CHAPTER 8

Soil Compaction

Soil compaction is one of the most critical components in the construction of roads, airfields, embankments, and foundations. The durability and stability of a structure are related to the achievement of proper soil compaction. Structural failure of roads and airfields and the damage caused by foundation settlement can often be traced back to the failure to achieve proper soil compaction.

Compaction is the process of mechanically densifying a soil. Densification is accomplished by pressing the soil particles together into a close state of contact with air being expelled from the soil mass in the process. Compaction, as used here, implies dynamic compaction or densification by the application of moving loads to the soil mass. This is in contrast to the consolidation process for fine-grained soil in which the soil is gradually made more dense as a result of the application of a static load. With relation to compaction, the density of a soil is normally expressed in terms of dry density or dry unit weight. The common unit of measurement is pcf. Occasionally, the wet density or wet unit weight is used.

Section I. Soil Properties Affected by Compaction

ADVANTAGES OF SOIL COMPACTION

Certain advantages resulting from soil compaction have made it a standard procedure in the construction of earth structures, such as embankments, subgrades, and bases for road and airfield pavements. No other construction process that is applied to natural soils produces so marked a change in their physical properties at so low a cost as compaction (when it is properly controlled to produce the desired results). Principal soil properties affected by compaction include—

- Settlement.
- Shearing resistance.
- Movement of water.
- Volume change.

Compaction does not improve the desirable properties of all soils to the same degree. In certain cases, the engineer must carefully consider the effect of compaction on these properties. For example, with certain soils the desire to hold volume change to a minimum may be more important than just an increase in shearing resistance.

SETTLEMENT

A principal advantage resulting from the compaction of soils used in embankments is that it reduces settlement that might be caused by consolidation of the soil within the body of the embankment. This is true because compaction and consolidation both bring about a closer arrangement of soil particles.

Densification by compaction prevents later consolidation and settlement of an embankment. This does not necessarily mean that the embankment will be free of settlement; its weight may cause consolidation of compressible soil layers that form the embankment foundation.

SHEARING RESISTANCE

Increasing density by compaction usually increases shearing resistance. This effect is highly desirable in that it may allow the use of a thinner pavement structure over a compacted subgrade or the use of steeper side slopes for an embankment than would otherwise be possible. For the same density, the highest strengths are frequently obtained by using greater compactive efforts with water contents somewhat below OMC. Large-scale experiments have indicated that the unconfined compressive strength of a clayey sand could be doubled by compaction, within the range of practical field compaction procedures.

MOVEMENT OF WATER

When soil particles are forced together by compaction, both the number of voids contained in the soil mass and the size of the individual void spaces are reduced. This change in voids has an obvious effect on the movement of water through the soil. One effect is to reduce the permeability, thus reducing the seepage of water. Similarly, if the compaction is accomplished with proper moisture control, the movement of capillary water is minimized. This reduces the tendency for the soil to take up water and suffer later reductions in shearing resistance.

VOLUME CHANGE

Change in volume (shrinkage and swelling) is an important soil property, which is critical when soils are used as subgrades for roads and airfield pavements. Volume change is generally not a great concern in relation to compaction except for clay soils where compaction does have a marked influence. For these soils, the greater the density, the greater the potential volume change due to swelling, unless the soil is restrained. An expansive clay soil should be compacted at a moisture content at which swelling will not exceed 3 percent. Although the conditions corresponding to a minimum swell and minimum shrinkage may not be exactly the same, soils in which volume change is a factor generally may be compacted so that these effects are minimized. The effect of swelling on bearing capacity is important and is evaluated by the standard method used by the US Army Corps of Engineers in preparing samples for the CBR test.

Section II. Design Considerations

MOISTURE-DENSITY RELATIONSHIPS

Nearly all soils exhibit a similar relationship between moisture content and dry density when subjected to a given compactive effort (see *Figure 8-1)*. For each soil, a maximum dry density develops at an OMC for the compactive effort used. The OMC at which maximum density is obtained is the moisture content at which the soil becomes sufficiently workable under a given compactive effort to cause the soil particles to become so closely packed that most of the air is expelled. For most soils (except cohesionless sands), when the moisture content is less than optimum, the soil is more difficult to compact. Beyond optimum, most soils are not as dense under a given effort because the water interferes with the close packing of the soil particles. Beyond optimum and for the stated conditions, the air content of most soils remains essentially the same, even though the moisture content is increased.

The moisture-density relationship shown in *Figure 8-1* is indicative of the workability of the soil over a range of water contents for the compactive effort used. The relationship is valid for laboratory and field compaction. The maximum dry density is frequently visualized as corresponding to 100 percent compaction for the given soil under the given compactive effort.

The curve on *Figure 8-1* is valid only for one compactive effort, as established in the laboratory. The standardized laboratory compactive effort is the compactive effort (CE) 55 compaction procedure, which has

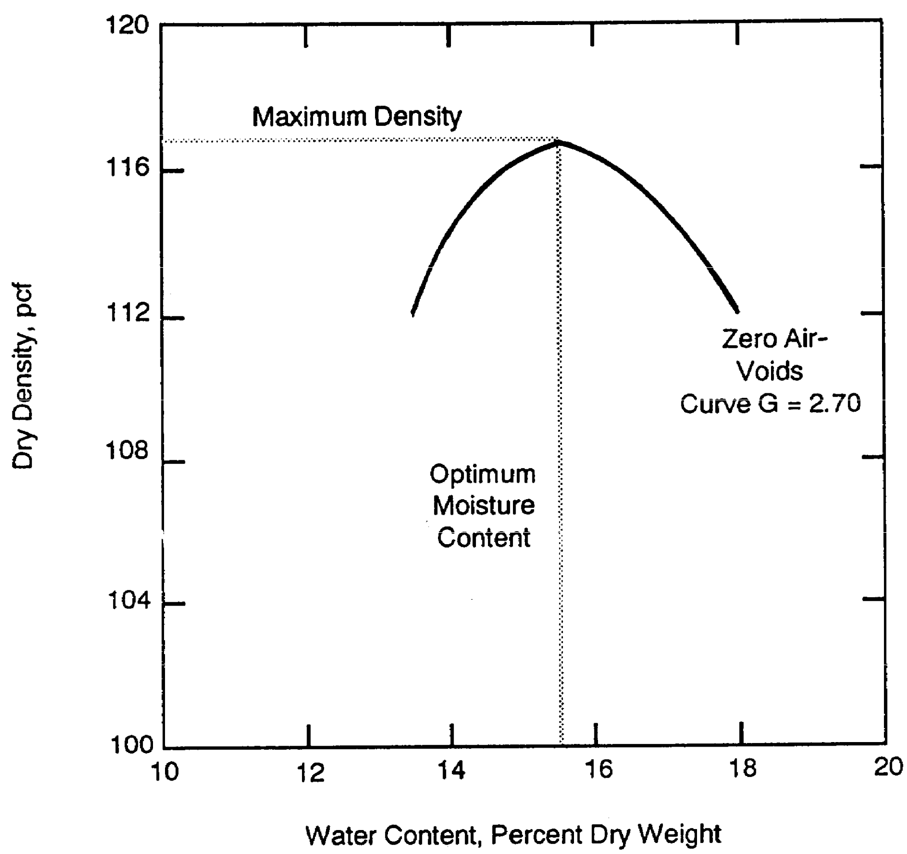


Figure 8-1. Typical moisture-density relationship.

been adopted by the US Army Corp of Engineers. Detailed procedures for performing the CE 55 compaction test are given in *TM 5-530.* The maximum dry density (ydmax) at the 100 percent compaction mark is usually termed the CE 55 maximum dry density, and the corresponding moisture content is the optimum moisture content. *Table 8-1, page 8-4,* shows the relationship between the US Army Corps of Engineers compaction tests and their civilian counterparts. Many times the names of these tests are used interchangeably in publications.

Figure 8-1 shows the zero air-voids curve for the soil involved. This curve is obtained by plotting the dry densities corresponding to complete saturation at different moisture contents. The zero air-voids curve represents theoretical maximum densities for given water contents. These densities are practically unattainable because removing all the air contained in the voids of the soil by compaction alone is not possible. Typically, at moisture contents beyond optimum for any compactive effort, the actual compaction curve closely parallels the zero air-voids curve. Any values of the dry density curve that plot to the right of the zero air-voids curve are in error. The specific calculation necessary to plot the zero air-voids curve are in *TM 5-530.*

Compaction Characteristics of Various Soils

The nature of a soil itself has a great effect on its response to a given compactive effort! Soils that are extremely light in weight, such as diatomaceous earths and some volcanic soils, may have maximum densities under a given compactive effort as low as 60 pcf. Under the same compactive effort, the maximum density of a clay may be in the range of 90 to 100 pcf, while that of a well-graded,

Table 8-1. Compaction test comparisons.

Test Designation	Blows Per Layer	No of Layers	Hammer Weight lb	Hammer Drop in	Mold	
					Volume cu ft	Diameter in
US Army Corps of Engineers (MIL-STD-631A)						
CE 55	55	5	10	18	0.0736	6
CE 12	12	5	10	18	0.0736	6
ASTM						
D-1557 Modified Proctor	25	5	10	18	0.0333	4
	56	5	10	18	0.0750	6
Standard Proctor	25	3	5.5	12	0.0333	4
American Association of State Highway and Transportation Officials (AASHTO)						
T-180 Modified AASHTO	25	5	10	18	0.0333	4
	56	5	10	18	0.0750	6
T-99 Standard AASHTO	25	3	5.5	12	0.0333	4

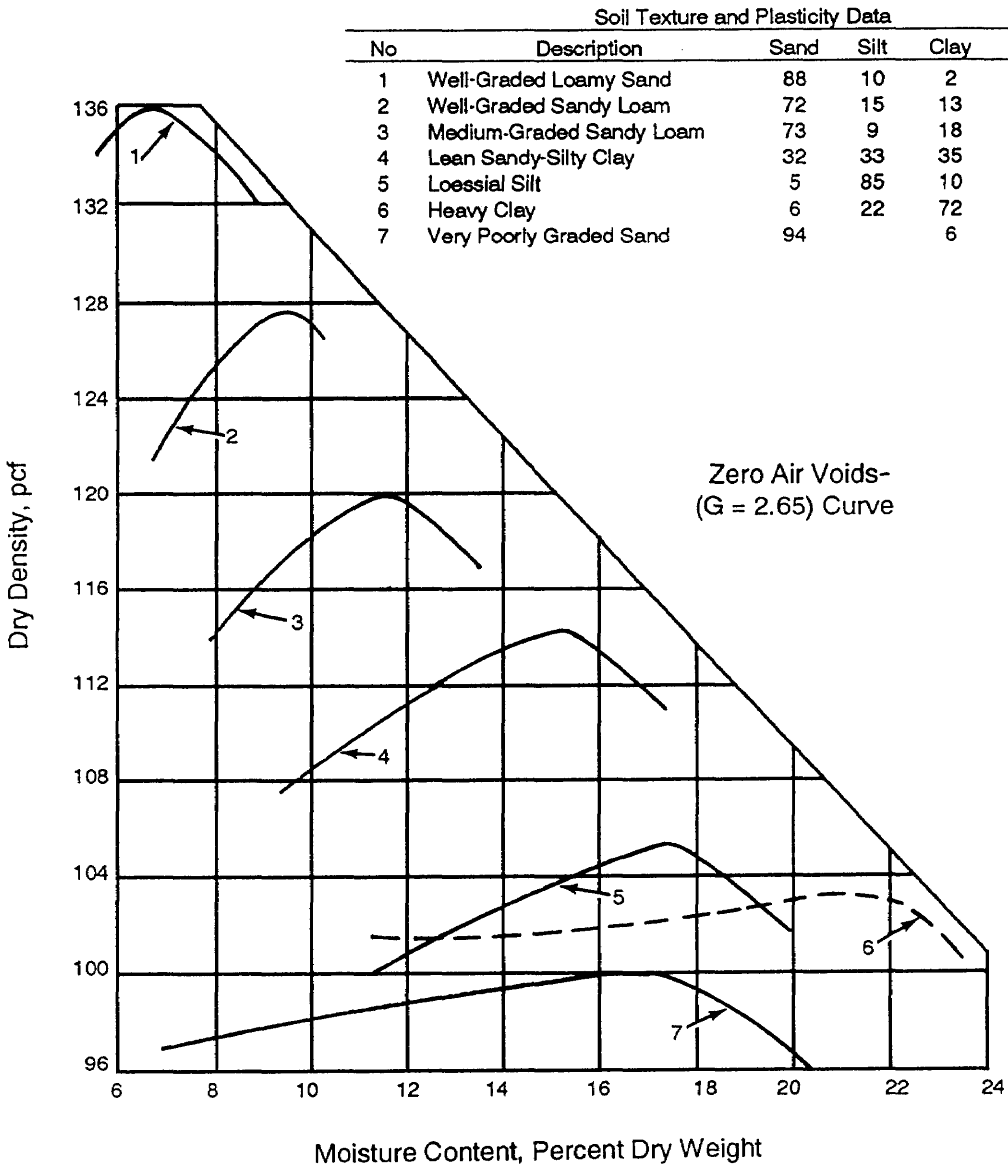
coarse granular soil may be as high as 135 pcf. Moisture-density relationships for seven different soils are shown in *Figure 8-2*. Compacted dry-unit weights of the soil groups of the Unified Soil Classification System are given in *Table 5-2, page 5-8*. Dry-unit weights given in column 14 are based on compaction at OMC for the CE 55 compactive effort.

The curves of *Figure 8-2* indicate that soils with moisture contents somewhat less than optimum react differently to compaction. Moisture content is less critical for heavy clays (CH) than for the slightly plastic, clayey sands (SM) and silty sands (SC). Heavy clays may be compacted through a relatively wide range of moisture contents below optimum with comparatively small change in dry density. However, if heavy clays are compacted wetter than the OMC (plus 2 percent), the soil becomes similar in texture to peanut butter and nearly unworkable. The relatively clean, poorly graded sands also are relatively unaffected by changes in moisture. On the other hand, granular soils that have better grading and higher densities under the same cormpactive effort react sharply to slight changes in moisture, producing sizable changes in dry density.

There is no generally accepted and universally applicable relationship between the OMC under a given compactive effort and the Atterberg limit tests described in *Chapter 4*. OMC varies from about 12 to 25 percent for fine-grained soils and from 7 to 12 percent for well-graded granular soils. For some clay soils, the OMC and the PL will be approximately the same.

Other Factors That Influence Density

In addition to those factors previously discussed, several others influence soil density, to a smaller degree. For example, temperature is a factor in the compaction of soils that have a high clay content; both density and OMC may be altered by a great change in temperature. Some clay soils are sensitive to manipulation; that is, the more they are worked, the lower the density for a given compactive effort. Manipulation has little effect on the degree of compaction of silty or clean sands. Curing, or drying, of a soil following compaction may increase the strength of



Soil Texture and Plasticity Data

No	Description	Sand	Silt	Clay	LL	PI
1	Well-Graded Loamy Sand	88	10	2	16	NP
2	Well-Graded Sandy Loam	72	15	13	16	0
3	Medium-Graded Sandy Loam	73	9	18	22	4
4	Lean Sandy-Silty Clay	32	33	35	28	9
5	Loessial Silt	5	85	10	26	2
6	Heavy Clay	6	22	72	67	40
7	Very Poorly Graded Sand	94		6	NP	

Figure 8-2. Moisture-density relationships of seven soils.

subgrade and base materials, particularly if cohesive soils are involved.

Addition of Water to Soil

Often water must be added to soils being incorporated in embankments, subgrades, and bases to obtain the desired degree of compaction and to achieve uniformity. The soil can be watered in the borrow pit or in place. After the water is added, it must be thoroughly and uniformly mixed with the soil. Even if additional water is not needed, mixing may still be desirable to ensure uniformity. In processing granular materials, the best results are generally obtained by sprinkling and mixing in place. Any good mixing equipment should be satisfactory. The more friable sandy and silty soils are easily mixed with water. They may be handled by sprinkling and mixing, either on the grade or in the pit. Mixing can be done with motor graders, rotary mixers, and commercial harrows to a depth of 8 inches or more without difficulty.

If time is available, water may also be added to these soils by diking or ponding the pit and flooding until the desired depth of penetration has taken place. This method usually requires several days to accomplish uniform moisture distribution. Medium clayey soils can be worked in the pit or in place as conditions dictate. The best results are obtained by sprinkling and mixing with cultivators and rotary mixers. These soils can be worked in lifts up to 8 inches or more without great difficulty. Heavy clay soils present many difficulties and should never be used as fill in an embankment foundation. They should be left alone without disturbance since usually no compactive effort or equipment is capable of increasing the in-place condition with reference to consolidation and shear strength.

The length of the section being rolled may have a great effect on densities in hot weather when water evaporates quickly. When this condition occurs, quick handling of the soil may mean the difference between obtaining adequate density with a few passes and requiring extra effort to add and mix water.

Handling of Wet Soils

When the moisture content of the soil to be compacted greatly exceeds that necessary for the desired density, some water must be removed. In some cases, the use of excessively wet soils is possible without detrimental effects. These soils (coarse aggregates) are called free-draining soils, and their maximum dry density is unaffected by moisture content over a broad range of moisture. Most often, these soils must be dried; this can be a slow and costly process. The soil is usually dried by manipulating and exposing it to aeration and to the rays of the sun. Manipulation is most often done with cultivators, plows, graders, and rotary mixers. Rotary mixers, with the tail-hood section raised, permit good aeration and are very effective in drying excessively wet soils. An excellent method that may be useful when both wet and dry soils are available is simply to mix them together.

Variation of Compactive Effort

For each compactive effort used in compacting a given soil, there is a corresponding OMC and maximum density. If the compactive effort is increased, the maximum density is increased and the OMC is decreased. This fact is illustrated in *Figure 8-3.* It shows moisture-density relationships for two different soils, each of which was compacted using two different compactive efforts in the laboratory. When the same soil is compacted under several different compactive efforts, a relationship between density and compactive effort may be developed for that soil.

This information is of particular interest to the engineer who is preparing specifications for compaction and to the inspector who must interpret the density test results made in the field during compaction. The relationship between compactive effort and density is not linear. A considerably greater increase in compactive effort will be required to increase the density of a clay soil from 90 to 95 percent of CE 55 maximum density than is required to effect the same changes in the density of a sand. The effect of variation in the compactive effort is as significant in the field rolling process as it is in the laboratory compaction procedure. In the field, the compactive effort is a function of the weight of the roller and the number of passes for the width and depth of the area of soil that is being rolled. Increasing the weight of the roller or the number of passes generally increases the compactive effort. Other factors that may be of consequence include—

- Lift thickness.
- Contact pressure.
- Size and length of the tamping feet (in the case of sheepsfoot rollers).
- Frequency and amplitude (in the case of vibratory compactors).

To achieve the best results, laboratory and field compaction must be carefully correlated.

COMPACTION SPECIFICATIONS

To prevent detrimental settlement under traffic, a definite degree of compaction of the underlying soil is needed. The degree depends on the wheel load and the depth below the surface. For other airfield construction and most road construction in the theater of operations, greater settlement can be accepted,

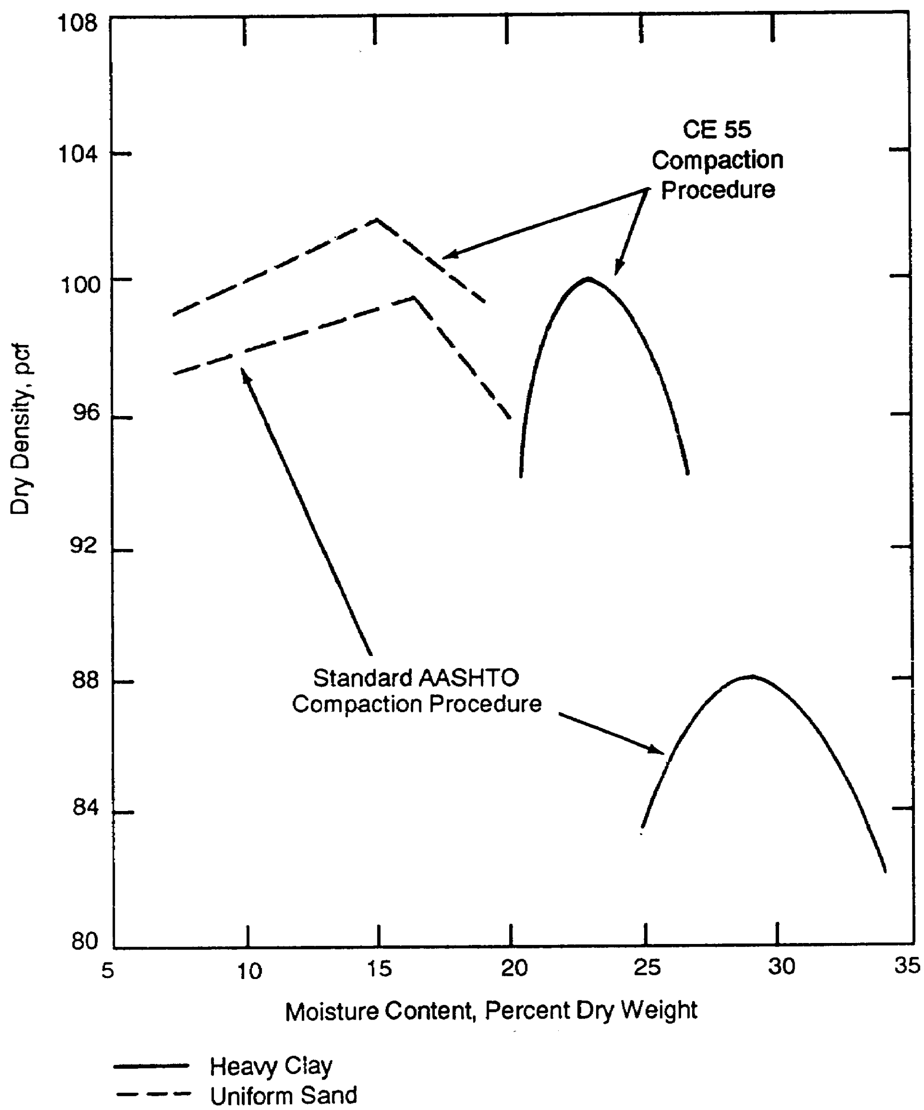


Figure 8-3. Moisture-density relationships of two soils.

although the amount of maintenance will generally increase. In these cases, the minimum compaction requirements of *Table 8-2, page 8-8,* should be met. However. strength can possibly decrease with increased compaction. particularly with cohesive materials. As a result, normally a 5 percent compaction range is established for density and a 4 percent range for moisture. Commonly, this "window" of density and moisture ranges is plotted directly on the GE 55 compaction curve and is referred to as the specifications block. *Figure 8-4, page 8-8,* shows a density range of 90 to 95 percent compaction and a moisture range of 12 to 16 percent.

CBR Design Procedure

The concept of the CBR analysis was introduced in *Chapter 6*. In the following procedures, the CBR analytical process will be applied to develop soil compaction specifications. *Figure 8-5, page 8-10,* outlines the CBR design process. The first step is to look at the CE 55 compaction curve on a *DD Form 2463, page 1.* If it is U-shaped, the soil is classified as "free draining" for CBR

Table 8-2. Minimum compaction requirements.

Soil Placement	Soil Definition	Remarks
Base	Cohesionless, CBR > 80	100 percent compaction
Subbase	Cohesionless, CBR 20-50	100 percent compaction
Select Subgrade	CBR < 20, any in-place soil	Cohesionless: 95 percent compaction Cohesive: 90 percent compaction Note: If subgrade CBR > 20, 100 percent compaction
Embankment fill 50 ft > H		Traffic areas Cohesionless: 95 percent compaction Cohesive: 90 percent compaction Nontraffic areas Cohesionless: 90 percent compaction Cohesive: 85 percent compaction
Backfill for trenches		Under pavement: same requirement as base through subgrade Nontraffic area: subtract 5 percentage points for each
Top 6 inches of sidewalks		Cohesionless: 90 percent compaction Cohesive: 85 percent compaction
Small water-retaining structures		Cohesionless: 95 percent compaction Cohesive: 90 percent compaction
Note: Cohesionless: PI ≤ , LL < 25 Cohesive: PI > 5		

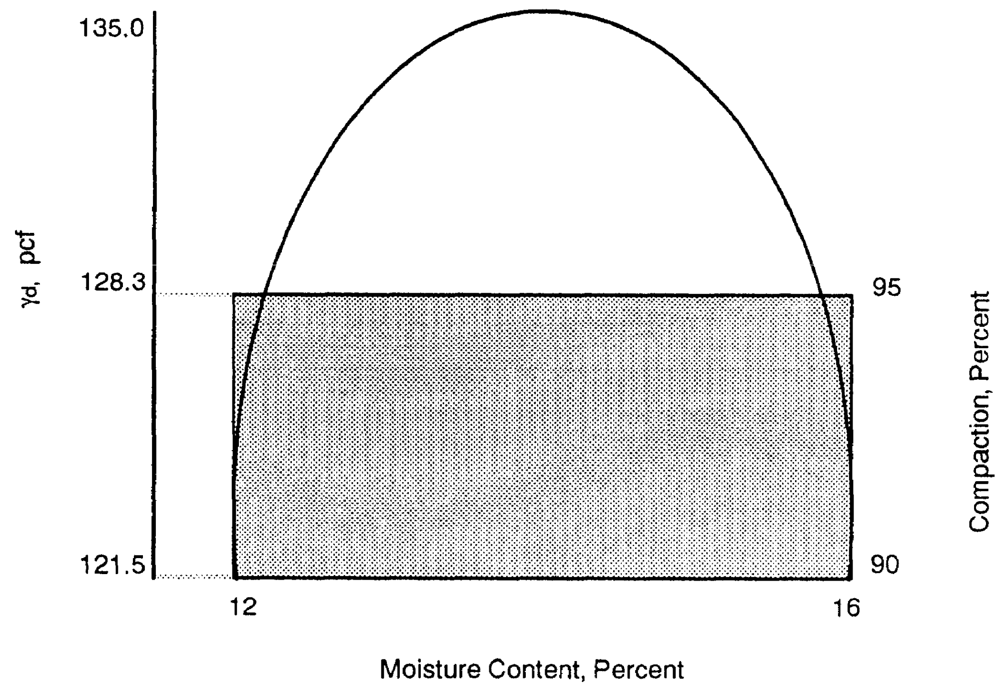


Figure 8-4. Density, compaction, and moisture content.

analysis and the left-hand column of the flowchart should be used through the design process. If it is bell-shaped, use the swell data graphically displayed on a *DD Form 1211*. Soils that, when saturated, increase in volume more than 3 percent at any initial moisture content are classified as swelling soils. If the percentage of swelling is ≤ 3 percent, the soil is considered nonswelling.

Regardless of the CBR classification of the soil, the density value from the peak of the CE 55 moisture density curve is ydmax. The next step is to determine the design moisture content range. For nonswelling soils, the OMC is used. When the OMC is used, the design moisture content range is ± 2 percent. For swelling and free-draining soils, the minimum moisture content (MMC) is used. The MMC is determined differently for swelling soils than it is for free-draining soils. The MMC for swelling soils is determined by finding the point at which the 3 percent swell occurs. The soil moisture content that corresponds to the 3 percent swell is the MMC. Free-draining soils exhibit an increase in density in response to increased soil moisture up to a certain moisture content, at which point no further increase in density is achieved by increasing moisture. The moisture content that corresponds to ydmax is the MMC. For both swelling and free-draining CBR soil classes, the design moisture-content range is MMC + 4 percent.

For swelling and free-draining soils, the final step in determining design compaction requirements is to determine the density range. Free-draining soils are compacted to 100-105 percent ydmax. Swelling soils are compacted to 90-95 percent γdmax.

Compaction requirement determinations for nonswelling soils require several additional steps. Once the OMC and design moisture content range have been determined, look at a *DD Form 1207* for the PI of the soil. If PI > 5, the soil is cohesive and is compacted to 90-95 percent ydmax. If the PI ≤ 5, refer to the CBR Family of Curves on page 3 of *DD Form 2463*. If the CBR values are insistently above 20, compact the soil to 100-105 percent ydmax. If the CBR values are not above 20, compact the soil to 95-100 percent γdmax.

Once you have determined the design density range and the moisture content range, you have the tools necessary to specify the requirements for and manage the compaction operations. However, placing a particular soil in a construction project is determined by its gradation. Atterberg limits, and design CBR value. *Appendix A* contains a discussion of the CBR design process.

A detailed discussion of placing soils and aggregates in an aggregate surface or a flexible pavement design is in *FM 5-430* (for theater-of-operations construction), *TM 5-822-2* (for permanent airfield design), and *TM 5-822-5* (for permanent road design).

Subgrade Compaction

In fill sections, the subgrade is the top layer of the embankment, which is compacted to the required density and brought to the desired grade and section. For subgrades, plastic soils should be compacted at moisture contents that are close to optimum. Moisture contents cannot always be carefully controlled during military construction, but certain practical limits must be recognized. Generally, plastic soils cannot be compacted satisfactorily at moisture contents more than 10 percent above or below optimum. Much better results are obtained if the moisture content is controlled to within 2 percent of optimum. For cohesionless soils, moisture control is not as important, but some sands tend to bulk at low moisture content. Compaction should not be attempted until this situation is corrected. Normally, cohesionless soils are compacted at moisture contents that approach 100 percent saturation.

In cut sections, particularly when flexible pavements are being built to carry heavy wheel loads, subgrade soils that gain strength with compaction should be compacted to the general requirements given earlier. This may make it necessary to remove the soil, replace it, and compact it in layers to obtain the required densities at greater depths. In most construction in the theater of operations, subgrade soil in cut sections should be scarified to a depth of about 6 inches and recompacted. This is commonly referred to as a scarify/compact in-place (SCIP) operation.

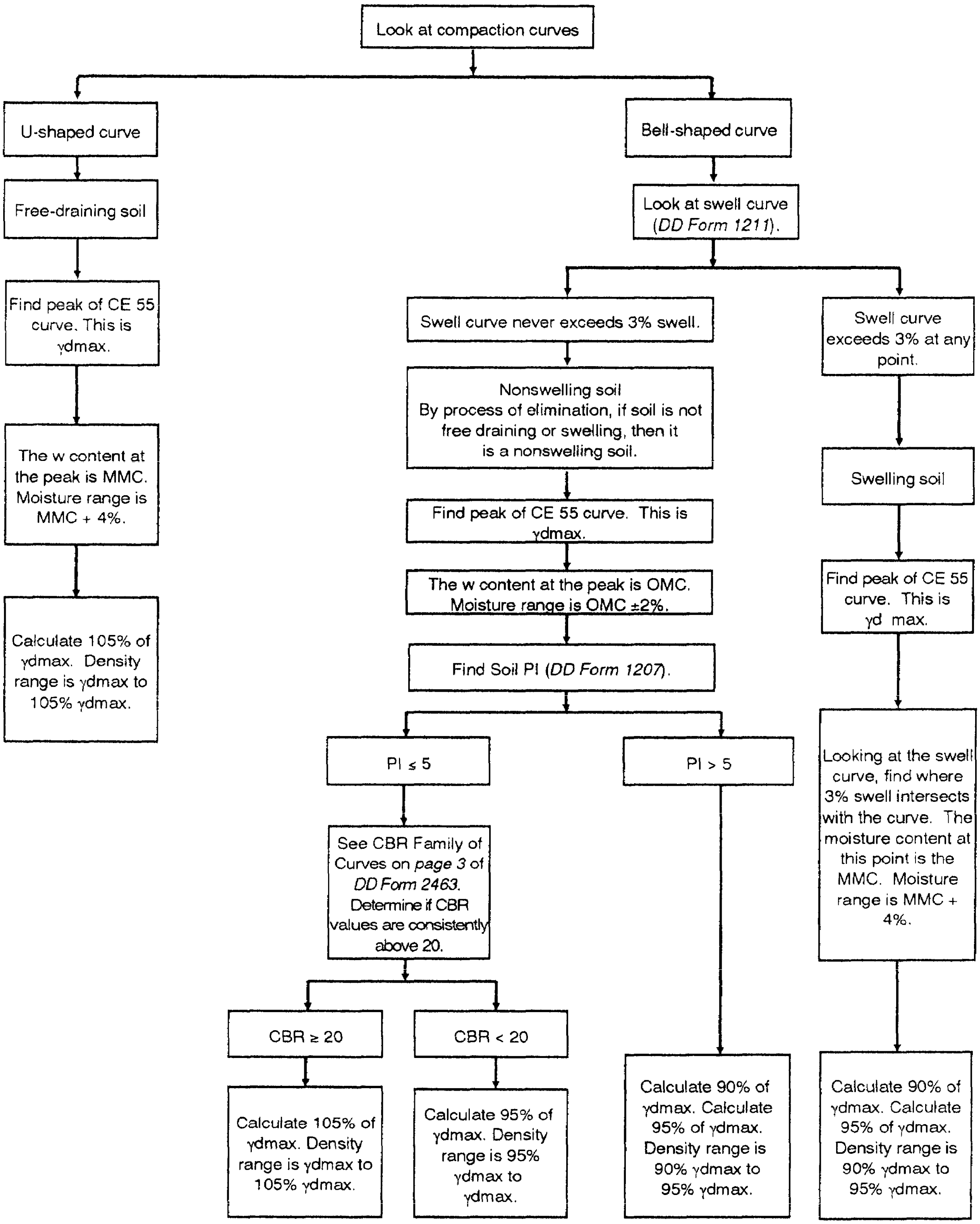


Figure 8-5. Density and moisture determination by CBR design method.

This procedure is generally desirable in the interest of uniformity.

Expansive Clays. As indicated previously, soils that have a high clay content (particularly (CH), (MH), and (OH)) may expand in detrimental amounts if compacted to a high density at a low moisture content and then exposed to water. Such soils are not desirable as subgrades and are difficult to compact. If they have to be used, they must be compacted to the maximum density obtainable using the MMC that will result in a minimum amount of swelling. Swelling soils, if placed at moisture contents less than the MMC, can be expected to swell more than 3 percent. Soil volume increases of up to 3 percent generally do not adversely affect theater-of-operations structures. This method requires detailed testing and careful control of compaction. In some cases, a base of sufficient thickness should be constructed to ensure against the harmful effects of expansion.

Clays and Organic Soils. Certain clay soils and organic soils lose strength when remolded. This is particularly true of some (CH) and (OH) soils. They have high strengths in their undisturbed condition, but scarifying, reworking, and compacting them in cut areas may reduce their shearing strengths, even though they are compacted to design densities. Because of these qualities, they should be removed from the construction site.

Silts. When some silts and very fine sands (predominantly (ML) and (SC) soils) are compacted in the presence of a high water table, they will pump water to the surface and become "quick", resulting in a loss of shearing strength. These soils cannot be properly compacted unless they are dried. If they can be compacted at the proper moisture content. their shearing resistance is reasonably high. Every effort should be made to lower the water table to reduce the potential of having too much water present. If trouble occurs with these soils in localized areas, the soils can be removed and replaced with more suitable ones. If removal, or drainage and later drying, cannot be accomplished, these soils should not be disturbed by attempting to compact them. Instead, they should be left in their natural state and additional cover material used to prevent the subgrade from being overstressed.

When these soils are encountered, their sensitivity may be detected by performing unconfined compression tests on the undisturbed soil and on the remolded soil compacted to the design density at the design moisture content. If the undisturbed value is higher, do not attempt to compact the soil; manage construction operations to produce the least possible disturbance of the soil. Base the pavement design on the bearing value of the undisturbed soil.

Base Compaction

Selected soils that are used in base construction must be compacted to the general requirements given earlier. The thickness of layers must be within limits that will ensure proper compaction. This limit is generally from 4 to 8 inches, depending on the material and the method of construction.

Smooth-wheeled or vibratory rollers are recommended for compacting hard, angular materials with a limited amount of fines or stone screenings. Pneumatic-tired rollers are recommended for softer materials that may break down (degrade) under a steel roller.

Maintenance of Soil Density

Soil densities obtained by compaction during construction may be changed during the life of the structure. Such considerations are of great concern to the engineer engaged in the construction of semipermanent installations, although they should be kept in mind during the construction of any facility to ensure satisfactory performance. The two principal factors that tend to change the soil density are—

- Climate.
- Traffic.

As far as embankments are concerned, normal embankments retain their degree of compaction unless subjected to unusual conditions and except in their outer portions, which are subjected to seasonal wetting and drying and frost action. Subgrades and bases are subject to more severe climatic changes and traffic than are embankments. Climatic changes may bring about seasonal or permanent changes in soil moisture and accompanying changes in density, which may distort the pavement surface. High-volume-change soils are particularly susceptible and should be compacted to meet conditions of minimum swelling and shrinkage. Granular soils retain much of their compaction under exposure to climatic conditions. Other soils may be somewhat affected, particularly in areas of severe seasonal changes, such as—

- Semiarid regions (where long, hot, dry periods may occur).
- Humid regions (where deep freezing occurs).

Frost action may change the density of a compacted soil, particularly if it is fine-grained. Heavy traffic, particularly for subgrades and bases of airfields, may bring about an increase in density over that obtained during construction. This increase in density may cause the rutting of a flexible pavement or the subsidence of a rigid pavement. The protection that a subgrade soil receives after construction is complete has an important effect on the permanence of compaction. The use of good shoulders, the maintenance of tight joints in a concrete pavement, and adequate drainage all contribute toward maintaining the degree of compaction achieved during construction.

Section III. Construction Procedures

GENERAL CONSIDERATIONS

The general construction process of a rolled-earth embankment requires that the fill be built in relatively thin layers or "lifts," each of which is rolled until a satisfactory degree of compaction is obtained. The subgrade in a fill section is usually the top lift in the compacted fill, while the subgrade in a cut section is usually compacted in in-place soil. Soil bases are normally compacted to a high degree of density. Compaction requirements frequently stipulate a certain minimum density. For military construction, this is generally a specified minimum percentage of CE 55 maximum density for the soil concerned. The moisture content of the soil is maintained at or near optimum, within the practical limits of field construction operations (normally ± 2 percent of the OMC). Principal types of equipment used in field compaction are sheepsfoot, smooth steel-wheeled, vibratory, and pneumatic-tired rollers.

SELECTION OF MATERIALS

Soils used in fills generally come from cut sections of the road or airfield concerned, provided that this material is suitable. If the material excavated from cut sections is not suitable, or if there is not enough of it, then some material is obtained from other sources. Except for highly organic soils, nearly any soil can be used in fills. However, some soils are more difficult to compact than others and some require flatter side slopes for stability. Certain soils require elaborate protective devices to maintain the fill in its original condition. When time is available, these considerations and others may make it advantageous to thoroughly investigate construction efforts, compaction characteristics, and shear strengths of soils to be used in major fills. Under expedient conditions, the military engineer must simply make the best possible use of the soils at hand.

In general terms, the coarse-grained soils of the USCS are desirable for fill construction, ranging from excellent to fair. The fine-grained soils are less desirable, being more difficult to compact and requiring more careful control of the construction process. *Table 5-2, page 5-8, and Table 5-3,* respectively contain more specific information concerning the suitability of these soils.

DUMPING AND SPREADING

Since most fills are built up of thin lifts to the desired height, the soil for each lift must be spread in a uniform layer of the desired thickness. In typical operations, the soil is brought in, dumped, and spread by scraper units. The scrapers must be adjusted carefully

Table 8-3. Soil classification and compaction requirements (average).

Soil Classification: Major Divison		Symbol	Description	Value as a Base, Subbase, or Subgrade	Potential Frost Action
Coarse-grained soils with 50% or more larger than No 200 sieve opening	Gravel and/or gravelly soils	GW	Well-graded gravels or gravel-sand mixture with 5% or less amount of fines	Good to excellent for subbase and subgrade. Fair to good for base.	None to very slight
		GP	Poorly graded gravels or gravel-sand mixture with little or no fines	Fair to good for all.	None to very slight
		GM	Silty gravel, gravel-sand-silt mixtures	Not suitable for base, 15% or less less of fines with PI of 5 or less. 50% or less of fines for subbase and subgrade.	Slight to medium
		GC	Clayey gravel, gravel-sand-clay mixture	Not suitable for base, 15% or less of fines with PI of 5 or less. Poor to good for subbase and subgrade.	Slight to medium
	Sand and/or sandy soils	SW	Well-graded sands or gravelly sand mixture with 5% or less amount of fines	Poor for base. Fair to good for subbase and subgrade.	None to very slight
		SP	Poorly graded sands or gravelly sand mixture with 5% or less amount of fines	Poor to not suitable for base. Poor to fair for subbase and subgrade.	None to very slight
		SM	Silty sands, sand-silt mixture	Not suitable for base. Poor to good for subbase and subgrade.	Slight to high
		SC	Clayey sands, sand-clay mixture	Not suitable for base. Poor to fair for subbase and subgrade.	Slight to high
Fine-grained soils with more than 50% smaller than No 200 sieve opening	Silt and clays with LL < 50	ML	Inorganic silt, silty fine sands	Not suitable for base or subbase. Poor to fair for subgrade.	Medium to very high
		CL	Inorganic clay of low to medium plasticity, lean clays	Not suitable for base or subbase. Poor to fair for subgrade.	Medium to high
		OL	Organic silt and organic silt-clay of low plasticity	Not suitable for base or subbase. Poor to very poor for subgrade.	Medium to high
	Silt and clays with LL > 50	MH	Inorganic silt micaeous or diatomaceous silty soil	Not suitable for base or subbase. Poor to fair for subgrade.	Medium to very high
		CH	Inorganic clay of high plasticity, fatty clays	Not suitable for base or subbase. Poor to fair for subgrade.	Medium
		OH	Organic clay of medium to high plasticity	Not suitable for base or subbase. Poor to very poor for subgrade.	Medium

Symbol	Sheepsfoot, Standard With Ballast (Towed by Dozer) Single Drum: 4 ft Dual Drum: 8 ft			Self-Propelled Vibratory Roller Rolling Width = 7 ft			Compactor, High Speed, Tamping Foot, Self-Propelled, BOMAG Model Rolling Width = 5 ft (Not Recommended for Finish Grade)		
	Compacted Lift Thickness (Inches)	Rolling Speed (mph) (vpm)	Number of Passes	Compacted Lift Thickness (Inches)	Rolling Speed (mph) (vpm)	Number of Passes	Compacted Lift Thickness (Inches)	Rolling Speed (mph) (vpm)	Number of Passes
GW	*	N/A	N/A	Best 18	4 mph 1,400 vpm or more	8	12	10	5
GP	*	N/A	N/A	Best 18	4 mph 1,400 vpm or more	8	12	10	5
GM	*	N/A	N/A	12	4 mph 1,100 vpm	6	9	10	6
GC	6	3	10	12	4 mph 700 vpm to none	6	9	8	7
SW	*	N/A	N/A	Best 18	4 mph 1,400 vpm or more	8	12	10	5
SP	*	N/A	N/A	Best 18	4 mph 1,400 vpm or more	8	12	10	5
SM	*	N/A	N/A	12	4 mph 1,100 vpm	6	9	10	6
SC	Best 6	3	10	12	3 mph 700 vpm to none	7	9	8	6
ML	6	3	10	8	3 mph 700 vpm to none	7	6	8	5
CL	Best 6	2	12	8	3 mph 700 vpm to none	7	6	4	5
OL	6	2	12	*	N/A	N/A	6	4	5
MH	6	2	12	*	N/A	N/A	6	4	6
CH	Best 6	2	14	*	N/A	N/A	6	3	6
OH	6	2	14	*	N/A	N/A	6	3	6

Symbol	13-Wheel Pneumatic Compactor With Ballast (Wheel Towed) 100 psi Rolling Width = 7 ft			50-Ton Pneumatic Compactor With Ballast (Wheel Towed) 100 psi Rolling Width = 7 ft			9-Wheel Pneumatic, Self-Propelled With Ballast 100 psi Rolling Width = 6 ft			Vibratory Roller (Wheel Towed) Rolling Width = 4 ft		
	Compacted Lift Thickness (Inches)	Rolling Speed (mph)	Number of Passes	Compacted Lift Thickness (Inches)	Rolling Speed (mph)	Number of Passes	Compacted Lift Thickness (Inches)	Rolling Speed (mph)	Number of Passes	Compacted Lift Thickness (Inches)	Rolling Speed (mph) (vpm)	Number of Passes
GW	6	5	10	18	5	10	6	6	5	12	4 mph 1,400 vpm or more	8
GP	6	5	10	18	5	10	6	6	6	12	4 mph 1,400 vpm or more	8
GM	6	4	10	12	4	8	6	6	7	9	4 mph 1,100 vpm	8
GC	6	4	10	12	3	8	6	5	7	9	4 mph 700 vpm to none	9
SW	6	5	10	18	5	9	6	6	7	12	4 mph 1,400 vpm or more	8
SP	6	5	10	18	5	9	6	6	7	12	4 mph 1,400 vpm or more	8
SM	6	4	10	12	4	7	6	6	8	9	4 mph 1,100 vpm	6
SC	6	3	12	12	3	7	6	5	8	9	3 mph 700 vpm to none	10
ML	4	3	7	9	4	6	4	4	6	6	3 mph 700 vpm to none	10
CL	4	3	7	9	3	6	4	4	6	6	3 mph 700 vpm to none	10
OL	4	3	7	9	3	6	4	4	6	*	N/A	N/A
MH	4	3	8	9	3	6	4	4	6	*	N/A	N/A
CH	4	2	9	9	3	7	4	3	6	*	N/A	N/A
OH	4	2	9	9	3	7	4	3	6	*	N/A	N/A

* NOT recommended

to accomplish this objective. Materials may also be brought in by trucks or wagons and dumped at properly spaced locations so that a uniform layer may be easily spread by blade graders or bulldozers. Working alone, bulldozers may form very short and shallow fills. End dumping of soil material to form a fill without compaction is rarely permitted in modern embankment construction except when a fill is being built over very weak soils, as in a swamp. The bottom layers may then be end dumped until sufficient material has been placed to allow hauling and compacting equipment to operate satisfactorily. The best thickness of the layer to be used with a given soil and a given equipment cannot be determined exactly in advance. It is best determined by trial during the early stages of rolling on a project. No lift, however, will have a thickness less than twice the diameter of the largest size particle in the lift. As stated previously, compacted lifts will normally range from 4 to 8 inches in depth (see *Table 8-3, page 8-13)*.

COMPACTION OF EMBANKMENTS

If the fill consists of cohesive or plastic soils, the embankment generally must be built up of uniform layers (usually 4 to 6 inches in compacted thickness), with the moisture content carefully controlled. Rolling should be done with the sheepsfoot or tamping-foot rollers. Bonding of a layer to the one placed on top of it is aided by the thin layer of loose material left on the surface of the rolled layer by the roller feet. Rubber-tired or smooth-wheeled rollers may be used to provide a smooth, dense, final surface. Rubber-tired construction equipment may provide supplemental compaction if it is properly routed over the area.

If the fill material is clean sand or sandy gravel, the moisture range at which compaction is possible is generally greater. Because of their rapid draining characteristics, these soils may be compacted effectively at or above OMC. Vibratory equipment may be used. Soils may be effectively compacted by combined saturation and the vibratory effects of crawler tractors, particularly when tractors are operated at fairly high speeds so that vibration is increased.

For adequate compaction, sands and gravels that have silt and clay fines require effective control of moisture. Certain soils of the (GM) and (SM) groups have especially great need for close control. Pneumatic-tired rollers are best for compacting these soils, although vibratory rollers may be used effectively.

Large rock is sometimes used in fills, particularly in the lower portion. In some cases, the entire fill may be composed of rock layers with the voids filled with smaller rocks or soil and only a cushion layer of soil for the subgrade. The thickness of such rock layers should not be more than 24 inches with the diameter of the largest rock fragment being not greater than 90 percent of the lift thickness. Compaction of this type of fill is difficult but may generally be done by vibration from the passage of tack-type equipment over the fill area or possibly 50-ton pneumatic-tired rollers.

Finishing in embankment construction includes all the operations necessary to complete the earthwork. Included among these operations are the trimming of the side and ditch slopes, where necessary, and the fine grading needed to bring the embankment section to final grade and cross section. Most of these are not separate operations performed after the completion of other operations but are carried along as the work progresses. The tool used most often in finishing operations is the motor grader, while scraper and dozer units may be used if the finish tolerances are not too strict. The provision of adequate drainage facilities is an essential part of the work at all stages of construction, temporary and final.

DENSITY DETERMINATIONS

Density determinations are made in the field by measuring the wet weight of a known volume of compacted soil. The sample to be weighed is taken from a roughly cylindrical hole that is dug in the compacted layer. The volume of the hole may be determined by one of several methods. including the use of—

- Heavy oil of known specific gravity.
- Rubber balloon density apparatus.

- Calibrated sand.
- Nuclear densimeter.

When the wet weight and the volume are known, the unit wet weight may then be calculated, as described in *FM 5-430.*

In very arid regions, or when working with soils that lose strength when remolded, the adequacy of compaction should be judged by performing the in-place CBR test on the compacted soil of a subgrade or base. The CBR thus obtained can then be compared with the design CBR, provided that the design was based on CBR tests on unsoaked samples. If the design was based on soaked samples, the results of field in-place CBR tests must be correlated with the results of laboratory tests performed on undisturbed mold samples of the in-place soil subjected to soaking. Methods of determining the in-place CBR of a soil are described in *TM 5-530.*

FIELD CONTROL OF COMPACTION

As stated in previous paragraphs, specifications for adequate compaction of soiI used in military construction generally require the attainment of a certain minimum density in field rolling. This requirement is most often stated in terms of a specified percentage range of CE 55 maximum density. With many soils, the close control of moisture content is necessary to achieve the stated density with the available equipment. Careful control of the entire compaction process is necessary if the required density is to be achieved with ease and economy. Control generally takes the form of field checks of moisture and density to—

- Determine if the specified density is being achieved.
- Control the rolling process.
- Permit adjustments in the field, as required.

The following discussion assumes that the laboratory compaction curve is available for the soil being compacted so that the maximum density and OMC are known. It is also assumed that laboratory-compacted soil and field-compacted soil are similar and that the required density can be achieved in the field with the equipment available.

Determination of Moisture Content

It may be necessary to check the moisture content of the soil during field rolling for two reasons. First, since the specified density is in terms of dry unit weight and the density measured directly in the field is generally the wet unit weight, the moisture content must be known so that the dry unit weight can be calculated. Second, the moisture content of some soils must be maintained close to optimum if satisfactory densities are to be obtained. Adjustment of the field moisture content can only be done if the moisture content is known. The determination of density and moisture content is often done in one overall test procedure; these determinations are described here separately for convenience.

Field Examination. Experienced engineers who have become familiar with the soils encountered on a particular project can frequently judge moisture content accurately by visual and manual examination. Friable or slightly plastic soils usually contain enough moisture at optimum to permit the forming of a strong cast by compressing it in the hand. As noted, some clay soils have OMCs that are close to their PLs; thus, a PL or “thread” test conducted in the field may be highly informative.

Field Drying. The moisture content of a soil is best and most accurately determined by drying the soil in an oven at a controlled temperature. Methods of determining the moisture content in this fashion are described in *TM 5-530.*

The moisture content of the soil may also be determined by air drying the soil in the sun. Frequent turning of the soil speeds up the drying process. From a practical standpoint, this method is generally too slow to be of much value in the control of field rolling.

Several quick methods may be used to determine approximate moisture contents under expedient conditions. For example, the sample may be placed in a frying pan and dried over a hot plate or a field stove. The temperature is difficult to control in this procedure, and organic materials may be burned, thus causing a slight to moderate error in the results. On large-scale projects where many samples are involved, this quick method may be used to speed up determinations by comparing the results obtained from this method with comparable results obtained by oven-drying.

Another quick method that may be useful is to mix the damp soil with enough denatured grain alcohol to form a slurry in a perforated metal cup, ignite the alcohol, and permit it to burn off. The alcohol method, if carefully done, produces results roughly equivalent to those obtained by careful laboratory drying. For best results, the process of saturating the soil with alcohol and burning it off completely should be repeated three times. This method is not reliable with clay soils. Safety measures must be observed when using this method. The burning must be done outside or in a well-ventilated room and at a safe distance from the alcohol supply and other flammable materials. The metal cup gets extremely hot, arid it should be allowed to cool before handling.

"Speedy" Moisture-Content Test. The "speedy" moisture test kit provided with the soil test set provides a very rapid moisture-content determination and can be highly accurate if the test is performed properly. Care must be exercised to ensure that the reagent used has not lost its strength. The reagent must be very finely powdered (like portland cement) and must not have been exposed to water or high humidity before it is used. The specific test procedures are contained in the test set.

Nuclear Denimeter. This device provides real-time in-place moisture content and density of a soil. Accuracy is high if the test is performed properly and if the device has been calibrated with the specific material being tested. Operators must be certified, and proper safety precautions must be taken to ensure that the operator does not receive a medically significant dose of radiation during the operation of this device. There are stringent safety and monitoring procedures that must be followed. The method of determining the moisture content of a soil in this fashion is described in the operator's manual.

Determination of Water to Be Added

If the moisture content of the soil is less than optimum, the amount of water to be added for efficient compaction is generally computed in gallons per square yards. The computation is based on the dry weight of soil contained in a compacted layer. For example, assume that the soil is to be placed in 6-inch, compacted layers at a dry weight of 120 pcf. The moisture content of the soil is determined to be 5 percent while the OMC is 12 percent. Assume that the strip to be compacted is 40 feet wide. Compute the amount of water that must be added per 100-foot station to bring the soi1 to optimum moisture. The following formula applies:

$$\text{Desired density (pcf)} \times \frac{W_{desired} - W_{actual}}{100} \times \text{Vol (cu ft)} \times \frac{1\ \text{gal}}{8.33\ \text{lb}}$$

Substituting in the above formula from the conditions given:

$$120\ \text{pcf} \times \frac{12 - 5}{100} \times 100\ \text{ft} \times 40 \times 0.5\ \text{ft} \times \frac{1\ \text{gal}}{8.33\ \text{lb}} = 2{,}017\ \text{gal/station}$$

If either drying conditions or rain conditions exist at the time work is in progress, it may be advisable to either add to or reduce this quantity by up to 10 percent.

COMPACTION EQUIPMENT

Equipment normally available to the military engineer for the compaction of soils includes the following types of rollers:

- Pneumatic-tired.
- Sheepsfoot.

- Tamping-foot.
- Smooth steel-wheeled.
- Vibratory.

Pneumatic-Tired Roller

These heavy pneumatic-tired rollers are designed so that the weight can be varied to apply the desired compactive effort. Rollers with capacities up to 50 tons usually have two rows of wheels, each with four wheels and tires designed for 90 psi inflation. They can be obtained with tires designed for inflation pressures up to 150 psi. As a rule, the higher the tire pressure the greater the contact pressures and, consequently, the greater the compactive effort obtained. Information available from projects indicates that large rubber-tired compactors are capable of compacting clay layers effectively up to about 6 inches compacted depth and coarse granular or sand layers slightly deeper. Often it is used especially for final compaction (proof rolling) of the upper 6 inches of subgrade, for subbases, and for base courses. These rollers are very good for obtaining a high degree of compaction. When a large rubber-tired roller is to be used, care should be exercised to ensure that the moisture content of cohesive materials is low enough so that excessive pore pressures do not occur. Weaving or springing of the soil under the roller indicates that pore pressures are developing.

Since this roller does not aerate the soil as much as the sheepsfoot, the moisture content at the start of compaction should be approximately the optimum. In a soil that has the proper moisture content and lift thickness, tire contact pressure and the number of passes are the important variables affecting the degree of compaction obtained by rubber-tired rollers. Generally, the tire contact pressure can be assumed to be approximately equal to the inflation pressure.

Variants of the pneumatic-tired roller inclue the pneumatic roller and the self-propelled pneumatic-tired roller.

Pneumatic Roller

As used in this manual, the term "pneumatic roller" applies to a small rubber-tired roller, usually a "wobble wheel. " The pneumatic roller is suitable for granular materials; however, it is not recommended for fine-grained clay soils except as necessary for sealing the surface after a sheepsfoot roller has "walked out. " It compacts from the top down and is used for finishing all types of materials, following immediately behind the blade and water truck.

Self-Propelled, Pneumatic-Tired Roller

The self-propelled, pneumatic-tired roller has nine wheels (see *Figure 8-6)*. It is very maneuverable, making it excellent for use in confined spaces. It corn pacts from the top down. Like the towed models, the self-propelled, pneumatic-tired roller can be used for compaction of most soil materials. It is also suitable for the initial compaction of bituminous pavement.

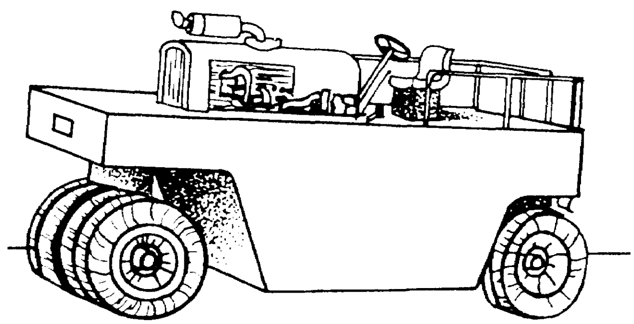


Figure 8-6. Self-propelled, pneumatic-tired roller.

For a given number of passes of a rubber-tired roller, higher densities are obtained with the higher tire pressures. However, caution and good judgment must be used and the tire pressure adjusted in the field depending on the nature of the soil being compacted. For compaction to occur under a rubber-tired roller, permanent deformation has to occur. If more than slight pumping or spring occurs under the tires, the roller weight and tire pressure are too high and should be lowered immediately. Continued rolling under these conditions causes a decrease in strength even though a slight increase in density may occur, For any given tire pressure, the degree of compaction increases with additional passes, although the increase may be negligible after six to eight passes.

Sheepsfoot Roller

This roller compacts all fine-grained materials, including materials that will break down or degrade under the roller feet, but it will not compact cohesion less granular materials. The number of passes necessary for this type of roller to obtain the required densities must be determined for each type of soil encountered. The roller compacts from the bottom up and is used especially for plastic materials. The lift thickness for sheepsfoot rollers is limited to 6 inches in compacted depth. Penetration of' the roller feet must be obtained at the start of rolling operations This roller "walks out" as it completes its compactive effort, leaving the top 1 to 2 inches uncompacted.

The roller may tend to "walk out" before proper compaction is obtained. To prevent this, the soil may be scarified lightly behind the roller during the first two or three passes, and additional weight may be added to the roller.

A uniform density can usually be obtained throughout the full depth of the lift if the material is loose and workable enough to allow the roller feet to penetrate the layer on the initial passes. This produces compaction from the bottom up; therefore, material that becomes compacted by the wheels of equipment during pulverizing, wetting, blending, and mixing should be thoroughly loosened before compaction operations are begun. This also ensures uniformity of the mixture. The same amount of rolling generally produces increased densities as the depth of the lift is decreased. If the required densities are not being obtained, it is often necessary to change to a thinner lift to ensure that the specified density is obtained.

In a soil that has the proper moisture content and lift thickness, foot contact pressure and the number of passes are the important variables affecting the degree of compaction obtained by sheepsfoot rollers. The minimum foot contact pressure for proper compaction is 250 psi. Most available sheepsfoot rollers are equipped with feet having a contact area of 5 to 8 square inches. The foot pressure can be changed by varying the weight of the roller (varying the amount of ballast in the drum), or in special cases, by welding larger plates onto the faces of the feet. For the most efficient operation of the roller, the contact pressure should be close to the maximum at which the roller will "walk out" satisfactorily, as indicated in *Figure 8-7.*

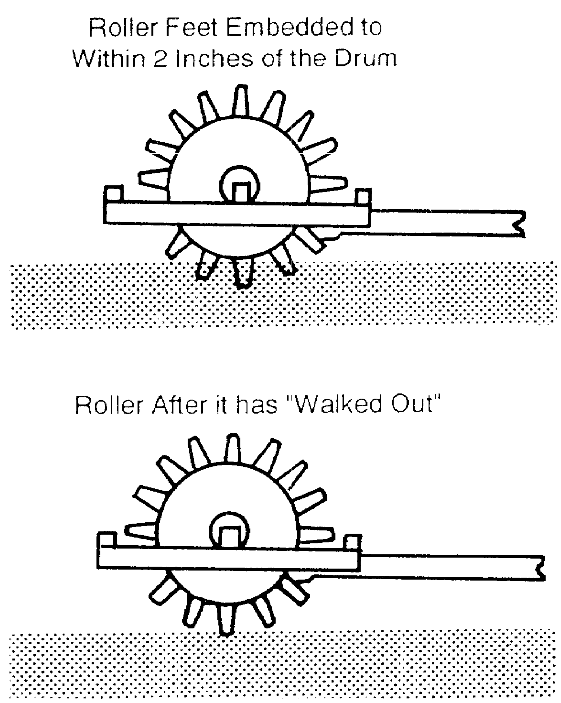


Figure 8-7. Compaction by a sheepsfoot roller.

The desirable foot contact pressure varies for different soils, depending on the bearing capacity of the soil; therefore, the proper adjustments have to be made in the field based on observations of the roller. If the feet of the roller tend to "walk out," too quickly (for example, after two passes), then bridging may occur and the bottom of the lift does not get sufficient compaction. This indicates that the roller is too light or the feet too large, and the weight should be increased. However, if the roller shows no tendency to "walk out" within the required number of passes, then the indications are that the roller is to (heavy and the pressure on the roller feet is exceeding the bearing capacity of the soil. After making the proper adjustments in foot pressure (by changingroller size), the only other variable is the repetition of passes. Tests have shown that density increases progressively withan increase in the number of passes.

Tamping-Foot Roller

A tamping-foot roller is a modification of the sheepsfoot roller. The tamping feet are trapezoidal pads attached to a drum. Tamping-foot rollers are normally self-propelled, and the drum may be capable of vibrating. The tamping-foot roller is suitable for use with a wide range of soil types.

Steel-Wheeled Roller

The steel-wheeled roller is much less versatile than the pneumatic roller. Although extensively used, it is normally operated in conjunction with one of the other three types of compaction rollers. It is used for compacting granular materials in thin lifts. Probably its most effective use in subgrade work is in the final finish of a surface. following immediately behind the blade, forming a dense and watertight surface. *Figure 8-8* shows a two-axle tandem (5- to 8-ton) roller.

Self-Propelled, Smooth-Drum Vibratory Roller

The self-propelled, smooth-drum vibratory roller compacts with a vibratory action that rearranges the soil particles into a denser mass (see *Figure 8-9).* The best results are obtained on cohesionless sands arid gravels. Vibratory rollers are relatively light but develop high dynamic force through an eccentric weight arrangement. Compaction efficiency is impacted by the ground speed of the roller and the frequency and amplitude of the vibrating drum.

Other Equipment

Other construction equipment may be useful in certain instances, particularly crawler-type tractor units and loaded hauling units, including rubber-tired scrapers. Crawler tractors are practical compacting units, especially for rock and cohesionless gravels and sands. The material should be spread in thin layers (about 3 or 4 inches thick) and is usually compacted by vibration.

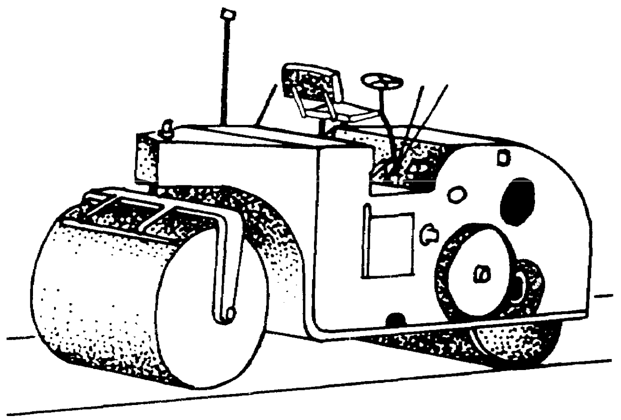


Figure 8-8. Two-axle, tandem steel-wheeled roller.

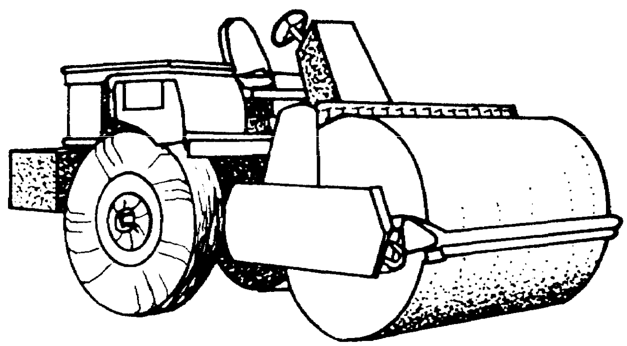


Figure 8-9. Self-propelled, smooth-drum vibratory roller.

COMPACTOR SELECTION

Table 8-3, page 8-13, gives information concerning compaction equipment and compactive efforts recommended for use with each of the groups of the USCS.

Normally, there is more than one type of compactor suitable for use on a project's type(s) of soil. When selecting a compactor, use the following criteria:

- Availability.
- Efficiency.

Availability

Ascertain the types of compactors that are available and operationally ready. On major construction projects or when deployed, it may be necessary to lease compaction equipment. The rationale for leasing compaction equipment is based on the role it plays in determining overall project duration and construction quality. Uncompacted lifts cannot be built on until they are compacted. Substituting less efficient types of compaction equipment decreases productivity and may reduce project quality if desired dry densities are not achieved.

Efficiency

Decide how many passes of each type of compactor are required to achieve the specified desired dry density. Determining the most efficient compactor is best done on a test strip. A test strip is an area that is located adjacent to the project and used to evaluate compactors and construction procedures. The compactive effort of each type of compactor can be determined on the test strip and plotted graphically. *Figure 8-10* compares the following types of compactors:

- Vibratory (vibrating drum) roller.
- Tamping-foot roller.
- Pneumatic-tired roller.

In this example, a dry density of 129 to 137 pcf is desired. The vibrating roller was the most efficient, achieving densities within the specified density range in three passes. The tamping foot compactor also compacted the soil to the desired density in three passes. However, the density achieved (130 pcf) is so close to the lower limit of the desired density range that any variation in the soil may cause the achieved density to drop below 129 pcf. The pneumatic-tired roller was the least efficient and did not densify the soil material to densities within the specified density range.

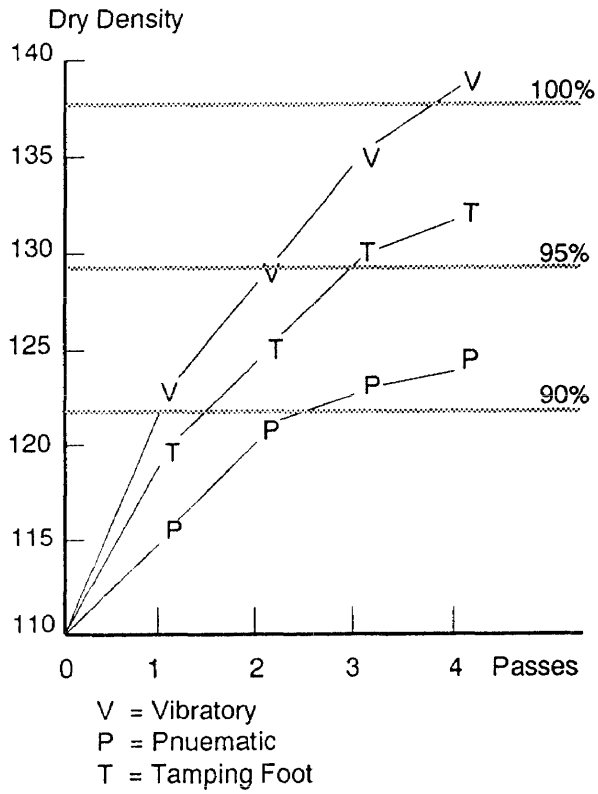


Figure 8-10. Use of test strip data to determine compactor efficiency.

Once the type(s) of compactor is selected, optimum lift thicknesses can be determined. *Table 8-3, page 8-13,* provides information on average optimum lift thicknesses, but this information must be verified. Again, the test strip is a way to determine optimum lift thickness without interfering with other operations occurring on the actual project.

In actual operation, it is likely that more than one type of compactor will be operating on the project to maintain peak productivity and to continue operations when the primary compactors require maintenance or repair. Test-strip data helps to maintain control of project quality while providing the flexibility to allow construction at maximum productivity.

Section IV. Quality Control

PURPOSE

Poor construction procedures can invalidate a good pavement or embankment design. Therefore, quality control of construction procedures is as important to the final product as is proper design. The purpose of quality control is to ensure that the soil is being placed at the proper density and moisture content to provide adequate bearing strength (CBR) in the fill. This is accomplished by taking samples or testing at each stage of construction. The test results are compared to limiting values or specifications, and the compaction should be accepted or reworked based on the results of the density and moisture content tests. A quality-control plan should be developed for each project to ensure that high standards are achieved. For permanent construction, statistical quality-control plans provide the most reliable check on the quality of compaction.

QUALITY-CONTROL PLAN

Generally, a quality-control plan consists of breaking the total job down into lots with each lot consisting of "X" units of work. Each lot is considered a separate job, and each job will be accepted or rejected depending on the test results representing this lot. By handling the control procedure in this way, the project engineer is able to determine the quality of the job on a lot-by-lot basis. This benefits the engineering construction unit and project engineer by identifying the lots that will be accepted and the lots that will be rejected. As this type of information is accumulated from lot to lot, a better picture of the quality of the entire project is obtained.

The following essential items should be considered in a quality-control plan:

- Lot size.
- Random sampling.
- Test tolerance.
- Penalty system.

Lot Size

There are two methods of defining a lot size (unit of work). A lot size may be defined as an operational time period or as a quantity of production. One advantage that the quantity-of-production method has over the operational-time-period method is that the engineering construction unit will probably have plant and equipment breakdowns and other problems that would require that production be stopped for certain periods of time. This halt in production could cause difficulties in recording production time. On the other hand, there are always records that would show the amount of materials that have been produced. Therefore, the better way to describe a lot is to specify that a lot will be expressed in units of quantity of production By using this method, each lot will contain the same amount of materials, establishing each one with the same relative importance. Factors such as the size of the job and the operational capacity usually govern the size of a production lot. Typical lot sizes are 2,000 square yards for subbase construction and 1,200 square yards for stabilized subgrade construction. To statistically evaluate a lot, at least four samples should be obtained and tested properly.

Random Sampling

For a statistical analysis to be acceptable, the data used for this analysis must be obtained from random sampling. Random sampling means that every sample within the lot has an equal chance of being selected. There are two common types of random sampling. One type consists of dividing the lot into a number of equal size sublets; one random sample is then taken from each of the sublets. The second method consists of taking the random samples from the entire lot. The sublet method has one big advantage, especially when testing during production, in that the time between testing is spaced somewhat; when taking random samples from the lot, all tests might occur within a short time. The sublet method is recommended when taking random samples. It is also recommended that all tests be conducted on samples obtained from in-place material. By conducting tests in this manner, obtaining additional samples for testing would not be a problem.

Test Tolerance

A specification tolerance for test results should be developed for various tests with consideration given to a tolerance that could be met in the field and a tolerance narrow enough so that the quality of the finished product is satisfactory. For instance, the specifications for a base course would usually state that the material must be compacted to at least 100 percent CE 55 maximum density. However, because of natural variation in material, the 100 percent requirement cannot always be met. Field data indicates that the average density is 95 percent and the standard deviation is 3.5. Therefore, it appears that the specification should require 95 percent density and a standard deviation of 3.5, although there is a good possibility that the material will further densify under traffic.

Penalty System

After the project is completed, the job should be rated based on the results of the statistical quality-control plan for that project. A satisfactory job, meeting all of the specification tolerances, should be considered 100 percent satisfactory. On the other hand, those jobs that are not 100 percent satisfactory should be rated as such. Any job that is completely unsatisfactory should be removed and reconstructed satisfactorily.

THEATER-OF-OPERATIONS QUALITY CONTROL

In the theater of operations, quality control is usually simplified to a set pattern. This is not as reliable as statistical testing but is adequate for the temporary nature of theater-of-operations construction. There is no way to ensure that all areas of a project are checked; however, guidelines for planning quality control are as follows:

- Use a "test strip" to determine the approximate number of passes needed to attain proper densities.
- Test every lift as soon as compaction is completed.
- Test every roller lane.
- Test obvious weak spots.
- Test roads and airfields every 250 linear feet, staggering tests about the centerline.
- Test parking lots and storage areas every 250 square yards.
- Test trenches every 50 linear feet.
- Remove all oversized materials.
- Remove any pockets of organic or unsuitable soil material.
- Increase the distance between tests as construction progresses, if initial checks are satisfactory.

CORRECTIVE ACTIONS

When the density and/or moisture of a soil does not meet specifications, corrective action must be taken. The appropriate corrective action depends on the specific problem situation. There are four fundamental problem situations:

- Overcompaction.
- Undercompaction.
- Too wet.
- Too dry.

It is possible to have a situation where one or more of these problems occur at the same time, such as when the soil is too dry and also under compacted. The specification block that was plotted on the moisture density curve (CE 55) is an excellent tool for determining if a problem exists and what the problem is.

Overcompaction

Overcompaction occurs when the material is densified in excess of the specified density range. An overcompacted material may be stronger than required, which indicates—

- Wasted construction effort (but not requiring corrective action to the material).
- Sheared material (which no longer meets the design CBR criteria).

In the latter case, scarify the overcompacted lift and recompact to the specified density. Laboratory analysis of overcompacted soils (to include CBR analysis) is required before a corrective action decision can be made.

Undercompaction

Undercompaction may indicate—

- A missed roller pass.
- A change in soil type.
- Insufficient roller weight.

- A change in operating frequency or amplitude (if vibratory rollers are in use).
- A defective roller drum.
- The use of an improper type of compaction equipment.

Corrective action is based on a sequential approach. Initially, apply additional compactive effort to the problem area. If undercompacting is a frequent problem or develops a frequent pattern, look beyond a missed roller pass as the cause of the problem.

Too Wet

Soils that are too wet when compacted are susceptible to shearing and strength loss, Corrective action for a soil compacted too wet is to—

- Scarify.
- Aerate.
- Retest the moisture content.
- Recompact, if moisture content is within the specified range.
- Retest for both moisture and density.

Too Dry

Soils that are too dry when compacted do not achieve the specified degree of densification as do properly moistened soils. Corrective action for a soil compacted too dry is to-

- Scarify.
- Add water.
- Mix thoroughly.
- Retest the moisture content.
- Recompact, if moisture content is within the specified range.
- Retest for both moisture and density.