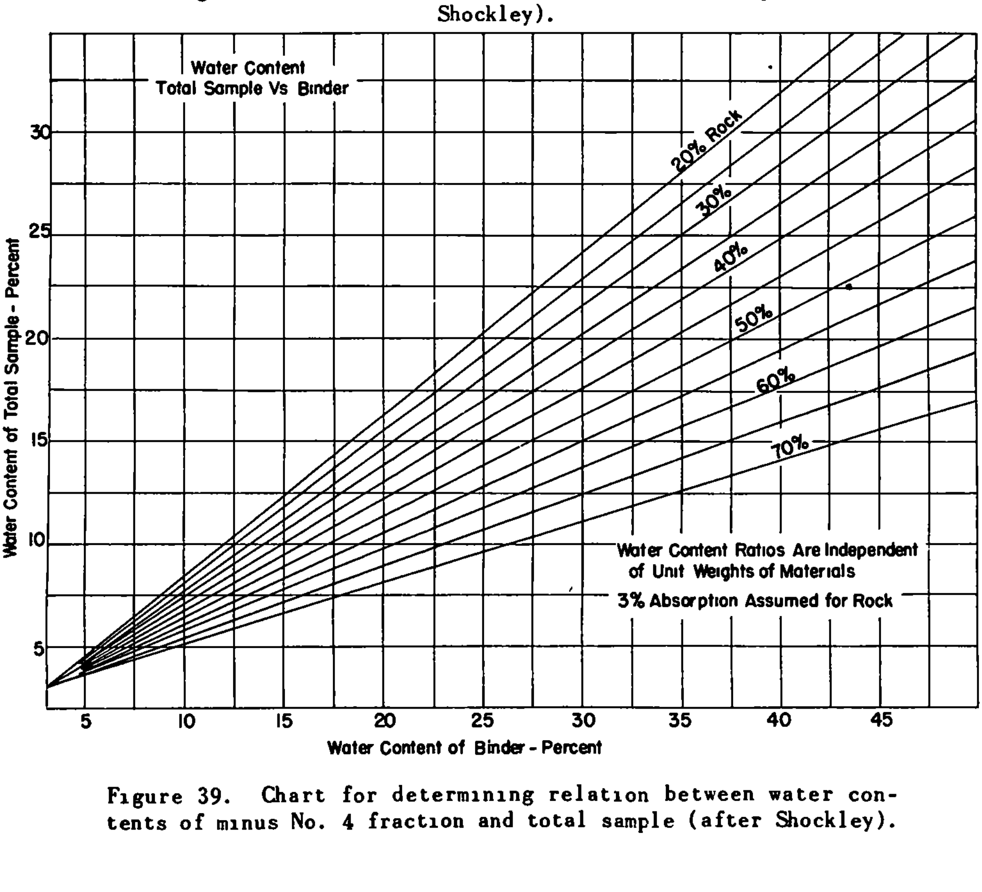


Figure 39. Chart for determining relation between water contents of minus No. 4 fraction and total sample (after Shockley).

duced to one to three and the correct curve (or tabulated data) used for associating the penetration resistance and wet weight to obtain the correct dry 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, i. e., 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 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 (1) determining the curve type, (2) selecting the percent of maximum dry weight which will define minimum moisture-content requirements, (3) plot the dry weight thus obtained (see Fig. 37) on the dry side of the dry weight curve. The vertical line through that point (Fig. 37) indicates the minimum moisture content. The 95 percent-density point, which is usually about the maximum that can be expected from the roller, 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 37.

Correcting for Coarse-Aggregate Content. The present AASHO Method of Test T 99 requires separation of the dried material on the No. 4 sieve and compaction of that portion passing the sieve. It does not provide for determination of the compacted weight of the total soil (including the plus-4 material) either by test or by computation. The same is true for the corresponding ASTM Test D-698-42 T.

Where it is desirable to calculate the weight per cubic foot and optimum moisture content for the entire sample it is necessary to determine the specific gravity and absorption of the coarse materials. Data from the compaction test on the material passing the No. 4 sieve and from specific gravity and absorption tests can be used for determining, by calculation, the theoretical maximum dry weight and optimum moisture content of the entire sample.

Case 1. Where the minus-4 material is sufficient in quantity to fill the voids in the plus-4 material.

The maximum dry weight of the total soil is computed from the following formula:

$$W_t = \frac{W_f \times W_c}{F\,W_c + C\,W_c(1 + A_c)} \quad \text{where}$$

W_t = Dry weight per cubic foot of entire sample at its optimum moisture content.

W_f = Dry weight per cubic foot of minus-No. 4-sieve material at its optimum moisture content.

W_c = Weight per cubic foot of plus-No. 4-sieve material = sp. gr. x 62.4 = 153.5

F = Percent minus-4 material expressed as a decimal.

C = Percent plus-4 material expressed as a decimal.

A_c = Percent absorption of plus-4 material expressed as a decimal.

If test data:

Remain on No. 4 Sieve

35% = 0.35
2.46 = sp. gr.
Absorp. 3% = 0.03

Pass No. 4 Sieve

65% = 0.65
117.4 = pcf. dry wt.
opt. m. c. = 17%

Then:

$$W_t = \frac{117.4 \times 153.5}{.65 \times 153.5 + .35 \times 117.4\,(1 + 0.03)} = \frac{18020.9}{142.098} = 126.82 \text{ pcf.}$$

The optimum moisture content of the total material will be:

$$M_t = (CA_c + FM_f) \quad \text{where}$$

M_t = Moisture content of the total soil
C = Percent retained on No. 4 sieve expressed as a decimal
A_c = Percent absorption of material retained on No. 4 sieve expressed as a decimal
F = Percent passing the No. 4 sieve expressed as a decimal
M_f = Moisture content of minus-No. -4-sieve material expressed as a decimal

The unit dry weight of the minus-No. -4-sieve material can be computed from the formula:

$$W_f = \frac{F\,W_t\,W_c}{W_c - W_t\,C\,(1 + A_c)}$$

If the test data are as given above then:

$$W_f = \frac{0.65 \times 126.82 \times 153.5}{153.5 - 126.82 \times 0.35\,(1 + 0.03)}$$

$$= \frac{12653.5}{107.78} = 117.4 \text{ pcf.}$$

The moisture content of the minus-No. -4-sieve portion will be

$$M_f = \frac{M_t - CA_c}{F}$$

The percentage of rock, moisture content, and dry weight per cubic foot may vary from one individual sample to another. It is desirable to compute the moisture and density relationships between total samples and the minus-No. -4 fraction and construct families of curves for different values of moisture content and percent rock. Such charts have been prepared by Shockley (32) and are reproduced here as Figures 38 and 39. The curves are for coarse aggregate (plus-No. -4-sieve material) having a specific gravity of 2.46 and an absorption value of 3 percent. The use of the curves is illustrated by the following example:

Given: Unit dry weight of total sample = 120 pcf. Plus-No. -4-sieve material = 50 percent. Moisture content of total sample = 15 percent.

To determine: (A) Unit weight of minus-4 material. On Figure 38 enter the scale on the left side of the chart at 120 pcf. and continue across to the intersection with the 50 percent plus -4-material line. From that point read directly down to the bottom of the scale to 100 pcf. which is the unit weight of minus-4 material desired.

(B) Moisture content of minus -4-sieve material. On Figure 39 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-4-sieve line. From that line read directly down to the bottom of the scale to 27 percent, which is the moisture content of the minus -4 material.

Case 2. Where the minus -4- sieve material is insufficient to fill the voids in the plus-4 material.

Acceptable subgrade and fill material and base-course material can be obtained in which the minus- No. -4 material is not sufficient to fill the voids in the plus-4 material. Reagel (33) has developed a chart and a nomograph to facilitate determination of standard dry weights for that condition. The chart is reproduced in Figure 40 and the nomograph in Figure 41.

In the chart, the dry weight of the minus -4 material has been determined as 112 pcf. and the specific gravity of the plus-4 material is 2.55. The first step is to locate Point A in the parallelogram of the chart at the intersection of the 112-lb. value with specific gravity of 2.55. This point on the coordinates is the condition where the plus-4 voids are just filled and shows the percent passing the No. 4 sieve to be 33.5 percent and the combined dry weight to be 139.4 pcf. The material in question has only 32 percent passing the No. 4 sieve. Then locate Point B by a 2.55 line in the parallelogram to a point at the intersection of 32 percent on the coordinate. The point on the other coordinate gives Point C and the solution as 135.7 pcf. for the standard weight of the combined material.

In the case of the nomograph (Fig. 41) the specific gravity given is 2.45 and the dry weight of the minus 4 material is again 112 pcf. A straight line connecting these values gives a value of 34.7 percent (Point A). The material has only 33 percent passing (Point B) which is less than 34.7 percent. A straight line from Point B through the specific gravity value of 2.45 intersects the combined weight

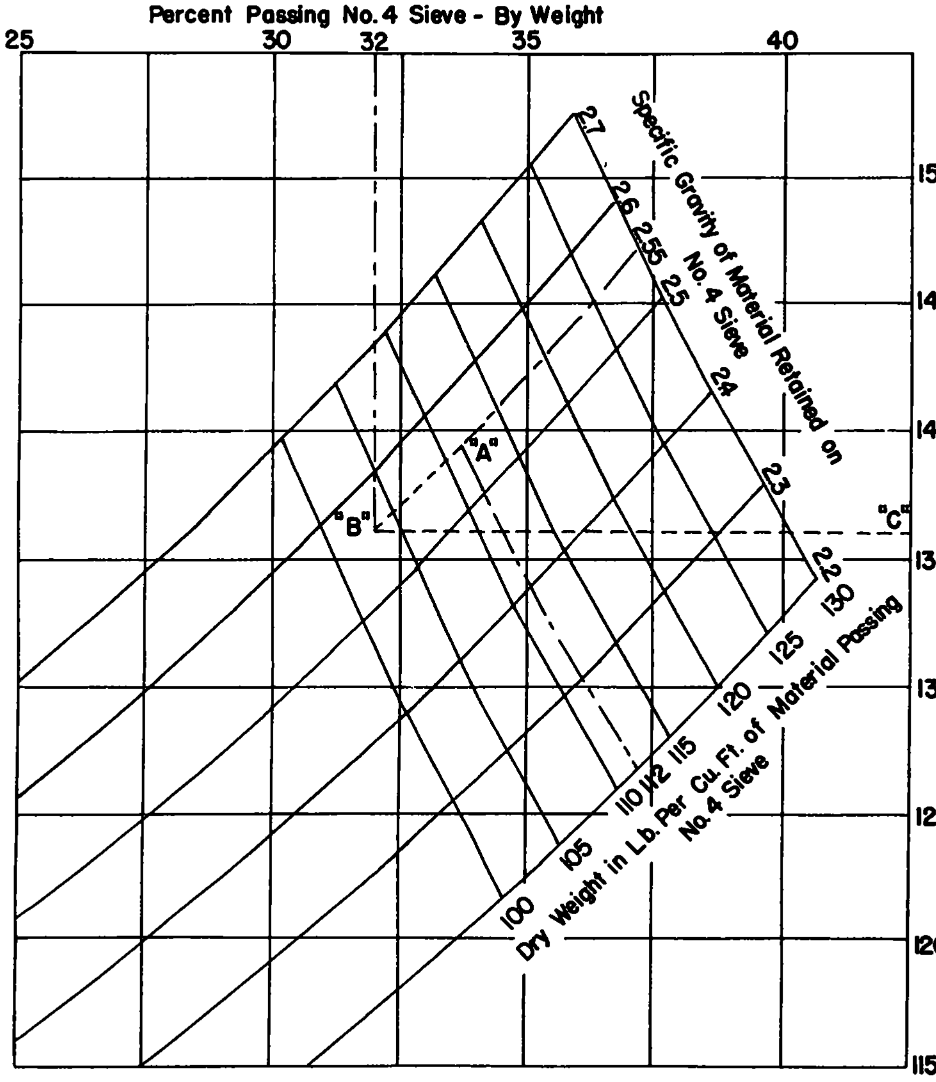


Figure 40. Combined dry-weight per cubic foot of rolled-stone base or stabilized-aggregate base when amount passing No. 4 sieve equals or is less than the voids (42 percent by volume) of the plus No. 4 material. The intersection of the coordinates of the parallelogram gives the conditions of minus No. 4 material exactly sufficient to fill the voids in the plus No. 4 material (after Reagel).

line at 131.9 lb. which is the standard dry weight per cubic foot for this material.

There are physical limits to any method of calculation of the influence of material coarser than the No. 4 sieve on the weight per unit volume (in pounds per cubic foot) of the total material. Theoretically, as the content of coarse aggregate is increased, the density of the total material increases until, at 100 percent coarse aggregate, the unit weight is that of solid rock. Practically, according to Abercrombie (35) and also according to Walker and Holtz (34), the weight of the total material begins to decrease when the coarse aggregate reaches some value, ranging from about 50 percent to 65 percent, until the proportion of coarse

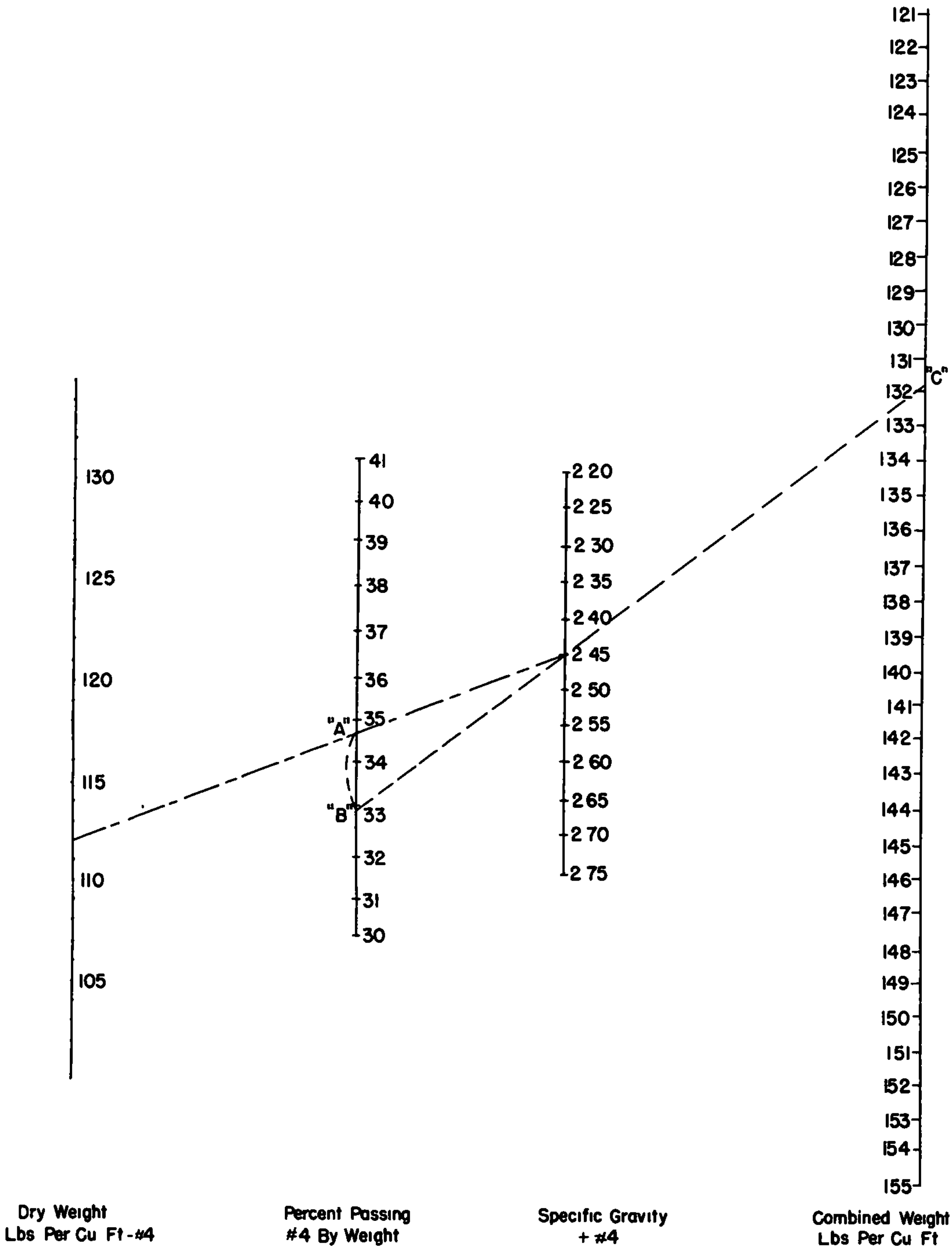


Figure 41. Nomograph for determining combined dry-weights of base materials (after Reagel).

aggregate approaches 100 percent, when the unit weight approaches the unit weight for the coarse aggregate alone.

CURRENT PRACTICES IN COMPACTION METHODS AND EQUIPMENT

The Committee on Compaction of Subgrades and Embankments of the Highway Research Board made its first survey of compaction in 1942. A second survey was made in 1946 and a third in 1951 and 1952. Data from the 1942 survey were published in Highway Research Board Wartime Road Problems 11, "Compaction of Subgrades and Embankments" August 1945. Data from the 1946 survey were published in Highway Research Board Bulletin 5, "Report of Committee on Compaction of Subgrades and Embankments" (1946).

The 1951-52 survey attempted to obtain similar data to those obtained in previous studies to determine if any trends were apparent in current practices. In addition, the 1951-52 study included summaries of current state highway standard specifications for compaction equipment and on methods of compaction of backfill of structural excavation and trench backfill.

The 1951-52 survey was broadened further to include data on compaction of granular bases to make this report of current

TABLE 19

LIFT-THICKNESS REQUIREMENTS BY REGIONS

Thickness of Layer Before Compaction	Number of Organizations	
	Total	In Each Region
in		
3-5	1	1 - Mountain
6	13	1 - Pacific 1 - Mountain 3 - Middle East 4 - Southeast 4 - North Central
6-8	1	1 - South Central
6-8-24	1	1 - Pacific
8	14	5 - Middle East 1 - Southeast 1 - South Central 6 - Mountain 1 - Pacific
9	1	1 - Middle East
9-12	1	1 - Northeast
12	10	7 - Northeast 1 - Middle East 1 - South Central 1 - North Central

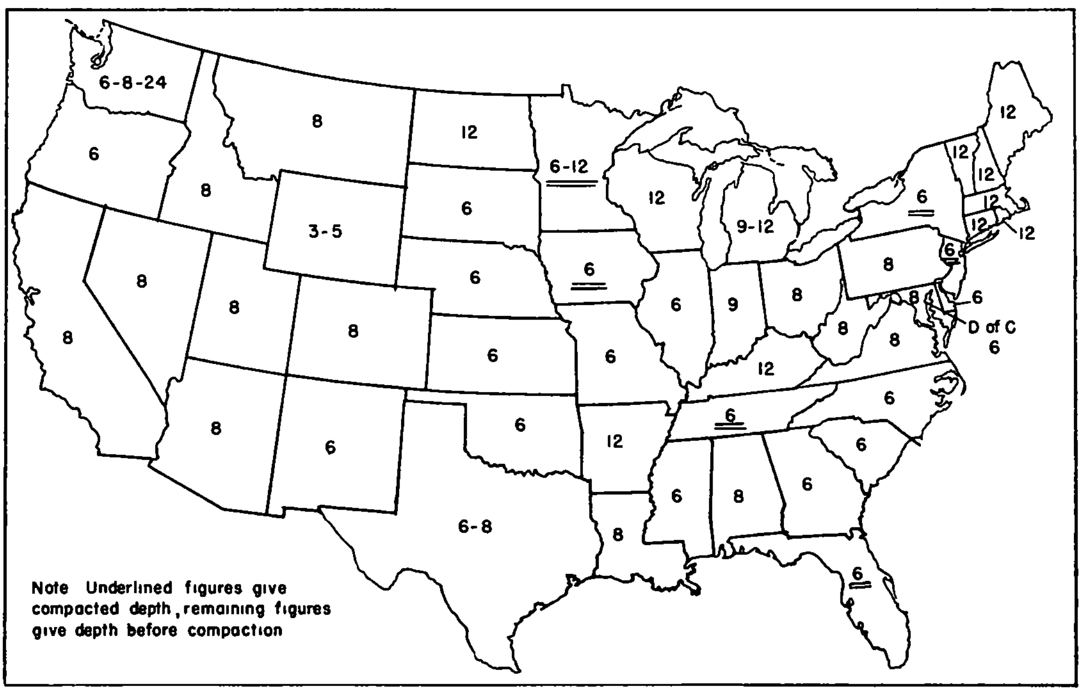


Figure 42. Current practices· depth of lift.

practices more nearly complete. Reporting of the data from the 1951-52 survey is made on the same regional basis as was made in 1942 and 1946.

Lift Thickness in Embankment Construction

The 1946 report brought out that there was a wide variance in lift thickness and showed that a majority of state highway departments specified a maximum lift thickness of 6 to 8 in., 17 organizations using a 6-in. -maximum and 13 using an 8-in. -maximum lift thickness. Those did not include 7 organizations which had more than one class of specifications, one of which fell in the 6-or 8-in. -depth group. The report also showed 8 organizations which used a 12-in. -maximum depth of lift. The 1942 and 1946 reports did not bring out whether the depth of lift was depth before compaction or compacted thickness.

The 1951-52 survey showed that of the state highway departments and the District of Columbia, 42 organizations specify thickness of lift before compaction and 7 specify thickness of lift after compaction.

A summary of lift thickness requirements of the 42 organizations by regions is given in Table 19.

Seven states specify compacted thickness. Six require 6 in. of compacted lift thickness, and one has two classes of compaction - requiring 6 and 12 in. of compacted depth respectively. Those states are all in the East.

The states specifying the 6-in. lifts (before compaction) specify slightly lower average density requirements than does the group which specifies the 8-in. loose depth. That may be due inpart to the fact that those states contain fairly large areas of clayey soils which are difficult to compact to high densities.

It is significant that 7 of the 10 states requiring a 12-in. depth before compaction are in New England, where generally the soils contain high percentages of coarse material, and where fine-grained soils are friable and can be compacted in lifts of greater thickness than can heavy clay soils.

Control of Compaction

Embankments. Compaction and moisture control requirements for embankments have changed some, but not greatly, since the 1946 report. The results of the 1951-52 survey are given in Table 20 and in Figures 42 and 43.

Subgrades. The 1951-52 survey sought information on methods of specifying compaction and moisture control for subgrades. The results of the survey are shown in Table 21. Thirty-four organizations indicated compaction requirements were no different from the requirements for embankments. The remaining replies indicated that closer attention, more rigid control, was being given to obtain compaction and moisture content in subgrades. Several states specify higher compaction for subgrades. Table 21 shows a wide variance in depth of compaction in the subgrade zone. In most instances the depth was given as 6 in. or was considered as surface rolling. Others required compaction to a depth of 8, 12, 18 and 30 in., as may be seen in Table 21.

Bases. Previous surveys did not record the compaction given granular bases (stabilized bases, clay-gravel bases, and sand-clay bases and other bases of natural aggregates; this does not include crushed-rock bases nor bases containing plastic or cementitious binders). The 1951-52 survey indicates that about three eights of the states provide for greater compaction of bases than of embankments (see Table 22). That is accomplished by decreasing lift thickness, increasing roller weight, specifying higher densities, or otherwise exercising more rigid control of rolling.

Cost of Compaction

Compaction is paid for directly in 12 states at an average cost for each state ranging from 3½ to 25 cents per cu. yd. with an overall average cost of slightly over 9 cents per cu. yd. Six of the eleven are from the Mountain States region; two from the South Central and one each from the Northeast, North Central, and Pacific areas. In the remaining states the cost of compaction is included in the bid price for excavation and borrow

TABLE 20

CONTROL OF LAYER THICKNESS, COMPACTION AND MOISTURE CONTENT IN EMBANKMENTS

Region and State	CONTROL OF COMPACTION			CONTROL OF MOISTURE CONTENT	
	Thickness of Layer		Compaction Requirement and measurement	Basis for control	Provision for drying excessively wet soils
	Loose (inches)	Compacted (inches)			
NORTHEAST					
Connecticut	12 max		Satisfactory Min 90% AASHO T 99 in special cases	Not specified	Not specified directly
Maine	12 max		Satisfactory	Not specified	Not specified directly
Massachusetts	12 max		Min 90% AASHO Modified	Not specified	Not specified directly Moisture content limited by density required
Michigan	12 max 9 max		(1) Under 12 in layer method—satisfactory (2) Controlled density method Min 95% AASHO T 99 for fine grained soils Min 95% Michigan cone method for granular materials	As required to obtain density As required to obtain density	If necessary to obtain density Also select material having proper moisture content to replace wet soils
New Hampshire	12 max		Satisfactory Min 6 passes of tamping type roller when "special compaction" is included in special provisions	Not specified	May be ordered to suspend work
New York		6 Av	Min 90% AASHO T 99	Sufficient to obtain required density	Yes
Rhode Island	12 max		Satisfactory	Not specified	Not specified directly
Vermont	12 max		Satisfactory Roll until roller is entirely supported by tamping feet	Not specified	Not specified directly
Wisconsin	12 max		Until no further compaction is evidenced under rollers	Visual	Material to be dried when excessively wet.
MIDDLE EAST					
Delaware	6 max		Min 95% of Modified AASHO	± 10% of optimum	Yes By manipulation.
District of Columbia	6 max		90–100% AASHO T 99 (See compaction Table 1)	At least equal to optimum	Yes By manipulation
Illinois	6 max		Min 90% Max density on wet wt curve AASHO T 99	Shall not exceed 110% of optimum	Yes No additional material may be placed
Indiana	9 max		Min 95% AASHO T 99 for soils	As required to obtain density	As required to obtain density
Kentucky	12 max		Min 90% AASHO T 99 for granular materials	As required to obtain density	As required to obtain density
			Satisfactory	Sprinkling required by engineer	Yes Shall be permitted to dry before being rolled
Maryland	8 max		90–100% AASHO T 99 (see compaction Table 2)	Sprinkling if required by engineer	Yes Shall be permitted to dry to a moisture which will allow compaction Must not be above 2 percentage points above optimum percentage
New Jersey.		6	(8 passes of sheepsfoot roller), (5 passes of pneumatic tire roller), (4 passes of 3-wheel 10-ton roller), 90–95% AASHO T 99 (special projects only)	Not specified	If too wet to support 3-wheeled roller is considered necessary to dry
Ohio	8 max		90–102% AASHO T 99 (see compaction Table 3)	Sprinkling if necessary to obtain density	Yes Dried to moisture content not greater than optimum ± 2%
Pennsylvania	8 max		Satisfactory	Not specified	Yes Wet material if suitable when dry shall be allowed to dry
Tennessee		6	Min 95% AASHO T 99	Optimum moisture content	Air dry excessively wet soils on job
Virginia	8 max		Minimum 95% AASHO T 99	Optimum moisture content	Yes Drying or mixing with drier soils before rolling
West Virginia	8 max		90–100% AASHO T 99 (see compaction Table 4	As required to obtain density	Yes Drying until density can be obtained.
SOUTHEAST					
Alabama	8 max		95–100% AASHO T 99 (100% in top layer)	As required to obtain density	Yes. By windrowing
Florida		6	Average 95% of Modified AASHO with no test less than 90%	Not specified	
Georgia	6 max		Min 95% AASHO T 99	As required to obtain density	Yes. By drying until density can be obtained
Mississippi	6 max		Min 90% AASHO T 99 for clay soils, Min	Satisfactory	As required to obtain density

South Carolina	6 max		Min 90% AASHO T 99 under high type pavement	Optimum ± 3%	Yes Drying if too wet
SOUTH CENTRAL					
Arkansas	12 max		Satisfactory	Moisture must be such that soil will compact properly	Yes, so soil will compact properly
Louisiana	8		Min 95% AASHO T 99	95% of optimum	Yes
Oklahoma	6 min		Not less than 90% AASHO T 99	When directed by engineer	Yes
Texas	6 to 8		Minimum 90 to 100% AASHO T 99	For special projects in gumbo soil slightly above to 5% below optimum	Specifications require rolling immediately after being brought to uniform moisture content No particular method of drying specified
NORTH CENTRAL					
Iowa		6	Usually to satisfaction of engineer Some percentage of modified AASHO in unusual cases.	Usually—as directed by engineer 90–110% of optimum in unusual cases	Yes
Kansas		6 max	Type A—Min 90% AASHO T 99	Sufficient to insure good bonding	Yes, by manipulation
		6 max	Type B—Compaction until roller feet ride surface of compacted lift	Sufficient to insure good bonding	Yes, by manipulation
		6 max	Type C—6–15 passes of sheepsfoot type roller	Sufficient to inure good bonding	Yes, by manipulation
Minnesota		6–12	(1) Ordinary compaction until no evidence of further compaction	Not specified	Not specified
		6 max	(2) Specified density method Generally 97–98% AASHO T 99	As required to obtain density	As required to obtain density.
Missouri	6 max		Min 90% AASHO T 99	As required to obtain density	As required to obtain density
Nebraska	6		Min 90% AASHO T 99 (Except in sand hill region where compaction with construction equipment is deemed adequate)	90% optimum ± 4	See Basis for Control
North Dakota	12 max		Standard compaction—rolling with sheepsfoot roller until no further compaction is obtained	Same as for extra compaction except no specific moisture values nor densities are stated Provision for watering dry soils	Yes Drying until desired compaction is obtained
	12 max		Min 95% AASHO T 99 when extra compaction is specified on plans	Moisture content as determined by the engineer	Yes Drying until specified compaction can be obtained
South Dakota	6 max		Compaction until tamping feet do not penetrate appreciably in soil	Not specified Sprinkling as ordered by engineer	Yes As directed by engineer.
MOUNTAIN					
Arizona	8 max		Min 95% AASHO T 99 specified by special provisions for high fills and fine grain soils.	Not specified, but sprinkling is provided for	Yes
Colorado	8 max		Min 90% Modified AASHO T 99 95% on granular soils.	Optimum ± 2% is objective	Yes.
Idaho (c)	8		(a) 90–100% AASHO T 99 (see Compaction Table 1)	Approved moisture content	Provision for drying
			(b) Compaction by routing all transporting and earth moving equipment over entire width of each layer	Satisfactory to engineer	Provision for drying
			(c) Same as (b) above except top foot shall be constructed in layers not exceeding 4 in loose thickness	Satisfactory to engineer	Provision for drying
Montana	8 max		90–100% AASHO T 99 (see Compaction Table 4)	Not specified As directed by engineer	Yes. Drying to proper consistency
Nevada	8 max		Min 90% California method 85% on some secondary roads	Not specified As directed by engineer	Not specified
New Mexico	6 max		Min 95% on soils having AASHO T 99 maximum density less than 120 p c f	Optimum to optimum minus 5%	Yes
			Min 90% on soils having AASHO T 99 maximum density more than 120 p c f	Optimum to optimum minus 5%	Yes
Utah	8 max		90 to 100% AASHO T 99 (See Compaction Table 4)	Based on optimum Ranges from 5 to 20	Yes
Wyoming	3 max		Non-rolled embankment (Compacted with construction equipment.)	As directed by engineer	Yes. Drying to permit acceptable compaction
	5 max		Satisfactory Try to obtain minimum 92% AASHO T 99	As directed by engineer	Yes. Drying to permit acceptable compaction.
PACIFIC					
California	8 max		Min 90% California method	Optimum or as required to obtain density	Yes.
Oregon	6 max		Min 95% AASHO T 99 in top 3 ft Min 90% below 3 ft	As directed by engineer	Yes Permitted to dry when possible
Washington (1)	24 max		(1) Satisfactory compaction by routing compaction equipment	Not specified	Not specified.
(2)	8 max		(2) Satisfactory compaction by rolling	Not specified	Not specified
(3)	6 max		(3) Minimum 95% AASHO T 99	Optimum ± 3%	Optimum ± 3%

(a) Using modified AASHO on some current projects.
(b) 12 in maximum in zone more than 3 ft. below surface of embankment 6 in maximum in top 3 ft of fill.

EMBANKMENT COMPACTION REQUIREMENTS

TABLE 1

Standard of Compaction or Maximum Density obtained by AASHO Method T 99 (P C F.)	Minimum Compaction Required (Percent of Maximum Density)
89 9 or less	100
90 to 99 9	100
100 to 109.9	95
110 to 119 9	95
120 to 129 9	90
130 and above	90

TABLE 2

CONDITION 1 Fills 10 ft or less in height and not subject to extensive floods		CONDITION 2 Fills exceeding 10 ft in height or subject to long periods of flooding	
Maximum Laboratory Dry Weight (P C F)	Minimum Field Compaction Requirements (Percent of Dry Weight)	Maximum Laboratory Dry Weight (P.C F.)	Minimum Field Compaction Requirements (Percent of Dry Weight)
89 9 and less	*	94.9 and less	**
90–99 9	100	95–99 9	100
100–109 9	95	100–109.9	100
110–119 9	95	110–119 9	98
120–129 9	90	120–129.9	95
130 and more	90	130 and more	95

* Soils having maximum dry weights of less than 90 p c f. will be considered unsatisfactory and shall not be used in embankment

** Soils having maximum dry weights of less than 95 p c.f. will be considered unsatisfactory and will not be used in embankment under condition 2 requirements.

TABLE 3

CONDITION 1 Fills 10 ft or less in height and not subject to extensive flooding		CONDITION 2 Fills exceeding 10 ft in height or subject to long periods of flooding	
Maximum Laboratory Dry Weight (P C F)	Minimum Field Compaction Requirements (Percent of Laboratory Maximum Dry Weight)	Maximum Laboratory Dry Weight (P C F)	Minimum Field Compaction Requirements (Percent of Laboratory Maximum Dry Weight)
89 9 and less	*	94 9 and less	**
90 0–102 9**	100	95.0–102 9	102
103 0–109 9	98	103 0–109.9	100
110 0–119 9	95	110.0–119 9	98
120 0 and more	90	120 0 and more	95

* Soils having maximum weights of less than 90 p c f will be considered unsatisfactory and shall not be used in embankment

** Soils having maximum dry weights of less than 95 p c f will be considered unsatisfactory and shall not be used in embankment under condition 2 requirements or in top 8 in. layer of embankment which will make up the subgrade for pavement or subbase under condition 1 requirements

Soil, in addition to the above requirements, shall have a liquid limit of not to exceed 65 and the minimum plasticity index number of soil with liquid limits between 35 and 65 shall be not less than that determined by the formula 0 6 Liquid Limit minus 9.0.

TABLE 4

Maximum Density Obtainable by AASHO Method T-99-49—Pounds Per Cubic Foot	Minimum Compaction Required—Per Cent of Maximum Density
90–99	100
100–119	95
120 and over	90

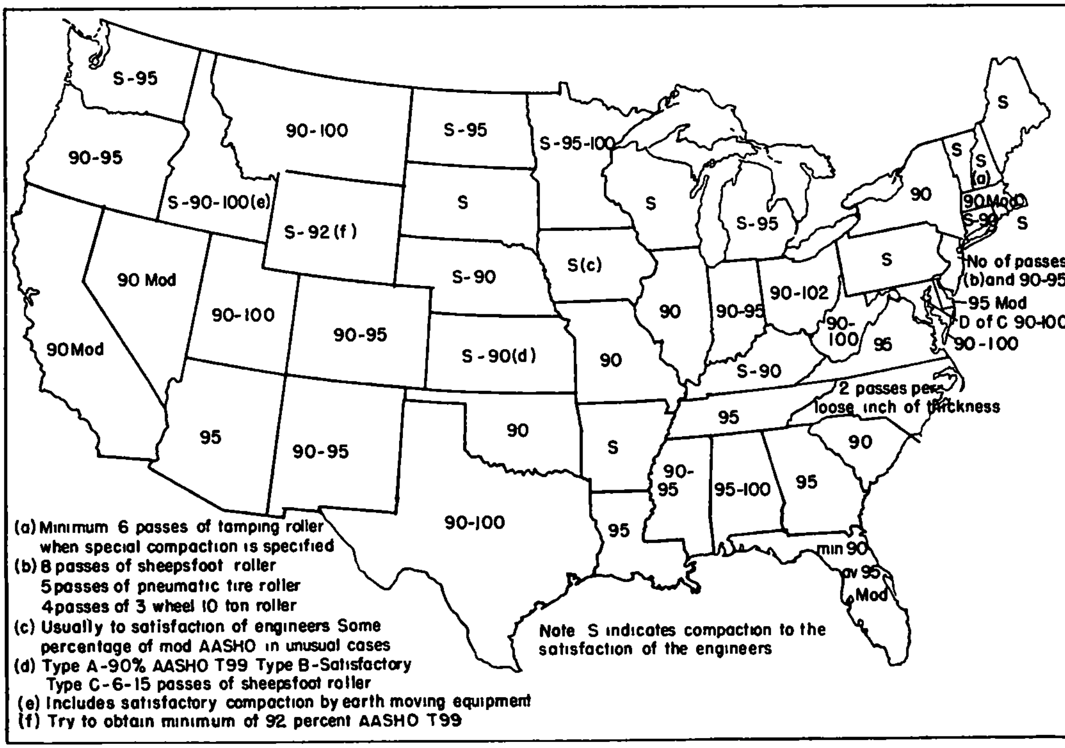


Figure 43. Current practices minimum compaction requirements for embankments. Values are percentages of AASHO T99-49 except as noted.

and is difficult to determine. Five states in which compaction is paid for indirectly estimated its cost as ranging from 1 to 8 cents per cu. yd. with an overall average of slightly over 4 cents per cu. yd.

Method of Testing

Nine of the states which conduct the laboratory compaction tests reported using new samples for each point on the compaction curve, the remainder of the group reusing the remaining part of the sample after the sample for moisture content determination has been removed.

Eleven states reported using mechanical mixers for incorporating water with soils for the laboratory compaction test. Five of those adopted the Hobart food mixer to that use; five used Lancaster type of laboratory mixer widely used for making test batches of concrete, most of them using the 12-in. -diameter bowl with the muller attachment; and one reported using a specially constructed mixer in which rubber-covered rolls operated at different speeds to provide the mixing action. That machine also provided a good means of breaking down soils for making the test.

Oven drying or drying in open pans over electric, gas, or gasoline stoves were used in almost every state for drying field samples for moisture-content determination.

The sand method of determining the volume of soils in the in-place density test was reported in use in 25 states; the rubber pouch, or "balloon," in 7 states; the volumeter method in 4 states, and the oil method in 2 states. Some of the departments reported using more than one method.

Backfilling of Trenches, Pipe Culverts and Sewers

During July 1949 the committee sponsored the publication of a review of the then current "State Highway Standard

TABLE 21

CONTROL OF COMPACTION AND MOISTURE CONTENT IN SUBGRADES

Region and State	Compaction requirements and measurements	Depth of subgrade compaction: In cuts	Depth of subgrade compaction: In previously compacted fills	Moisture control requirements
NORTHEAST				
Connecticut	Thoroughly and uniformly compacted 10-ton 3-wheel roller.			No requirements specified
Maine	Compacted 10-ton, 3-wheel or approved pneumatic tired roller.			No requirements specified
Massachusetts	Compacted self-propelled roller weighing not less than 12 tons.			No requirements specified
Michigan	When required, same as for embankments			Same as for embankments
New Hampshire	Rolled to a firm unyielding surface with 10-ton, 3-wheel roller			No requirements specified
New York	Min 95 percent AASHO T 99 for top 4 ft below crown grade, 2 ft wider than pavement and downward and outward on 1 to 1 slope	Not less than 8 inches	No requirement	Sufficient to obtain density Same as for embankments
Rhode Island	Compacted uniformly with approved roller weighing not less than 10 tons			No requirements specified
Vermont	Compacted with 3-wheel power roller			No requirements specified
Wisconsin	Same as for embankments			No requirements specified
MIDDLE EAST				
Delaware	Minimum 95 percent Modified AASHO	Constructing equipment will probably compact sufficiently	No requirement	Optimum ± 10 percent
District of Columbia	90–100 percent AASHO T 99 (See compaction table 1–S).	12 inches	12 inch (old fills)	At least equal to optimum
Illinois	Compaction to the satisfaction of the engineer	Covered by special provisions in special cases	Same as for other locations	Provision for wetting or drying subgrade
Indiana	Same as for embankments			As required to obtain density Must be satisfactory at time of paving or placing subbase
Kentucky	Satisfactory All soft and yielding material replaced with suitable material			See compaction requirements
Maryland	Compaction with tandem or 3-wheel, 10-ton roller, also sheepsfoot or any other method to secure required compaction			Soft, unstable material shall be removed
New Jersey	Same as for embankments	Surface rolling	Surface rolling	No requirements specified
Ohio	95–105 percent AASHO T 99 (See compaction table 2–S)	Min 6 inches	Min 6 inches	Not greater than optimum +2% (see compaction table) Not greater than optimum in elastic soils
Pennsylvania	Same as for embankments	Excavate 9 ins below final grade		No requirements specified Excessively wet material removed
Tennessee	Same as embankments Compaction performed with 10-ton roller or pneumatic tired roller		6 inches max	Control by field and laboratory tests
Virginia	Minimum 95 percent AASHO T 99	8 inches	8 inches	Optimum moisture content
West Virginia	Scarified to not more than 4" and compacted with 10-ton, 3-wheel roller to firm unyielding surface	4 inches	4 inches	No requirements specified but must be firm and unyielding
SOUTHEAST				
Alabama	Minimum 100 percent AASHO T 99	6 inches	6 inches	Only as required to obtain density Manipulation until dry enough to compact
Florida	Same as for embankments (Av , 95% Modified AASHO with no test less than 90%	12 if stabilization is required—6 if no stabilization is required		Optimum used as guide only Provision for drying
Georgia	Same as for embankments, Minimum (95% AASHO T 99)	6 in except 12 in over solid rock	6 inches	No requirements specified

Mississippi	Minimum 95% AASHO T 99	6 inches	6 inches	No requirements specified Soft yielding materials removed
North Carolina	Thoroughly compacted with power driven roller weighing not less than 330 lb per inch of width of tread			No requirements specified except at discretion of engineer
South Carolina	Same as for embankments (Min 90% AASHO T 99 under high type pavements)	6 inches where used	6 inches where used	Optimum ± 3 percent
SOUTH CENTRAL				
Arkansas	Same as for embankments	8 inches		No requirements specified
Louisiana	Same as for embankments (95% AASHO T 99)	8 inches loose	8 inches loose	95% of optimum
Oklahoma	95% of Standard Proctor Density for subgrades	6 inches	6 inches	Based on optimum
Texas	Same as for embankments (90 to 100% AASHO T 99)	6 inches	6 inches	Same as for embankments (slightly above to 5% below optimum)
NORTH CENTRAL				
Iowa	Min 95% AASHO T 99 specified for subgrade for Flexible Type Pavement Subgrade rolling for rigid type pavement	6 inches	6 inches	90 to 110 percent of optimum for flexible sprinkling when necessary for rigid type
Kansas	Thoroughly compacted with approx 5-8 ton tandem or 3-wheel rollers for subgrade for PCC pavement			No requirements specified
	Type AA Min 95% AASHO T 99	6 in to 12 in	6 in to 12 in	As required to obtain density
	Type AAA Min 100% AASHO T 99	6 in to 12 in	6 in to 12 in	As required to obtain density
Minnesota	Same as for specified density method for embankments according to special provision (generally 97 or 98% AASHO T 99)	Generally upper 12 inches	Generally upper 12 inches where required	Min 80% of optimum
Missouri	Same as for embankments (Min 90% AASHO T 99)	18 inches	18 inches	No requirements specified except as required to obtain density
Nebraska	Same as for embankments (Min 90% AASHO T 99)	6 inches	Same as for embankments	100% ± 3 (concrete pavements only)
North Dakota	Same as for embankments (Min 95% AASHO T 99 when specified)	Standard scarify and recompact to 12" to density of adjacent fills	Same as for embankments (stress uniformity)	As required to obtain compaction
South Dakota	Same as embankments	12 inches	Scarify 6 inches and recompact	No requirements specified Provisions for drying if necessary to secure stable roadbed
MOUNTAIN				
Arizona	Same as for embankments (Min 95% AASHO T 99 by special provision)	6 inches when required	6 inches when required	No requirement specified Engineer tries to obtain approximately optimum
Colorado	Same as for embankments except when subgrade is of selected materials	12 inches	12 inches	Optimum ± 2 is objective
Idaho	Higher compaction required in subgrades than in embankments (see Table 3-S)	12 inches	18 inches	No requirement specified except at direction of engineer
Montana	Same as for embankments except last 10 ft below grade on high fills	8 inches	8 inches	Moisture control required as directed by engineer
Nevada	Same as for embankments			No requirements specified
New Mexico	Same as for embankments (90 to 95% AASHO T 99)	6 inches	6 inches	Optimum to optimum—5% Provision for drying
Utah	Same as for embankments (90 to 100% AASHO T 99)	8 inches ±	8 inches ±	Provision for wetting or drying subgrade at direction of engineer
Wyoming	Same as for embankments to a depth of at least 6 inches	Min 6 inches	Min 6 inches	Requirements based on working range of Wyoming A, B and C type curves
PACIFIC				
California	Min 90% California method compaction 4 in compacted layers for 2½ ft below profile grade	30 inches	30 inches	Same as for embankment
Oregon	Same as for embankments (95% AASHO T 99)			No requirement specified Provision for wetting or drying
Washington	Same as for embankments	Up to 22 in in special cases	1 to 6 in (surface rolling only)	Optimum ± 3 in compaction Method C only.

SUBGRADE COMPACTION REQUIREMENTS

TABLE 1-S

Standard of compaction or Maximum Density obtained by Method AASHO T 99 (p c f)	Minimum compaction required (Percent of Maximum Density)
90 to 99 9	100
100 to 109 9	95
110 to 119 9	95
120 to 129 9	90
130 and above	90

TABLE 2-S

Maximum laboratory dry weight (p.c f)	Minimum subgrade compaction requirements (Percent of laboratory maximum dry weight)
94 9 and less	**
95 0-102.9	105
103 0-109 9	102
110.0-119 9	100
120 0 and more	95

** Soils with a maximum dry weight of less than 95 p c f shall be unsatisfactory for use in the 6-inch compacted soil layer immediately beneath the pavement and shall be replaced with suitable soil or granular layer

The moisture content of all subgrade materials at time of compaction shall not be greater than 2 percent over the optimum. The moisture content at the time of compaction of granular materials containing 15 to 40 percent passing a number 200 sieve, of predominantly silty or sandy silt soils for which the plasticity index is less than 10, or other approved subgrade material which displays pronounced elasticity or deformation under construction equipment shall not exceed optimum

TABLE 3-S

Maximum laboratory dry weight (pounds per cu ft)	Minimum field compaction requirements (percent of laboratory determined dry weight)
89 9 and less	100
90 0 to 99 9	100
100 0 to 109 9	100
110 0 to 119 9	100
120 0 to 129 9	95
130 0 and over	95

Specifications on Compaction of Backfill of Trenches and around Pipe Culverts and Sewers" (36). That was done as a result of the increasing quantity of work being done in urban areas. That summary of practices in compaction of trench backfill is included in this overall review of current practices.

Compaction requirements can be placed into two broad groups: those requiring compaction of backfill but not specifying density requirements and those controlling compaction of backfill by specifying compaction to some minimum required density.

Group A - Compaction Without Density Control

Of the 48 states and the District of Columbia, 41 specify that the soil shall be tamped or that the soil shall be thoroughly or carefully, firmly or solidly tamped, rammed or compacted. Nearly all specify quality of compaction in terms of "to the satisfaction of the engineer."

Tamping Methods and Equipment. The above group provides the following requirements for tamping methods and equipment (when inaccessible to a roller).

Of these 41 states, 11 do not state whether compaction of backfill shall be by hand or mechanical methods, nor do they state requirements for hand tamping equipment.

Five states mention hand tamping but make no mention of mechanical tamping. Two of these 5 states list no requirements for hand tamping equipment. One state provides only that heavy iron tampers be used. Two states require "heavy iron tampers" having tamping faces not exceeding 25 sq. in. in area. Nine states specify mechanical tamping only. Sixteen states provide for either mechanical or hand tamping methods.

For hand tamping equipment: nine states require heavy iron tampers with tamping faces not exceeding 25 sq. in. in area. One state requires tampers weighing not less than 12 lb. and having a tamping face of not more than 50 sq. in. One state requires tampers weighing not less than 15 lb. and having a tamping face area 6 in. by 6 in. One state requires tampers weighing not less than 20 lb. and having a tamping face area not larger than 6 in. by 6 in. One state requires tampers weighing not less than 50 lb. and having a face not exceeding 100 sq. in. in area. Three states give no requirements for hand tamping equipment.

Lift Thickness. All states in this group of 41 states specify some requirement for depth of lift. Of this group, 35 state clearly the depth of lift either as loose thickness or state that the material shall be placed in layers of some given thickness and compacted. They are tabulated according to depth of lift as follows:

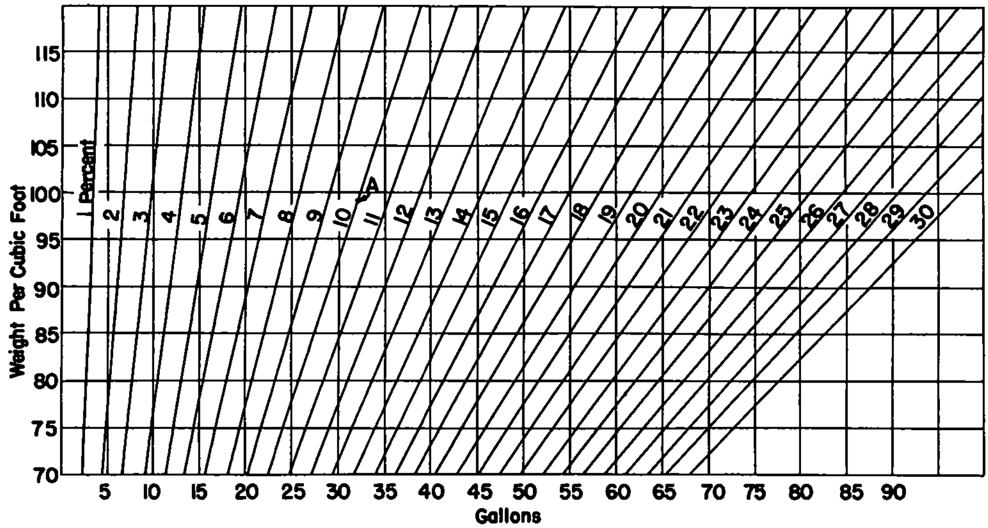


Figure 44. Chart for determining gallons of water required per cubic yard of embankment (after "Kansas Highway Manual").

Depth of Lift (inches loose)	States Specifying
4	3
6	29
8	1
9	1
12	1

In addition, one state provides for a 4-in. depth for hand tamping and a 6-in. depth (loose) for mechanical tamping, another specified layer not exceeding 8 in. for mechanical tamping and that for hand tamping layers shall not be more than 4 in. Four additional states specified 6-in. depths of lift but it was not clear whether the depth was loose depth or compacted depth.

Moisture Control. Nineteen states provide for the addition of water, if necessary to facilitate compaction. A major portion of those states specify, "Each layer, if dry, shall be moistened and then compacted." One state provides, (in addition to moistening) for saturation of sandy and granular soils. The remaining states in this group do not provide for addition of water to facilitate compaction.

Materials Requirements. Thirty-four of this group of states specify that the material shall be approved or shall be selected material free from large lumps or clods, stones, rock, sod, roots, frozen lumps, etc. Three states provide for the use of granular materials. Five states provide for acceptable selected materials or when specified, granular materials.

Provision for Saturating, Flooding, or Puddling. One state permits thorough saturation of granular materials meeting certain grading requirements. One state permits flooding and tamping of special granular materials meeting certain grading requirements. One state permits puddling around pipe only. One state permits water puddling up to the natural ground line as an alternate to hand tamping.

Group B - Compaction with Density Control

Density Requirements. Eight highway departments control compaction of backfill (within the scope of this review) by specifying some minimum density requirements: Three require not less than 90 percent of maximum density as determined by Method of Test AASHO Designation: T 99. One requires not less than 95 percent of maximum density as determined by Method of Test AASHO Designation: T 99. Two require not less than 90 percent relative density as determined

TABLE 22

CONTROL OF COMPACTION OF GRANULAR BASES

REGION AND STATE	COMPACTION REQUIREMENTS Comparison with Requirements for Embankments or Subgrades
NORTHEAST	
Connecticut	Rolling to give satisfactory compaction in layers not to exceed 6 in depth (compacted)
Maine	Use 8-inch loose lifts compared to 12 for embankments
Massachusetts	Use 12-ton power roller on bases compared to 10-ton for embankments
Michigan	*Subbase*—Same as for embankments (95% of Michigan Cone Method) [1] Base—(Processed gravel) Satisfactory compaction
New Hampshire	Use min 10-ton 3-wheel roller and roll to satisfaction of engineer
New York	Require rolling with 10-ton rollers in separate layers of max 6 in depth Tamping rollers in some areas where roller cannot be used
Rhode Island	Same as for embankments
Vermont	Same except 3-wheel power roller is used on bases
Wisconsin	Provision is made to require power rollers if desired compaction is not attained by hauling equipment Compaction is 3 to 5 in layers
MIDDLE EAST	
Delaware	Same as for embankments
District of Columbia	Same as for embankments 90–100% AASHO T 99
Illinois	Compacted to satisfaction of engineer
Indiana	Density and moisture content satisfactory to engineer.
Kentucky	Must be within 5 lb of Proctor Density Also pneumatic tire roller required with other rollers
Maryland	No density requirements stated Rolled with 10-ton power roller
New Jersey	100% AASHO T 99 for subbase "Type A" Provision for moisture control
Ohio	No density requirements Compaction with a 3-wheel roller weighing 10 tons or more or an approved pneumatic tire roller to satisfaction of Engineer
Pennsylvania	Same except pneumatic tire and sheepsfoot rollers are permitted
Tennessee	Rolling requirements are more rigid than for embankments Thickness of compacted layer is set between 2 5 and 4 inches.
Virginia	No density requirements Compaction as required by Engineer
West Virginia	Compaction to the satisfaction of the engineer.
SOUTHEAST	
Alabama	Density 100 percent AASHO T 99 Moisture content optimum ± 2 percent
Florida	Same as for embankments
Georgia	Bases require 100 percent of AASHO T 99. (Embankments require 95 percent)
Mississippi	Bases require 100 percent of AASHO T 99 (Embankments 90–95 percent) Contractor maintains for 10 days If contractor obtains 105% then maintenance clause is waived
North Carolina	Bases or subbases are thoroughly compacted by rolling satisfactory to engineer
South Carolina	Density 95 percent AASHO T 99 required.
SOUTH CENTRAL	

Arkansas	Different layer thickness used Compaction under traffic
Louisiana	Same as for embankments
Oklahoma	95% of Standard Proctor Density for stabilized aggregate base course Provision for moisture control
Texas	Density requirements based on compaction of individual samples consisting of total material up to 2 in top sizes
NORTH CENTRAL	
Iowa	Density 100 percent AASHO T 99. Moisture content that which will insure maximum compaction
Kansas	Min. 100% AASHO T 99 Aggregate binder bases min 4 in compacted lifts and not less than 125 p c f.
Minnesota	Placed in 3 in layers and compacted to 98 percent AASHO T 99
Missouri	Density 90-95% AASHO T 99 except when otherwise covered by special provisions Compacted granular base 90% Stabilized aggregate or rolled stone bases 95%
Nebraska	Density 90% AASHO T 99 (for concrete pavements) Moisture content 100% optimum ± 3 Density 95–100% AASHO T 99 (for flexible pavements). No moisture requirement except as necessary for construction
North Dakota	Subbase—same as standard compaction for embankments Base—1 33 times dry loose weight of material but not to exceed 140 p c f dry weight in place for material weighing 100 p c f or more loose weight
South Dakota	Base course density shall be 1 33 times loose dry wt of aggregate or 140 lb. max required Subbases rolled with pneumatic tire roller (250 lb per in width of roller) to an unyielding condition
MOUNTAIN	
Arizona	Same as for embankments
Colorado	No density tests made Rolling to satisfaction of engineer Minimum of 4 passes with suitable rolling equipment.
Idaho	No density requirements Compaction controlled by layer thickness
Montana	Watering and rolling required Greater attention is given projects where watering and rolling are paid for as separate items
Nevada	Rolled with power roller weighing at least 8 tons until maximum compaction is obtained Placed in thinner layers If more than 4 in. place in two or more layers
New Mexico	No density required as no test deemed satisfactory Compaction to satisfaction of engineer
Utah	Rolling until maximum feasible compaction has been obtained
Wyoming	No density requirement Watering, processing and rolling to satisfaction of engineer
PACIFIC	
California	Minimum relative compaction not specified but minimum amount and type of rolling equipment is specified.
Oregon	As required by engineer
Washington	Thinner lifts Rolling with 3-wheel or pneumatic tire rollers until material does not creep under roller.

[1] The Michigan Cone Method consists of compacting granular soils into a funnel-shaped mold having a solid bottom in the large end and equipped with a stopper for the small end The bottom shall be so shaped that there will be no sharp corners inside the mold The base or large end of the mold shall be approximately 5¾ inches in diameter and the small end shall be not less than 2½ inches The mold shall be approximately 8½ inches in height and shall have a volume of approximately 1,300 cubic centimeters or 0 0459 cubic feet The sample shall be thoroughly mixed, then compacted in the mold in three equal layers, each layer receiving 25 blows The blows shall be delivered by raising the mold approximately 4 inches and striking it sharply down on a concrete or heavy timber base After the third layer has been placed the blows shall be continued with the wood stopper reversed and held firmly over the opening. Sand shall be added at intervals to keep the mold full, and operations continued until no further consolidation occurs The compacted soil shall be carefully leveled off to the top of the mold and weighed, and the wet and dry volume weights determined For complete test procedure and description of equipment see "The Use and Treatment of Granular Backfill" by R L Greenman, Michigan Engineering Experiment Station, Bulletin 107, 1948

by the California method. Two have minimum density requirements similar to those specified in Standard Specifications for Materials for Embankments and Subgrades AASHO Designation: M 57.

Four of the eight departments which specify minimum density requirements make no reference to method of compaction or equipment. Two departments specify mechanical tamping. The remaining two specify mechanical tampers or hand tampers, having a tamping face not exceeding 25 sq. in. in area.

Lift Thickness. Highway Departments specifying the density method of control of compaction of backfill provide the following requirements for maximum thickness of lift during compaction.

TABLE 23

HIGHWAY DEPARTMENT REQUIREMENTS FOR TRENCH BACKFILLING

Group	Requirements		No. of States and D.C.
A	Specifications require compaction but do not specify density		41
	Tamping Provisions:		
	Mechanical tamping only specified		9
	Hand or mechanical tamping allowed		16
	Hand tamping mentioned only		5
	Tamping method not mentioned		11
	Depth of Layer or Lift:		
	Depth placed before compaction, in.		
		4	3
		6	29
		8	1
		9	1
		12	1
	Depths 4 to 8 in., but with particular requirements for hand tamping		2
	Depth 6 in., but not clear as to loose or compacted		4
	Moisture Control		
	Some provision		19
	No provision		22
	Materials Requirements.		
	Provision for select or approved materials		34
	Permission to Saturate, Flood or Puddle		4
B	Specifications require density control		8
	Tamping Provisions		
	Mechanical tamping specified		2
	Hand or mechanical tamping allowed		2
	Tamping method not mentioned		4
	Compaction Requirements		
	Not less than 95% max. density (AASHO T 99)		1
	Not less than 90% max. density (AASHO T 99)		3
	Not less than 90% rel. density (California Method)		2
	Depth of Layer or Lift:		
	Not to exceed	Basis	
	4 in.	loose	2
	6 in.	loose	2
	6 in.	compacted	2
	4 to 6 in.	loose	1
	8 in.	loose	1
	Moisture Control, provision made		8
	Materials Requirements:		
	Granular backfill specified		2
	Select or approved backfill specified		6
	Provision for puddling		1

No. of Dept.	Depth of Lift Requirements
2	Not to exceed 6 in. compacted depth
2	Not to exceed 6 in. loose depth
2	Not to exceed 4 in. loose depth
1	Not to exceed 8 in. loose depth
1	Not to exceed 4 and 6 in. loose depth depending on construction method.

Moisture Control. All of the eight highway departments specifying the density method have provision for control of moisture content during compaction.

Materials Requirements. Two of the eight departments specify granular backfill and give grading requirements, and one department specifies granular backfill around pipe and selected material for the remaining part of the trench. The remaining five departments call for selected or approved material free from large or frozen lumps, rocks, roots and similar extraneous material.

Provision for Saturating, Flooding or Puddling. One highway department in this group provided puddling as an alternate to tamping to obtain the required density, but that method must be used on material from deposits indicated on plans or on material meeting specified grading requirements.

Statement of Requirements for Backfilling Sewers

Twelve States have specification items covering sewers, storm sewers, sanitary sewers, or storm and sanitary sewers. Because these specifications do differ in some states from those given for pipe culverts and trench backfill, data on specifications for sewers are given separately in the following summary:

State 1. Sanitary sewer. Suitable materials are tamped around pipe and to a depth of 2 ft. above the pipe. Remainder thoroughly settled and compacted by tamping and flooding. No moisture control given.

State 2. Sewer. Suitable materials are hand tamped to 1 ft. above sewer. Balance filled to within 1/2 ft. of top and flooded.

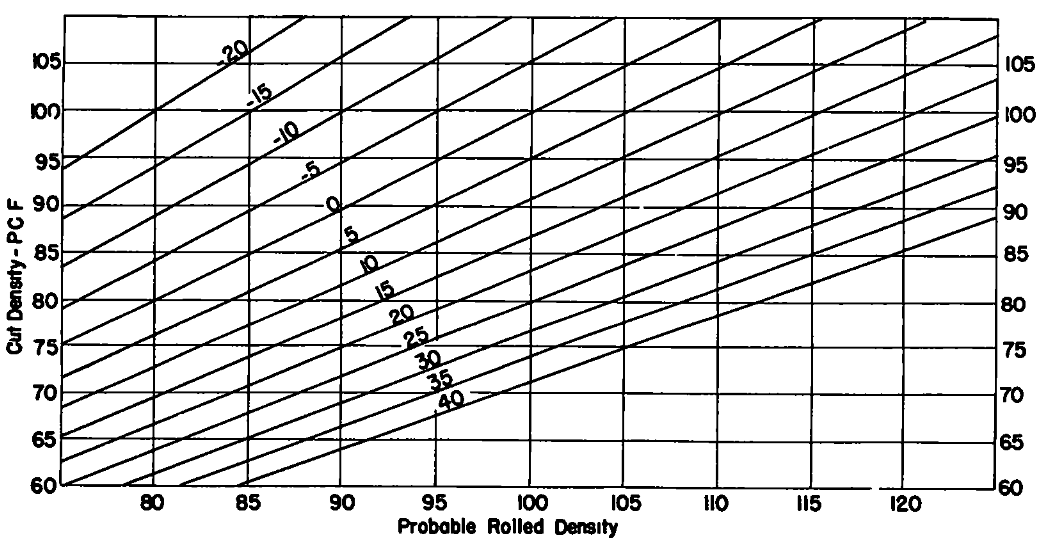


Figure 45. Chart for determining shrinkage from cut to fill (after "Kansas Highway Manual").

TABLE 24

CURRENT STATE HIGHWAY STANDARD SPECIFICATIONS FOR COMPACTION OF BACKFILL FOR STRUCTURAL EXCAVATION

Region and State	Depth of Lift	Compaction	Moisture Control	Tamping Equipment and Methods
NORTHEAST				
Connecticut	12 in max. loose	Min 95% AASHO T 99	Puddling permitted	Power rollers, motorized equipment or hand equipment of type (b), and vibratory equipment
Maine	9 in max loose	Thoroughly compacted	Not specified	Tamping or flushing with water
Massachusetts	6 in max loose	Thoroughly compacted	Not specified	Tamped Equipment not shown under excavation for structure but type (a) equipment shown under backfilling of pipe culverts Puddling of clean granular material permitted
Michigan	9 in max loose	Same as Emb controlled density method for granular material (95% cone method)	Same as for embankments	Power and hand equipment. Details on tamping equipment not given Vibratory equipment used extensively Flooding permitted on permission of engineer
New Hampshire	8 in. max loose	Thoroughly consolidated	Not specified	Approved power tamping devices
New York	4 in max loose	Min 95% AASHO T 99	As required to obtain density	Mechanical rolling or tamping Mechanical tampers shall be equal in weight and power to Ingersoll-Rand No. CC45 with a tamping foot area not to exceed 50 sq in.
Rhode Island	12 in max loose	Well compacted	Not specified	Equipment not specified under structure excavation and backfill but mechanical tampers or hand tampers type (a) shown under bedding and backfill for pipe culverts
Vermont	12 in max loose	Thoroughly compacted	Not specified	Mechanical or hand tampers. Details on tamping equipment not given.
Wisconsin	12 in max loose	Thoroughly compacted	Not specified	Equipment not specified under excavation for structures
MIDDLE EAST				
Delaware	6 in max loose (power equipment) 4 in max loose (hand equip)	Min 95% Modified AASHO	Optimum ± 10 percent	Mechanical tampers Details on tamping equipment not given
District of Columbia	6 in max loose	Same as embankments (90–100% AASHO T 99)	At least equal to optimum	Power rollers or mechanical tampers Mechanical tampers capable of exerting a blow equal to 250 lb per sq ft of tamping area and have a dead weight in excess of 40 lb
Illinois	6 in max	Thoroughly tamped	Not specified	Mechanical tampers of approved design
Indiana	Grade B special borrow max 6 in loose Special filling material 12 in max loose	Thoroughly compacted Thoroughly saturated	Not specified	Mechanical tamps (preferably). For small areas hand tamps, min weight 15 lb having a face area 6 by 6 in
Kentucky	6 in max loose	Thoroughly compacted	Sufficient to insure desired compaction and density	Approved mechanical tamping devices
Maryland	6 in max loose	Same as embankments (90–100% AASHO T 99)	Sufficient to insure proper compaction	Mechanical tampers
New Jersey	6 in max (subsurface structure excavation)	Satisfactory	Not specified	Mechanical tampers Puddling of foundation excavation and subsurface structure excavation Details on equipment not specified
Ohio	4 in. max loose	Same as embankments (90–102% AASHO T 99)	Sufficient to insure density	Pneumatic tampers
Pennsylvania	4 in max loose	Thoroughly tamped or rolled	Not specified	Mechanical tampers
Tennessee	6 in max loose for tamping roller 3" max loose for mechanical tamp.	Thoroughly compacting each layer	Compacted at optimum moisture content as determined by laboratory tests on backfill material	Tamping rollers and mechanical tamps are used
Virginia	6 in max loose	Thoroughly tamped	Not specified	Mechanical tamper capable of exerting a blow equal to 250 p s f of tamping area
West Virginia	6 in max loose for rolling 4 in max loose for tamping	Thoroughly compacted	Not specified	Roller minimum weight 10 tons Pneumatic backfill tamper (25 to 35 lb) having a piston blow rather than a hammer blow
SOUTHEAST				
Alabama	6 in max. loose	Same as embankments (95% AASHO T 99)	Provision for adding water or drying	Mechanical tamping and/or rolling
Florida	8 in max loose	Thoroughly compacted	Provision for adding water or drying	Approved mechanical equipment
	4 in max loose	Thoroughly compacted	Provision for adding water or drying	Approved hand tampers weighing not less than 50 lb and having a face area not exceeding 100 sq in
Georgia	6 in max compacted	Well tamped	Not specified	(Foundations excavation for bridges) Power driven tamper
	6 in max loose	Min 95% AASHO T 99	Sufficient to allow specified	(Embankment adjacent to structures) Roller or power driven

			compaction	mechanical tamper
Mississippi	6 in max compacted	Thoroughly compacted	Not specified	(Backfilling for structure) Mechanical or hand tamping Details on tamping equipment not given
	6 in max compacted	90–95% AASHO T 99	Satisfactory	(Embankment adjacent to structures) Pneumatic tired or sheepsfoot rollers
North Carolina	6 in max. loose	Same density as adjacent portion of embankment	Not specified	Approved mechanical tamper which will deliver at least 185 p s f of tamping area
South Carolina	6 in max loose	Thoroughly compacted	Not specified	Equipment not specified under excavation for structure
SOUTH CENTRAL				
Arkansas	6 in max loose (Spec Prov.)	Satisfactorily compacted	Not specified	Hand or mechanical tampers
Louisiana	6 in max loose	Satisfactorily compacted	Provision for moistening—If too wet dried in borrow	Mechanical rammers or hand tampers of type (a)
Oklahoma	6 in max loose	Same as emb (90% AASHO T 99)	Provision for moistening	Equipment not specified under excavation for structures
Texas	10 in max loose	Same as for emb 90–100% AASHO T 99	As required to obtain density	Equipment not specified under structural excavation.
NORTH CENTRAL				
Iowa	6 in max loose	Compacted Satisfactory to Engineer	Not specified	Approved roller or mechanical tamper. Pneumatic tampers shall be supplied with air at a pressure of not less than 100 p s i
Kansas	6 in max compacted	Min 90% AASHO T 99	Sufficient for thorough bonding and density	Rolling, mechanical tampers or hand tampers of type (a)
Minnesota	6 in max compacted	Thoroughly compacted	Not specified	Approved rollers or mechanical tampers
Missouri	6 in max loose	Same as embankments (90% AASHO T 99)	Provision for moistening	Rollers, mechanical tampers or hand tampers of type (a).
Nebraska	6 in max loose	Min 90% AASHO T 99	Same as embankments	Rollers, mechanical tampers
North Dakota	8 in max loose	Extra Comp Min 95% AASHO T 99	Provision for moistening	Rollers, mechanical tampers or hand tampers of type (a)
South Dakota	4 in max loose	Satisfactorily compacted	Not specified	Mechanical tampers
MOUNTAIN				
Arizona	8 in. max loose (6 in. max alongside pipe)	To a density satisfactory to engineer	Provision for moistening	Rollers, mechanical tampers or hand tampers of type (a).
Colorado	6 in max loose	Thoroughly compacted	Provision for moistening	Mechanical tamper, Ingersoll-Rand Model 34 Backfill tamped or acceptable equivalent with 5 in diameter butt min operating air pressure 80 p s i
Idaho	6 in loose	Same as embankments (90–100% AASHO T 99)	As approved by engineer	Approved air, gasoline or electric driven tamper
Montana	8 in max loose	Thoroughly compacted	Not specified	Mechanical or hand tampers (excavation for structures)
	8 in max loose	Same as embankments (90–100% AASHO T 99)	Provision for wetting or drying	Tamping, pneumatic or power rollers (Embankments placed around structures)
Nevada	4 in max loose	Same as embankments (Min 90% modified AASHO)	Provision for moistening	Tamped, puddled or rolled (Note this refers to selected granular material) Pneumatic or hand tampers
New Mexico	4 in max loose	Same as embankments (Min 95% AASHO T 99)	Provision for moistening or non-use of wet material	Pneumatic or mechanical tamping units Tamper head area 19–29 sq in and deliver a blow of not less than 175 p s i of tamper head area
Utah	8 in max loose	Thoroughly compacted	Not specified	Equipment not specified under excavation for structures
Wyoming	5 in max loose	To a density satisfactory to engineer	Provision for moistening Prohibit use of wet material	Mechanical tamper — Thor model 60 BFT Tamper with 6 in diameter tamper head or acceptable equivalent Tamper must operate at about 750 strokes per minute under air pressure of 70–80 p s i Also pneumatic, sheepsfoot or smooth steel roller
PACIFIC				
California	4 in. max loose	Ponding of sandy or granular material Same as embankments (90% California method)	Provision for moistening	Tamped or rolled Equipment not specified
Oregon	6 in max loose	95% AASHO T 99	Provision for drying Same as for embankments	As approved by engineer
Washington	6 in max loose	Same as embankments (95% AASHO T 99)	Optimum ± 3 percentage points (Method C)	Air driven tampers with tamping foot area of 36–64 sq in min air pressure 75 p s i Gasoline driven tampers Barco or equal with tamping foot area 36–64 sq in
Bureau of Public Roads	12 in max loose	Satisfactorily compacted	Provision for moistening	Mechanical rammers or hand tampers of type (a)

NOTE —Type (a) requires tampers (usually heavy, iron tampers) having tamping faces not exceeding 25 sq in in area
Type (b) requires tampers weighing not less than 12 lb and having a tamping face not exceeding 50 sq in

State 3. Storm sewers. Suitable materials are placed in 4-in. layers and thoroughly tamped to a depth of 1 ft. above the pipe. Materials for the remaining depth are placed in 6-in. layers and each layer tamped. No moisture control given.

State 4. Storm sewers. Suitable materials are placed and compacted in accordance with one of three methods.
Method 1. Placed in layers of 6 inch loose depth and tamped.
Method 2. Use Method 1 to 12 in. above the pipe. Remaining materials are placed in lifts of 12 in. and each lift inundated.
Method 3. Same as Method 2 except that the trench is filled and jetted to within two feet of the pipe.
No moisture control specified for Methods 1 and 2.

State 5. Storm sewers - If under pavement. Selected granular materials are used. If crushed stone is used it is tamped in layers not exceeding 6 in. If sand or gravel is used it is placed in 12-in. layers, each layer is thoroughly saturated to secure maximum compaction.
If not under pavement. Selected granular and ordinary materials are used. Selected granular materials are placed in 4-in. layers to a height of 1 ft. above the pipe. Ordinary materials are thoroughly tamped in 6-in. layers for the remainder of the depth. No moisture control specified.

State 6. Storm and sanitary sewers. Ordinary materials are carefully hand tamped in 4-in. layers up to a height of 6-in. above the pipe. Remainder tamped in 6-in. lifts. No moisture control specified.

State 7. Pipe sewers. Ordinary materials are used if satisfactory. If not satisfactory, pit-run sand with 100 percent passing a 3-in. sieve is placed in layers not exceeding 6-in. and each layer thoroughly compacted. No moisture control specified.

State 8. Storm sewers. Ordinary suitable materials are placed in layers not exceeding 4 in. loose measure and compacted to density requirements given for roadway (AASHO T-99 table of densities). Moisture control required but no limits given.

State 9. Sewers. Suitable materials are placed in 6-in. layers and solidly tamped. Provision is made for adding water to dry soils.

State 10. Sewers. Suitable materials passing a 1-in. ring are compacted to the level of the top of the pipe. Water settling may be used above top of pipe when specially permitted by the engineer. No moisture control specified.

State 11. Storm sewers. Selected soil, sand, or rock dust is thoroughly tamped. No specified depth of lift nor moisture control are given. Puddling is recommended for sandy or gravelly materials.

State 12. Storm sewers. Approved materials shall be used. If stone gravel or slag is specified for backfilling, the sewer pipe shall be covered with clean gravel or broken stone or slag placed around and above it to a height of not less than 4 in. above the surface of the pipe. Material shall be deposited simultaneously on both sides of the pipe in uniform layers not to exceed 4 in. in thickness, solidly tamped or rammed with proper tools so as not to injure pipe. No moisture control specified.

The foregoing statement of requirements for backfilling over sewer pipe can be summarized more briefly as follows:

Six of the twelve states provide only for compaction, with no provision for puddling, flooding, or jetting. Two states provide for compaction and indicate that flooding or puddling may be permitted, one stating specifically that puddling is recommended only for sandy soils and gravelly soils. One state specified that the material shall be thoroughly settled by tamping and flooding. One state has provisions for use of compaction, flooding and jetting. One state provides for compaction of ordinary and angular (crushed rock) granular materials, permitting flooding only on rounded granular materials. Only one state provides simply for "flooding" without any qualifications or reservations.

Backfilling Structural Excavation

The 1951-52 survey included a review of Current State Highway Standard Specifications to summarize compaction and moisture control requirements for backfilling of structural excavation (see Table 24).

Lift Thickness. The specifications show a wide range of variation in thickness of lift. Four states specify a 6-in. compacted thickness. Two do not specify layer thickness. The remainder (two specifications are shown for some states) are divided in specifying thickness of lift (loose measurement):

Loose Depth in.	Number of Organizations Specifying
4	8
5	1
6	24[a]
8	5
9	2
10	1
12	4
4-6	1
4-8	1
6-12	1
Not specified	1

[a]Five states required a 6-in. compacted depth.

Compaction. Thirty organizations stated their requirements for backfill compaction simply in terms of being thoroughly or satisfactorily compacted or well tamped or in similar terms. Seventeen states which required compaction in terms of some percent of a maximum density showed identical requirements for embankments and structural backfill. Four specified 90 percent of AASHO T 99, seven specified 95 percent, one specified 90-95 percent, 5 specified 90-100, one specified 90-102, two required 90 percent and one required 95 percent of a modified method. There are 16 organizations which specify density control of backfill compared to 39 which specify density control of embankments.

Nearly all organizations provided for the use of mechanical tamping equipment; 32 required mechanical tampers; several states provided for hand-tamping equipment. The hand equipment referred to was of two types. Type A was usually referred to as heavy iron tampers having tamping faces not exceeding 25 sq. in. in area. Type B tampers were described as weighing not less than 12 lb. and having a tamping face not exceeding 50 sq. in.

COMPACTION EQUIPMENT

Because of the important part of equipment in obtaining compaction, a summary has been made of State Highway Department Standard Specifications for rolling and tamping equipment. Data on various items which are mentioned in specifications are given in Table 25.

Sheepsfoot-Type Rollers

Contact Area of Tamping Feet. Most organizations allow a wide range of size of tamping-foot contact area. This may be seen from the summary of specification requirements:

Range in Contact Area (sq. in.)	No. of Organizations
4 to 8	1
4 to 9	2
4 to 10	2
4 to 12	8
4 to 13	2
4 to 18	1
5 min.	2
5 approx.	1
5 to 8	3
5 to 10	1
$5\frac{1}{2}$ min.	1
6 to 8	2
8 to 12	1
13 max.	1

(Note: Two states provide for two ranges of sizes. They are incorporated in the above tabulation.)

An analysis of the specifications on a regional basis shows no difference in specifications for contact area for any specific region.

Contact Pressure. An analysis of standard specifications covering pressures of sheepsfoot-type rollers also showed a wide range in minimum contact pressure requirements. The range is:

TABLE 25

CURRENT STATE HIGHWAY STANDARD SPECIFICATION REQUIREMENTS FOR TAMPING (SHEEPSFOOT) TYPE ROLLERS FOR EMBANKMENT CONSTRUCTION

Region and state	Diameter of drums (in)	Width of drums (in)	Minimum number of feet per drum	Number of feet per row	Minimum spacing of feet (ins. center to center)	Size of tamping feet		Pressure on tamping feet		Operating speed (m p h)	Capacity (Max cu yds. per unit per hour)	Remarks
						Minimum length (inches)	Contact area (sq in)	Permissible range of pressure on feet (lb per sq in)	Basis for measurement			
NORTHEAST												
Connecticut												No specification
Maine												No specification
Massachusetts								50 min	Total weight on 1 row of feet		100	
Michigan								200 min				Compaction by hauling equipment largely replacing sheepsfoot roller
New Hampshire						6	4–12	100 min	Total weight on 1 row of feet			
New York						7	5–10	200–500	Total weight on 1 row of feet	3–5	1200 cu yds /day	
Rhode Island												No specification
Vermont						7	5 min	200 min	Total weight on 1 row of feet			
Wisconsin								150 min				
MIDDLE EAST												
Delaware					Uniformly spaced 8 min	7	4–18	450 max (a)	Total weight on 1 row of feet			(a) Fully loaded [1]
District of Columbia						7	4–12	Min 200 loaded	Total weight on 1 row of feet			
Illinois	48 min							100 min (a)		3 max	125	(a) Minimum weight of 90 lb per in of width
Indiana												No specification
Kentucky						7	Approx 5	Approx 200 min (a)				(a) Specification calls for 1,000 lb per ft minimum
Maryland								200 min				
New Jersey						6½		200 min	Total weight on 1 row of feet			
Ohio												Weights, dimensions of units, and number spacing and dimensions of tamping feet shall be such that the specified compaction may be obtained
Pennsylvania												No specifications for tamping type rollers except that they be approved
Tennessee		42 min			6–10			200 min				
Virginia								200 min				Type not specified Min 200 p s i Specified for any type roller
West Virginia		48 min				7		150 min	Total weight on 1 row of feet			
SOUTHEAST												
Alabama					See (a)	7	5 min	200 min	Total weight on 1 row of feet			(a) Approximately 2 tamping feet for each 1 3 sq ft of tamped area
Florida	40 min	48 min	112		6	7	5–8 (a)	200–400 (a)	Total weight on 1 row of feet			(a) On loams, clay loams and soil with considerable aggregate
Georgia							8–12 (b)	50–200 (b)	Total weight on 1 row of feet			(b) On sandy loams
Mississippi					6–12	7	4–10	200 min (loaded)				
North Carolina					See (a)	7	4–9	200 min				(a) Specifies spacing of about 2 tamping feet per sq ft
South Carolina												No specification

SOUTH CENTRAL												
Arkansas												No specification
Louisiana						7		110 empty 165 filled	Total weight on 1 row of feet			Minimum weight 50 lbs per linear inch of drum length when empty Minimum weight 75 lbs per linear inch of drum length when loaded
Oklahoma						7	13 max	Min 90 (a)				(a) Under working conditions the roller shall have a minimum weight of 90 lbs per linear inch of length of drum
Texas	40 min 60 min	42 min 60 min			6–10	7 7	5–8 6–8	125–175 Up to at least 550	Total weight on 1 row of feet Same	2–3 2–3		Specifications for "Tamping" Spec for "Heavy Tamping." One tamping ft for each 0 65 to 0 7 sq ft of drum area
NORTH CENTRAL												
Iowa						6 5		200 min	Total weight on 1 row of feet			
Kansas					6–12	7	4–12	200 min (a)	Total weight on 1 row of feet			(a) When loaded
Minnesota								150 min	Total weight on 1 row of feet			
Missouri								100 min (a)				(a) Also requires minimum weight of 90 lbs per in of length of drum
Nebraska					6–10	7	4 to approx 12	Min 80 empty Min 150 loaded	Total weight on 1 row of feet			
North Dakota						7		Min 150 loaded				
South Dakota	60 min	60 min	120	4 min		6	4–8 (a)	Min 300 empty Min 550 loaded	Total weight on 1 row of feet	3–5		Provision for removal of feet after being worn down more than ¾ in
MOUNTAIN												
Arizona		48 min				6	4–13	85–275 min (a)	Total weight on 1 row of feet			(a) Based on specification that minimum load is 1,100 lbs per tamping foot
Colorado	60 min	60 min			13 min (a)	7	5–8	250–500	No feet per drum x area of feet ——— 20	3 min	200 (10 ft unit)	(a) Space between 1 foot and to 2 nearest feet in adjacent row shall average not more than 13 inches
Idaho	48 min				6–12	7	4–10	250 min	Total weight on 1 row of feet	2–3		
Montana		48 min			6–10	7	4–12	150 min	Total weight on 1 row of feet	2–3	125	
Nevada		48 min						100 min (a)		3 min		(a) Also requires minimum weight of 90 lbs per in of width
New Mexico	40 min	49 min	60			7	5½ min	300 min	Total area of feet on which roller is supported	3 min		Tent Spec require 60" x 60" drums, 112 feet per drum, 5–8 sq in contact area, and 300–500 p s i pressure
Utah	60 min	60 min	Min 20 rows	8–12		7	6–8	Min 325 loaded	Total weight on 1 row of feet(a)		100	(a) Same as for Wyoming below
Wyoming	60 min	60 min	80–120	4–6		7	6–8	325 min	Total weight on 1 row of feet when less than 24 rows of feet See note (a)	2 5 min		(a) For 24 or more rows o feet ground pressure is determined by dividing total weight by 4 5% of total cross sectional area of all feet Provision for renewal if worn ¾ inches or more
PACIFIC												
California					6–12 (a)	7	4–12	250 min	Total weight on one row of feet		150 (8 ft unit)	(a) Space between rows and between feet in one row
Oregon Washington	36 min	48 max			6–12	7	4–9	150 min Min 135 (empty) Min 250 (loaded)	Total weight on one row of ft	2–3		
Bureau of Public Roads.		48 min				6	4–13	85–275 min (a)	Total weight on one row of ft			(a) Based on specification that min load is 1100 lb per tamper foot
Civil Aeronautics Administration		48 min			6–10	7	4–12	Min 120 (empty)	Tamping feet in contact with ground.			

[1] Sheepsfoot rollers will not be included in revised specifications

TABLE 26

CURRENT STATE STANDARD HIGHWAY SPECIFICATION REQUIREMENTS FOR PNEUMATIC TIRE ROLLERS FOR EMBANKMENT CONSTRUCTION

Region and State	Type	Rolling width (inches)	Gross weight (tons)	Operating Weight per tire (lb)	Compression		Inflation pressure (p s i)	Operating speed (m p h)	Capacity (max. cu yds. per unit per hour)	Remarks
					(Lb per in. of width of tire tread)	(Lb per in. width of roller)				
NORTHEAST										
Connecticut										Not specified.
Maine										Permitted
Massachusetts										Not specified.
Michigan										Required for sandy soils. No specifications
New Hampshire										Not specified
New York		48 min 84 max.		1000–2000						Min 1-7 ft roller for each 1600 cu. yds per day.
Rhode Island										Not specified.
Vermont										Not specified
Wisconsin						150 min				
MIDDLE EAST										
Delaware					300 lbs./lin. in.					Not specified but may be approved.
District of Columbia					200 min..		45 min			
Illinois	9-wheel 2-axle min.				225 min			3 max	125	
Indiana										Not specified.
Kentucky										Not specified.
Maryland			10							
New Jersey					225 min					
Ohio	Single or double axle									Weight dimensions of roller number and spacing of tires shall be such that specified compactions may be obtained.
Pennsylvania										Not specified.
Tennessee			8							
Virginia							200			No type specified Min 200 p s i. specified for any type roller.
West Virginia										Equipment shall be such that specified comp. may be obtained.
SOUTHEAST										

Alabama	2-axle	Approx. 60			325 min					
Florida										Not specified
Georgia										Not specified
Mississippi	2-axle 7-wheel min		8 min							
North Carolina	2-axle	Approx 60			325 min					
South Carolina										Not specified.
SOUTH CENTRAL										
Arkansas										Not specified
Louisiana										Not specified.
Oklahoma										Not specified
Texas	2-axle 9-wheel min	Approx 60			100–325			4–12		
NORTH CENTRAL										
Iowa										Not specified but may be approved
Kansas					225 min		45 min			
Minnesota						150 min				
Missouri										Not specified.
Nebraska										Not specified
North Dakota										May be used, if approved
South Dakota										Not specified
MOUNTAIN										
Arizona	2-axle	60 min, 84 max	7 min	1400 min						
Colorado	2-axle	60 min		1000–2000				3 min		
Idaho	4-wheel, min. 15" tire	Approx 60			200 min			2–3		Approved type.
Montana										Contractor may use any type method to obtain specified den
Nevada	2-axle	60			225 min			3 min		
New Mexico	2-axle 9-wheel	60 min			200		60 min (See Note (a).	3 average		(a) Spec. prov. specify loaded scrapers 18 T exclusive of wt of scraper.
Utah	3-wheel min.	60 min		6000 min			60 min	3 min		May be used on light fills
Wyoming		Approx 60			250 min			3 average		Note (1)
PACIFIC										
California										Not specified.
Oregon										Not specified
Washington	2-axle	60 min, 90 max	4–11 (a)							(a) Weight to be adjusted as required to obtain compaction.
Bureau of Public Roads.										Not specifi3d.

[1] New special provision provide for rolling subgrade, grade, subbase or base with pneumatic tired scrapers weighing not less than 18 tons exclusive of weight of scraper. Min. tire pressure 60 p s i

TABLE 27

CURRENT STATE HIGHWAY STANDARD SPECIFICATION REQUIREMENTS FOR SMOOTH WHEEL POWER ROLLERS FOR EMBANKMENT CONSTRUCTION

State and Region	Tandem type			3-wheel type				Type not Specified		Operating speed (m.p.h.)	Capacity (max cu. yds. per unit per hour)	Remarks
	Weight (tons)	Roller width (inches)	Compression pressure (lb. per inch of width of roll)	Weight (tons)	Diam. of drive rolls (inches)	Width of drive rolls (inches)	Compression pressure (lb per inch of width of drive roll)	Weight (tons)	Compression pressure (lb. per inch of width of roll)			
NORTHEAST												
Connecticut								10 min				
Maine				10 min								
Massachusetts								10 min			100	
Michigan												Not specified.
New Hampshire												Not specified.
New York				10 min			325 min			3 av., 5 max.	1200 per day	3-wheel type inferred.
Rhode Island				10 min								
Vermont												Not specified.
Wisconsin.	8 min		250 min	8 min			250 min					
MIDDLE EAST												
Delaware												Not specified
District of Columbia				10 min	68 min	18 min	340 min.			2 min		
Illinois				10 min						6 max	125	
Indiana				10 min								
Kentucky				10								
Maryland	10 min			10 min								
New Jersey				10 min			330 min					
Ohio				10 min	68 min	18 min	340 min			2 min		
Pennsylvania				10 min			330 min					
Tennessee	10 min			10 min								
Virginia							Min. 200 p.s.i. (a)					(a) Type of roller not specified. Min. 200 p.s.i spec. for any type roller.
West Virginia				10 min							100	

SOUTHEAST												
Alabama				10								
Florida												Not specified
Georgia												Not specified
Mississippi												Not specified
North Carolina				10 min			330 min					
South Carolina												Not specified.
SOUTH CENTRAL												
Arkansas				8–12								
Louisiana								10	170			
Oklahoma									200 min			
Texas				10 min	48 min	20 min	325 min			2–3	100	
NORTH CENTRAL												
Iowa												Not specified
Kansas												Not specified
Minnesota									150 min			
Missouri												Not specified
Nebraska						18–24	275 min					
North Dakota												Not specified.
South Dakota												Not specified.
MOUNTAIN												
Arizona	8 min			10–14								
Colorado								8 min	325 min	3 min		
Idaho												Wt not spec. Den required must be approved.
Montana				10 min			325 min			2–3	125	
Nevada	8 min			10 min						3 min		
New Mexico												Not specified.
Utah	10 min		300 min	10 min			300 min					May be used on light embankments.
Wyoming	8–12 (a)			8–12 (a)								(a) May be either tandem or 3-wheel type.
PACIFIC												
California				10min (a)			325 min				150	
Oregon												Not specified.
Washington				10 min			325 min					
Bureau of Public Roads				10 min							125	
Civil Aeronautics Administration.				10 min								

TABLE 28

CURRENT STATE HIGHWAY STANDARD SPECIFICATION REQUIREMENTS [1] FOR PNEUMATIC TIRE ROLLERS AND SMOOTH WHEEL POWER ROLLERS FOR COMPACTION OF GRANULAR BASES [2]

Region and State	Pneumatic Tire Rollers: Type	Rolling width (inches)	Gross weight (tons)	Operating weight per tire (pounds)	Compression: (Lb /in width of tire)	Compression: (Lb /in of rolling width	Compression: Inflation pressure (p.s.i)	Operating speed (m.p h.)	Capacity (max. cu. yd. per unit per hour)	Tandem type: Weight (tons)	Tandem type: Compression (Lb /in of width of roll)	3-wheel type: Weight (tons)	3-wheel type: Compression (Lb /in of width of drive roll)	Operating speed (m.p h.)	Capacity (max. cu. yd or tons or sq yds. per unit per hour)	Remarks
NORTHEAST																
Connecticut												10 min			150 sq yd. (a)	(a) Rolled gravel base—bottom course
Maine	(a)											10				(a) An approved pneumatic tired roller may be used
Massachusetts										12 min (a)		12 min (a)				(a) Requires a self-propelled roller
Michigan	(a)															(a) Required but no specifications covering pneumatic tire roller
New Hampshire												10 min				
New York												10 min				Approved roller weighing not less than 10 tons
Rhode Island												10 min				
Vermont												10 min				
Wisconsin											Min 250 (a)		Min 250 (b)			(a) Max 68% of gross weight on driving rolls. (b) Max. 72% of gross weight on driving rolls. Hauling Equipment Engineer may require special rolling equipment if not attained during contract Rubber tired rollers are used.
MIDDLE EAST																
Delaware												10 min (a)				(a) For W B Macadam. No requirement for gravel.
District of Columbia										8-10 (a)	200-260	8-12 (a)	290-380			(a) Weight approved for job
Illinois										6-10	200-325	6-10	200-325			(a) Gravel or crushed stone surface course Type A
Indiana	2-axle, 9-wheel, min				Up to 200					10 min		10 min				Permit use of crawler tread tractors having a bearing of at least 6 lb per sq in of tread. Vary lift thickness to obtain desired density
Kentucky										7-10		7-10				
Maryland										10 (a)		10 (a)				(a) Requires a 10-ton "power roller"
New Jersey			8 min		225 min							8 min (a)	Min 330			(a) On a tire not more than 24 in. wide.
Ohio	(a)											10 min	Min 300	2		(a) Weight, dimensions of roller and number and spacing of tires shall be such that specified compaction may be obtained.
Pennsylvania										8	250	10 min	Min 330			Specified for crushed rock.
Tennessee												10		2	500 sq yds	
Virginia										10 (a)		10 (a)				(a) For W B Macadam only Sheepsfoot or other approved types for stabilized and pit run base courses.
West Virginia	Approved type											10 min (a)				(a) Reconstructed base course, Coarse to Fine gradings.

SOUTHEAST																
Alabama	2-axle	Approx 60			325 min											
Florida	2-axle				325 min											
Georgia												10 min				
Mississippi	2-axle, 7-wheel min		8 min													Use sheepsfoot rollers on some bases along with wheeled rollers
North Carolina	(a)											8-10				(a) Pneumatic tire rollers satisfactory to engineer
South Carolina												8-10				
SOUTH CENTRAL																
Arkansas												10 min				Also traffic compaction
Louisiana												10 min	Min 350			
Oklahoma	2-axle	Approx 60	5 min					10 max				10 min (a)	Min 200			(a) Min 10 tons for W B Macadam
Texas	2 axle, 9-wheel, min	Approx 60			325 min			2-3	100			10 min	Min 325	2-3	100	
NORTH CENTRAL																
Iowa					Min 200 (a)		Min 25				Min 200		Min 200			(a) Min 200 lb per in of width of roller
Kansas					225 Min		Min 45			8-12		8-12				(a) Sheepsfoot type may be used on sand and sandy loam bases
Minnesota						Min 150				(a)		(a)				(a) Smooth wheel rollers permitted for surface finish rolling No specifications for weight
Missouri	Multi-Wheel				200 min					2-5 (a)		2-5 (a)				(a) For final surface rolling
Nebraska					200 min		Min 45			(a)		(a)				(a) May be used if approved by engineer
North Dakota			10		200 min		25-40 (a)			10 max	Min 250	10 max	Min 250			(a) 25 p.s.i for 10,000 and 40 p.s.i for 20,000 lb gross load
South Dakota	2-axle min	60 min				Min 250					Min 200		Min 200			
MOUNTAIN																
Arizona	2-axle	Min 60 Max 84	7 min	1400 min				Most favorable	125	8 min		10-14		Most favorable	125	
Colorado	2-axle	Min 60		1000-2000 (a)				3 min	200			8 min	325 min	3 min	200	(a) Operating weight to be as ordered by engineer
Idaho	2-axle, 9-wheel min	Approx 60			200 min			2-3		8-10		8 or 10		2-3		Approved pneumatic tire roller if thickness of layer is 3 in or less. If greater, requirements are same as for embankments.
Montana	2-axle (a)	Min 48 Max 72			160 min							8 min				(a) May be used if approved by engineer
Nevada					225					8 min		10 min				
New Mexico	2-axle, 9-wheel				200			3 min				8-12		3 min		
Utah	Min 3-wheel	60 min		6000 min			60 min	3 min		10 min	300	10 min	300 min	200-300 f p m.		
Wyoming	2-axle	Approx 60			Min 250 (Loaded)			2-5		8-12 (a)		8-12 (a)		2-5		(a) Type not specified.**
PACIFIC																
California	Single or Double axle	Min 48 Max 84		1000-2000 (a)								10 min	325 min		400 T	(a) Operating weight to be as ordered by engineer
Oregon												10 min			40 T (a)	(a) Type A crushed rock
Washington	2-axle	60-90	4-11 (a)										Min 325			(a) Weight (within limits shown) to be as ordered by engineer
Bureau of Public Roads												8 min				
Civil Aeronautics Administration		60 min			Min 275 (Loaded)							10 min	Min 330		25	

[1] From Current State Highway and Federal Standard Specifications Only
[*] Granular bases are soil type bases and may be gravel bases, stabilized gravel bases, stabilized soil type roads, etc An effort has been made to exclude roller requirements for crushed stone type bases, and bases involving cementitious, liquid plastic admixture
** New special provisions provide for rolling subgrade, grade, subbase or base with pneumatic tired scraper weighing not less than 18 tons exclusive of weight of scraper Min. tire pressure 60 p.s.i.

Minimum Permissible Contact Pressure by Tamping Feet psi.	No. of Organizations Specifying
550 (loaded)	1
450	1
325	1
300	2
250	3
200	14
200 (loaded)	1
150	4
135	1
125	1
110	1
100	5
90	1
85	1
80	1
50	2

Other significant specification requirements for sheepsfoot rollers are given in Table 25, "Current State Highway Standard Specification Requirements for Tamping (Sheepsfoot) Type Rollers for Embankment Construction."

Pneumatic-Tire Rollers. Twenty-three organizations included some requirements for the pneumatic-tire roller in specifications for compaction of embankments (see Table 26).

Smooth-Wheeled Power Rollers. Thirty-four organizations have specification requirements for power rollers for embankment construction (see Table 27).

Granular-Base Compaction. A summary of specifications for pneumatic-tire rollers is given in Table 28, "Current State Highway Standard Specification Requirements for Pneumatic Tire Rollers . . . for Compaction of Base Courses."

Smooth-Wheel Power Rollers. A summary of "Current State Highway Standard Specifications for Smooth Wheel Power Rollers" is given in Table 28.

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Appendix

MANUFACTURERS' SPECIFICATIONS

The 1951-52 survey of current practice includes data on current state highway and federal specifications for various types and sizes of compacting equipment. In order to present more nearly complete data on compacting equipment, manufacturers who were known producers of such equipment were contacted by letter requesting equipment specifications. Tables A through E include data received in reply to those requests.

The list of manufacturers is not complete but is sufficiently inclusive to indicate the ranges in types and sizes of equipment and may be of value in preparation of specifications for compacting equipment. The data are presented in the tables following.

TABLE A

MANUFACTURERS SPECIFICATIONS FOR PNEUMATIC TIRE ROLLERS

Manufacturer	Type	Rolling width (in)	Tire size (in)	Inflation pressure (p.s.i.)	Gross operating weight: Empty (Tons)	Gross operating weight: Empty (Pounds)	Gross operating weight: Loaded (a) (Tons)	Gross operating weight: Loaded (a) (Pounds)	Load per wheel (b): Empty (Pounds)	Load per wheel (b): Loaded (Pounds)	Range of ground pressure (Lb per in of roller width	
Tampo Manufacturing Co, San Antonio, Texas	5-axle, 9-wheel	60	7 50 x 15	30-35	1 4	2,750	6 03	18,000	305	2,000	47-325	
	7-axle, 13-wheel	84	7 50 x 15	30-35	1 8	3,700	12 6	26,000	308	2,000	47-325	
Wm Bros Boiler Manufacturing Co, Minneapolis, Minn	2-axle, 7-wheel	46	7 50 x 15 (4-ply)		1	1,980	7	14,000	283	2,000	43-304	Use of 6-ply tires increases capacities 15% Maximum overload capacity 7, 9 and 13 tons Maximum load for 1 to 5 mph rolling 6, 8 and 11 tons Maximum speed 5 mph
	2-axle, 9-wheel	60	7 50 x 15 (4-ply)		1 3	2,550	9	18,000	284	2,000	43-300	
	2-axle, 13-wheel	84	7 50 x 15 (4-ply)		1 8	3,600	13	26,000	277	2,000	43-310	
	Single axle, 4-wheel	106	18 x 24 (24-ply)	50-90	10	20,200	35	70,000	5,050	17,500	189-660	
	Single axle, 4-wheel	106	18 x 24 (24-ply)	50-90	12	22,600	50	100,000	5,650	25,000	226-942	
M J Dunn Company, St Paul, Minn	3-axle, 5-wheel	72 to 75	17 x 16		2	4 000	5-14	10,000 28,000	800	800 5,600	53-373	With calcium chloride in tires add 2,500 lbs
Southwest Welding & Mfg Company, Alhambra, Calif	6 independently sprung wheels	90	11 00 x 20	80	3 6	7,250	15	30,000	1,812	7,500	81-333	
	4 independently sprung wheels	80	14 00 x 20	80	5 25	10,500	25	50,000	2,625	12,500	131-625	
	4 independently sprung wheels	118	18 00 x 24	90	15	30,000	50	100,000	7,500	25,000	254-847	
	4 independently sprung wheels	126	21 00 x 24	80	15 7	31,500	70	140,000	7,875	35,000	238-1111	
	4 independently sprung wheels	140	24 00 x 32	90	24	48,000	100	200,000	12,000	50,000	343-1428	
	4 independently sprung wheels	184	30 00 x 33	150	45	90,000	200	400,000	22,500	100,000	489-2174	
Willamette Iron and Steel Co, Portland, Oreg	2 oscillating axles, 4-wheel	114 (c)	18 00 x 24 (24-ply)	Not Specified	13 5	27,000	50	100,000	6,750	25,000	60-220	
Supercompactors, Inc, Sacramento, Calif	2-axle (dual oscillating 4-wheel box)	174	30 00 x 33 (60-ply)	30-150	40	80,000	200	400,000	20,000	100,000	460-2299	
	2-axle (dual oscillating, 4-wheel box)	112	21 00 x 25 (44-ply)	30-150	18	36,000	100	200,000	9,000	25,000	322-1785	
	Single box, eccentric axle, 4-wheel.	94	16 00 x 21 (36-ply)	30-150	9 5	19,000	60	120,000	4,500	30,000	202-1277	
	Single box, eccentric axle, 4-wheel	85	16 00 x 21 (36-ply)	30-150	7 5	15,000	60	120,000	45,000	30,000	175-1412	
W E Grace Mfg Co, Dallas, Texas	3-axle Open body type Self-propelled 11-wheel roller	66	Front 7 5 x 10 Drive 9 x 24 Rear 7 5 x 15					1,120 4,460 5,920		1,120 1,115 987		
							Total	11,500				
	3-axle (d) Tank body type Self-propelled 11-wheel roller	66	Front 7 5 x 10 Drive 9 x 24 Rear 7 5 x 15				*	*	*	*	*	*Approximately same as for open body type
Shovel Supply Co, Dallas, Texas.	2-axle (e), oscillating 4-wheel		16 x 21 or 18 x 24		12 25	24,500	50	100,000	6,125	25,000		In two models —one for sand ballast, the other for cast iron blocks
	2-axle dual oscillating, 4-wheel box		30 x 33 (60-ply)	150	38 5	77,000	200	400,000	19,250	100,000		Cast iron ballast blocks
Iowa Mfg Co, Cedar Rapids, Iowa	1-axle, 2-wheel	48	24 00 x 33 (36-ply)	40-100	15 0	30,000	30	60,000	7,500	15,000		(Variable from static to maximum vibrator input)
	1-axle, 2-wheel dual	48	12 00 x 20 (14-ply)	40-100	6 3	12,500	12 5	25,000	6,250	12,500		

(a) Loaded weight is product of rolling width and maximum ground pressure in pounds per inch of roller width
(b) Load per wheel is gross weight divided by number of wheels
(c) Computed by editor from spacing of 18-inch tires
(d) Tank body has capacity of 1,000 gallons and may be equipped with spray bar
(e) Furnished in two models Model RT 100 for cast iron ballast Model RT 100S for sand ballast

TABLE B

MANUFACTURERS SPECIFICATIONS FOR TAMPING (SHEEPSFOOT) TYPE ROLLERS

Manufacturer	Model and type	Dimensions of drums: Number	Dimensions of drums: Length [1] (in)	Dimensions of drums: Diameter [2] (in)	Data on tamping feet: No per drum [3]	Data on tamping feet: Tamping area of each foot (sq in)	Data on tamping feet: Length of foot (in)	Data on tamping feet: Number of feet on ground [4]	Weights (lb): Empty	Weights (lb): Loaded with water	Weights (lb): Loaded with wet sand	Contact pressure (p.s i) [5]: Empty	Contact pressure (p.s i) [5]: Loaded with water	Contact pressure (p.s i) [5]: Loaded with wet sand
American Steel Works, Kansas City, Mo	MS 48, Single	1	48	40	112	5 5	7	4	3,220	4,895	6,436	146	222	293
	MS 60, Single	1	60	40	140	5 5	7	5	3,610	6,090	8,372	131	221	304
	MS 72, Single	1	72	40	168	5 5	7	6	4,049	7,285	10,263	123	221	311
	MD 96, Oscillating	2	48	40	112	5 5	7	8	6,190	9,724	13,242	141	221	301
	MD 120, Oscillating	2	60	40	140	5 5	7	10	7,100	12,160	16,815	129	221	306
	MT 144, Oscillating	3	48	40	112	5 5	7	12	10,000	14,800	19,948	151	224	302
	AS 48, Single	1	48	60	90	7	7	3	4,100	8,300	12,075	195	395	575
	AS 66, Single	1	66	60	120	7	7	4	5,460	11,060	16,072	195	395	574
	AD 96, Oscillating	2	48	60	90	7	7	6	8,000	16,380	24,000	190	390	571
	AD 132, Oscillating	2	66	60	120	7	7	8	10,640	21,840	31,864	190	390	569
American Steel Works, Kansas City, Mo [6]	B3 48, Non-oscillating	1	48	54	72	7	7	3	3,750	7,060	10,050	179	336	479
	B4 48, Non-oscillating	1	48	54	72	7	7	4	3,750	7,060	10,050	134	252	359
	B4 66, Non-oscillating	1	66	54	96	7	7	4	5,160	8,470	11,460	184	303	410
	B6 96, Oscillating	2	48	54	72	7	7	6	7,000	13,670	19,800	166	325	470
	B8 96, Oscillating	2	48	54	72	7	7	8	7,000	13,670	19,800	125	244	353
	B8 132, Oscillating	2	66	54	96	7	7	8	9,820	16,440	22,420	175	284	401
	CS 79, Non-oscillating	1	79	73	136	8	18	4	9,700	19,695	28,915	303	615	904
	CD 158, Oscillating	2	79	73	136	8	18	8	19,300	39,295	57,725	302	614	902
Slusser-McLean Scraper Company, Sidney, Ohio	Single	1	48	40	112	6	7	4	3,000	4,935	6,870	125	205	286
	Oscillating	2	48	40	112	6	7	8	6,000	9,870	13,740	125	205	286
	Oscillating	3	48	40	112	6	7	12	9,000	14,805	20,610	125	205	286
Tampo Manufacturing Company, San Antonio, Texas	H1, One-drum	1	48	40	112	6	7	4	3,200	5,134		132	212	
	H2, Two-drum	2	48	40	112	6	7	8	6,300	10,168		132	212	
	501, One-drum	1	60	60	120	6	7	4	7,200	12,317	16,876	300	512	703
	502, Two-drum	2	60	60	120	6	7	8	14,400	24,634	33,752	300	512	703
	501R, One-drum	1	72	60	120	7	8	4	8,400	13,517	18,076	300	483	645
	502R, Two-drum	2	72	60	120	7	8	8	16,800	27,034	36,152	300	483	645

Wm Bros Boiler and Manufacturing Company, Minneapolis, Minn	M1 5½, Single	1	48	40	112	5½	7	4	2,925	4,860	6,800	133	221	309
	M1 7, Single	1	48	40	112	7	7	4	3,035	4,960	6,910	108	178	247
	M2 5½, Oscillating	2	48	40	112	5½	7	8	5,850	9,720	13,600	133	221	309
	M2 7, Oscillating	2	48	40	112	7	7	8	6,070	9,920	13,820	108	178	247
	M3 5½, Oscillating	3	48	40	112	5½	7	12	9,180	14,980	20,800	139	227	315
	M3 7, Oscillating	3	48	40	112	7	7	12	9,520	15,320	21,140	113	183	252
	G1 55-8, Single	1	60	60	112	7	8	4	8,300	13,700	19,100	296	490	682
	G2 55-8, Oscillating	2	60	60	112	7	8	8	17,600	28,100	38,900	310	500	695
	G1 55-9½, Single	1	60	60	120	7	9½	4	9,490	14,890	20,290	340	530	725
	G2 55-9½, Oscillating	2	60	60	120	7	9½	8	19,720	30,520	41,320	353	545	740
R G LeTourneau, Inc , Peoria, Ill	X1, Single	1	48	41½	88	5 4	8	4	3,610	5,606	7,610	167	260	353
	X2, Oscillating	2	48	41½	88	5 4	8	8	6,590	10,583	14,590	152	245	337
	X3, Oscillating	3	48	41½	88	5 4	8	12	9,570	15,560	21,570	147	240	333
	X4, Oscillating	4	48	41½	88	5 4	8	16	12,550	20,537	28,550	145	240	330
	120, Tournapacker Oscillating	2	60	60	120	7 07	8¼	4	17,700	29,360	40,070 [7]	626	1,035	1,420
McCoy Company, Denver, Colo	USHD 65, Oscillating	2	60	72	138	6 to 9	8¼ or 9¼	4	23,500	36,959	50,500			
	USHD 66, Oscillating	2	72	72	168	6 to 9	8¼ or 9¼	4	26,700	43,186	60,342			
	USHD 55, Oscillating	2	60	60	120	6 or 7	8¼	4	15,000	25,075	35,312	535-625	890-1,040	1120-1308
Baker Manufacturing Company, Springfield, Ill [8]	SF S96, Oscillating	1	48	40	96	5 75	7	4	3,210	5,100	6,100	139	221	266
	SF D96, Oscillating	2	48	40	96	5 75	7	4	6,570	10,040	12 040	143	225	263
	SF T96, Oscillating	3	48	40	96	5 75	7	4	9,860	15,500	18 500	141	233	268
Bucyrus-Erie Company, South Milwaukee, Wis [8]	TDO, Oscillating	2	48	40	112	6	7	8	6,225	9,825	11,825	135	210	250
W E Grace Manufacturing Co , Dallas, Texas [8]	RSX 112, Oscillating	2	48	40	112	5 5	7⅛	8	6,200			140	224	310
	TX 96, Oscillating	2	42	40	96	5 5	7⅛	4	5,700			130	200	270
	X 112, Single	1	48	40	112	5 5	7⅛	4	3,200			144	228	314
	RPX 104, Oscillating	2	48	40	104	5 5	7⅛	4	7,200			163	248	332
	LXX 95, Oscillating	2	48	60	95	7	8	(9)	12,400			230	375	500
	LX5X120, Oscillating	2	60	60	120	7	8	(9)	14,250			259	455	652
	LX6X136, Oscillating	2	72	60	136	7	8	(9)	16,250			286	525	765
Shovel Supply Co , Dallas, Texas	Ferguson 112, Oscillating	2	48	40	112	5 5	7	8	6,340	10,200		150	242	
	Gebhard 22, Oscillating	2	72	60	144	6 25	8	8				425	685	
	Gebhard 22, Oscillating	2	60	60	120	5 5	7½	8	14,200	25,920		320	590	
	Model 112W, Oscillating	2	48	40	112	5 5	7	8	8,020	11,880		180	270	327
	Model 112W-48, Oscillating	2	48	48	112	5 5	8	8	9,700	15,280	21,190	220	347	481
	Model 2, Reclamation Oscillating	2	60	60	120	7 06	10	4	28,500	37,860	47,400	1,010	1,340	1,678

[1] Length of each drum [2] Diameter without feet [3] Number of feet shown here is standard Manufacturers provide more or fewer feet as may be specified Most manufacturers are prepared to furnish special shapes and sizes if desired [4] Number in one row times number of drums per unit [5] Based on one row of feet in contact with ground [6] Manufacturers computations [7] Loaded with water and boxes loaded with sand [8] Data from Powers Road and Street Catalogue, 1950–51 [9] Not closer than 11 in , not farther than 13 in c c diagonally 3 ft for each 2 sq ft of drum area

TABLE C

MANUFACTURERS SPECIFICATIONS FOR STANDARD WEIGHT 3-WHEEL POWER ROLLERS

Manufacturer	Model	Type	Weight group (tons)	Transmission speeds					Dimensions of rolls				Roller compression (Lb per lin in)		Roll overlap (in each side)	Overall rolling width (inches)	
									Guide roll		Drive roll						
				Low	Int	3	4	High	Diam (in)	Width (in)	Diam (in)	Width (in)	Guide roll	Drive roll			
Galion Iron Works and Manufacturing Company, Galion, Ohio	Warrior	3-wheel	6	1 4	2 9			5 0	36	41	55	18	98	224	3½	70 with 18" rolls	
	Warrior	3-wheel	7	1 2	2 5			4 3	38	41	60	18	114	261	3½	70 with 18" rolls	20-in width rear rolls available
	Warrior	3-wheel	8	1 2	2 5			4 3	38	41	60	18	130	298	3½	70 with 18" rolls	20-in width rear rolls available
	Chief	3-wheel	10	1 4	2 9			5 0	44	44	69	20	152	335	4	76 with 20" rolls	22- and 24-in width rear rolls available
	Chief	3-wheel	12	1 4	2 9			5 0	44	44	69	20	182	403	4	76 with 20" rolls	22- and 24-in width rear rolls available
	Trench	3-wheel	8½	1 5				3 5			60	20					
Huber Manufacturing Company, Marion, Ohio		3-wheel	5	1 7				3 4	34	37	52	18	97	217	3	67 with 18" rolls	
		3-wheel	6	1 7				3 4	34	37	52	18	97	239	3	67 with 18" rolls	
		3-wheel	8	2 0	4 0			5 2	40	40	60	18	134	308	2½	71 with 18" rolls	
		3-wheel	10	2 0	4 0			5 2	44	43	69	20	148	348	4	75 with 20" rolls	24-in width rear rolls available
		3-wheel	12	2 0	4 0			5 2	44	43	69	20	187	415	4	75 with 20" rolls	24-in width rear rolls available
W A Riddell Corp, Bucyrus, Ohio	10 G 54	3-wheel	10	1 96	3 20			5 38	44	42	68	20	168	354	4	74 with 20" rolls	
	12 G 54	3-wheel	12	1 96	3 20			5 38	44	42	68	20	193	405	4	74 with 20" rolls	
Austin-Western Company, Aurora, Ill	Cadet	3-wheel	6	1 31	3 59			5 86	36½	37	52	18	106	230	3-5/8	65¾ with 18" rolls	Weights for gasoline motor powered roller for 6-, 7-, 8-, 10 and 12-ton rollers
	Cadet	3-wheel	7	1 31	3 59			5 86	36	37	52	18	124	271	3-5/8	65¾ with 18" rolls	
	Cadet	3-wheel	8	1 35	3 70			6 04	37	37	54	18	136	314	3-5/8	65¾ with 18" rolls	Special (8-ton) available with 22-in wheels
	Autocrat	3-wheel	10	1 1	3 0			4 9	43	45	68	20	168	330	4½		22- and 24-in rear rolls available
	Autocrat	3-wheel	12	1 1	3 0			4 9	43	45	68½	20	195	387	4½		22- and 24-in rear rolls available

TABLE D

MANUFACTURERS SPECIFICATIONS FOR VARIABLE WEIGHT 3-WHEEL POWER ROLLERS

Manufacturer	Model	Type	Weight group (tons)	Transmission speeds (Miles per hour)						Dimensions of rolls				Roller compression (Lb per lin in)					Roll over-lap (in on each side)	Overall rolling width (inches)	
										Guide roll		Drive roll		Guide roll		Drive roll					
				Low	Int	3	4	High	Reverse	Diam (in)	Width (in)	Diam (in)	Width (in)	Min	Max.	Min	Max with water	Max. with wet sand			
Buffalo - Springfield Roller Co , Springfield, Ohio	VM-18	3-wheel	5-7	1 7	2 5	3 6		5 2	Same	36	38	55	16	101	130	226	267	307	3	64 with 16" rolls	18 in width rear rolls available
	VM-19	3-wheel	6-8	1 7	2 5	3 6		5 2	Same	36	38	55	18	102	131	233	278	322	3	68 with 18" rolls	20 in width rear rolls available
	VM-21	3-wheel	7-10	1 7	2 5	3 6		5 2	Same	41	40	60	18	122	156	264	316	369	4	68 with 18" rolls	20 and 22 in width rear rolls available
	VM-24	3-wheel	8-11	1 7	2 5	3 6		5 2	Same	41	40	60	18	125	159	317	366	414	4	68 with 18" rolls	20, 22, and 24 in width rear rolls available
	VM-31C	3-wheel	10-12½	1 5	2 3	3 5		5 0	Same	44	44	69	20	141	178	363	430		4	76 with 20" rolls	22 and 24 in width rear rolls available
	VM-32C	3-wheel	12-15	1 5	2 3	3 5		5 0	Same	44	44	69	20	145	180	446	504	563	4	76 with 20" rolls	22 and 24 in width rear rolls available

TABLE E

MANUFACTURERS SPECIFICATIONS FOR VARIABLE WEIGHT TANDEM POWER ROLLERS
(Does not include 3-axle type)

Manufacturer	Model	Type	Weight group (tons)	Transmission speeds (Miles per hour)					Dimensions of rolls				Roller Compression—(Lb per lin in)					
									Guide roll		Drive roll		Guide roll *		Drive roll			
				Low	Int	3	4	High	Diam (in)	Width (in)	Diam (in)	Width (in)	Min	Max	Min	Max with water	Max with sand	
Galion Iron Works and Manufacturing Company, Galion, Ohio		Tandem	3-5	1 5				3 4	30	40	48	42	66	89	109	171		
		Tandem	5-8	1 5				3 4	40	50	53	50	108	144	130	207		
		Tandem	8-12	2 23				4 65	48	54	60	54	123	178	184	282		
		Tandem	10-14	2 23				4 65	48	54	60	54	152	206	217	317		
Buffalo-Springfield, Springfield, Ohio	KT-7	Tandem	3-5	1 59 2 12				3 02 4 04	30	38	40	38			112	150	178	
	KT-16C	Heavy duty tandem	5-8	1 75	2 5	3 5		5 0	40	50	53	50			140	224		
	KT-17C	Heavy duty tandem	6-9	1 75	2 5	3 5		5 0	40	50	53	50			151	233		
	KT-240	Heavy duty tandem	8-12	1 75	2 5	3 5		5 0	48	54	00	54			185	285		
	KT-25C	Heavy duty tandem	10-14	1 75	2 5	3 5		5 0	48	54	60	54			240	340		
	VT-48	Heavy duty tandem	15-21	1 35	1 9	2 75		4 1	51½	59	71¾	59			330	505		
Clyde Iron Works, Duluth, Minn	21	Tandem	1-1¼	Up to →	→	→	→	2 14	20	24	26	28			47 2	67 5		
	80	Tandem	3-4	Up to →	→	→	→	2 44	28	36	36	42			107	155		
Huber Manufacturing Company, Marion, Ohio		Tandem	3-4	2 6				4 4	27	34	44	38	64	68	112	171		
		Tandem	4-5	2 6				4 4	27	34	44	38	64	68	150	198		
		Tandem	5-8	1 95				3 62	40	50	52	50	97	135	125	203		
		Tandem	8-10	1 95				3 62	40	50	52	50	111	147	209	266		
		Tandem	8-12	2 9				5 7	48	54	60	54	114 8	173 3	207 4	298 6		
		Tandem	10-14	2 9				5 7	48	54	60	54	133	185	240	328		
Littleford Bros , Cincinnati, Ohio	185 Vari-Packer	Tandem	4-6	2				4	30	40	48	42	71	98	100	170		
Essick Manufacturing Company, Los Angeles, Calif	200	Tandem	1½-2	1-1 8				2 8-3 4	30	26½	40	30	40	40	60	110		
	300	Tandem	2-3	1-1 2				2 2-4 1	30	26½	40	30	40	60	110	148		
	400	Tandem	3-4	1-2				1½-4	30	34	48	38	40	60	105	160		
	500	Tandem	3½-5	1-3 2				1 5-5	34	36	48	38	59	73	156	200		
	800	Tandem	5-8	2 3				4 2	40	50	50	50	95	130	135	195		
Austin-Western Company, Aurora, Ill		Tandem	5-8	1 0/2 26				2 26/4 63	40	50	52	50			145	224		Weights are for gasoline-powered models
			8 10½	1 0/2 26				2 26/4 63	40	50	52	50			242	309		
Tampo Mfg Co , San Antonio, Texas	5-8	Tandem	5-8	2				4	40	50	52	50	93	130	124	198		

* Where compression for guide roll is not given it was not shown by manufacturer

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