5

Compacting and Finishing

5–1 PRINCIPLES OF COMPACTION

The Compaction Process

Compaction is the process of increasing the density of a soil by mechanically forcing the soil particles closer together, thereby expelling air from the void spaces in the soil. Compaction should not be confused with *consolidation,* which is an increase in soil density of a cohesive soil resulting from the expulsion of water from the soil's void spaces. Consolidation may require months or years to complete, whereas compaction is accomplished in a matter of hours.

Compaction has been employed for centuries to improve the engineering properties of soil. Improvements include increased bearing strength, reduced compressibility, improved volume-change characteristics, and reduced permeability. Although the compaction principles are the same, the equipment and methods employed for compaction in building construction are usually somewhat different from those employed in heavy and highway construction. Some of the building construction characteristics producing these differences include the limited differential settlement that can be tolerated by a building foundation, the necessity for working in confined areas close to structures, and the smaller quantity of earthwork involved.

The degree of compaction that may be achieved in a particular soil depends on the soil's physical and chemical properties (see Chapter 2), the soil's moisture content, the compaction method employed, the amount of compactive effort, and the thickness of the soil layer being compacted (lift thickness). The four basic compaction forces are static weight, manipulation (or kneading), impact, and vibration. Although all compactors utilize *static weight* to achieve compaction, most compactors combine this with one or more of the other compaction forces. For example, a plate vibrator combines static weight with vibration. *Manipulation* of soil under pressure to produce compaction is most effective in plastic soils. The forces involved in impact and vibration are similar except for their frequency. *Impact or tamping* involves blows delivered at low frequencies, usually about 10 cycles per second (Hz), and is most effective in plastic soils. *Vibration* involves higher frequencies, which may extend to 80 cycles per second (Hz) or more. Vibration is particularly effective in compaction of cohesionless soils such as sand and gravel. The selection and employment of compaction equipment is discussed in Section 5–2.

Optimum Moisture Content

Although soil moisture content is only one of the five factors influencing compaction results, it is a very important one. As a result, a standard laboratory test called a *Proctor test* has been developed to evaluate a soil's moisture-density relationship under a specified compaction effort. Actually, there are two Proctor tests which have been standardized by the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO). These are the Standard Proctor Test (ASTM D 698, AASHTO T-99) and the Modified Proctor Test (ASTM D 1557, AASHTO T-180). Characteristics of these two tests are given in Table 5–1. Since the modified test was developed for use where high design loads are involved (such as airport runways), the compactive effort for the modified test is more than four times as great as for the standard test.

To determine the maximum density of a soil using Proctor test procedures, compaction tests are performed over a range of soil moisture contents. The results are then plotted as dry density versus moisture content as illustrated in Figure 5–1. The peak of each curve represents the maximum density obtained under the compactive effort supplied by the test. As you might expect, Figure 5–1 shows that the maximum density achieved under the greater compactive effort of the modified test is higher than the density achieved in the standard test. Note the line labeled "zero air voids" on Figure 5–1. This curve represents

Table 5–1 Characteristics of Proctor compaction tests

Test Details	Standard	Modified
Diameter of mold		
in.	4	4
mm	102	102
Height of sample		
in.	5 cut to 4.59	5 cut to 4.59
mm	127 cut to 117	127 cut to 117
Number of layers	3	5
Blows per layer	25	25
Weight of hammer		
lb	5.5	10
kg	2.5	4.5
Diameter of hammer		
in.	2	2
mm	51	51
Height of hammer drop		
in.	12	18
mm	305	457
Volume of sample		
cu ft	1/30	1/30
l	0.94	0.94
Compactive effort		
ft-lb/cu ft	12,400	56,200
kJ/m^3	592	2693

the density at which all air voids have been eliminated; that is, all void spaces are completely filled with water. Thus it represents the maximum possible soil density for any specified water content. Actual density will always be somewhat less than the zero air voids density because it is virtually impossible to remove all air from the soil's void spaces.

The moisture content at which maximum dry density is achieved under a specific compaction effort is referred to as the *optimum moisture content of the soil.* Referring to Figure 5–1, we see that for the Standard Proctor Test the optimum moisture content for this soil is about 20% of the soil's dry weight. Notice, however, that the optimum moisture content for the modified test is only about 15%. This relationship is typical for most soils. That is, a soil's optimum moisture content decreases as the compactive effort is increased. If tests are run at several different levels of compactive effort, a line of optimum moisture contents may be drawn as shown in Figure 5–1 to illustrate the variation of optimum moisture with compactive effort. The effect of soil type on compaction test results is illustrated in Figure 5–2. While most soils display a similar characteristic shape, notice the rather flat curve obtained when compacting uniform fine sands (curve 5). The compaction curve for heavy clays (curve 7) is intermediate between that of uniform fine sands and those of the more typical soils.

The importance of soil moisture content to field compaction practice can be demonstrated using Figure 5–1. Suppose that specifications require a density of 100 lb/cu ft (1.6 g/cm^3) for this soil and that the compactive effort being used is equal to that of the Standard Proctor Test. From Figure 5–1 it can be seen that the required density may be achieved at any

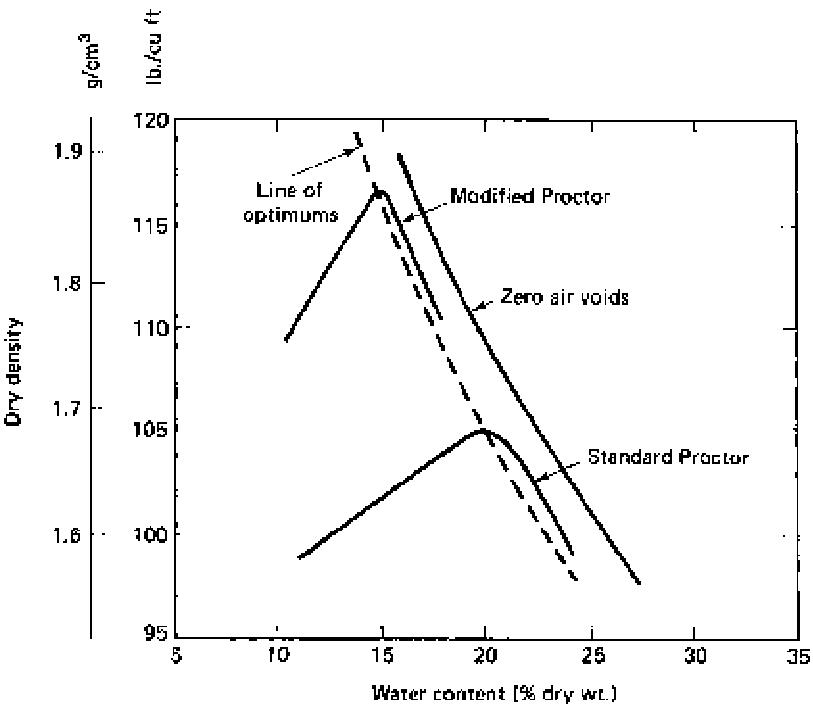


Figure 5–1 Typical compaction test results.

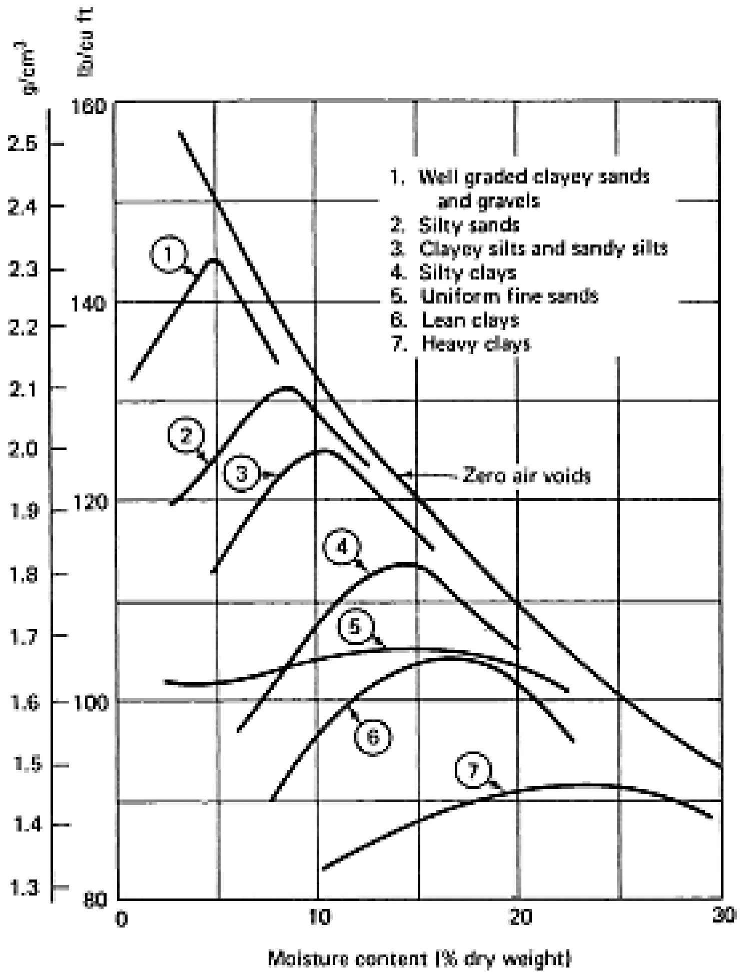


Figure 5–2 Modified Proctor Test results for various soils. (Courtesy of Dr. Harvey E. Wahls)

moisture content between 13 and 24%. However, a density of 105 lb/cu ft (1.68 g/cm^3) can only be achieved at a moisture content of 20%. Relationships among field and laboratory results for various soils, different types of equipment, and varying levels of compactive effort are discussed in Section 5–2.

Compaction Specifications

Compaction specifications are intended to ensure that the compacted material provides the required engineering properties and a satisfactory level of uniformity. To ensure that the required engineering properties are provided, it is customary to prescribe the characteristics of the material to be used and a minimum dry density to be achieved. If the natural site material is to be compacted, only a minimum density requirement is needed. The Proctor test is widely used for expressing the minimum density requirement. That is, the specification will state that a certain percentage of Standard Proctor or Modified Proctor density must be obtained. For the soil of Figure 5–1, 100% of Standard Proctor density corresponds to a dry density of 105 lb/cu ft (1.68 g/cm^3). Thus a specification requirement for 95% of Standard Proctor density corresponds to a minimum dry density of 99.8 lb/cu ft (1.60 g/cm^3).

Typical density requirements range from 90% of Standard Proctor to 100% of Modified Proctor. For example, 95% of Standard Proctor is often specified for embankments, dams, and backfills. A requirement of 90% of Modified Proctor might be used for the support of floor slabs. For the support of structures and for pavement base courses where high wheel loads are expected, requirements of 95 to 100% of Modified Proctor are commonly used.

A lack of uniformity in compaction may result in differential settlement of structures or may produce a bump or depression in pavements. Therefore, it is important that uniform compaction be obtained. Uniformity is commonly controlled by specifying a maximum variation of density between adjacent areas. Compaction specifications may range from performance specifications in which only a minimum dry density is prescribed to method specifications that prescribe the exact equipment and procedures to be used. (See Section 18–4 for a discussion of specifications.)

Measuring Field Density

To verify the adequacy of compaction, the density (soil or asphalt) actually obtained in the field must be measured and compared with the specified density. (Compaction of asphalt pavements is further discussed in Section 8–2.) The methods available for performing in-place density tests include a number of traditional methods (liquid tests, sand tests, etc.), nuclear density gauges, nonnuclear density gauges, and equipment-mounted compaction measurement systems. All of the traditional test methods involve removing a material sample, measuring the volume of the hole produced, and determining the dry weight of the material removed. Compacted density is then found as the dry weight of material removed divided by the volume of the hole.

Liquid tests measure the volume of material removed by measuring the volume of liquid required to fill the hole. A viscous fluid such as engine oil is poured from a calibrated container directly into the hole when testing relatively impermeable soils such as clays and silts. A method used for more permeable materials involves forcing water from a calibrated container into a rubber balloon inserted into the hole. *Sand tests* involve filling both the hole and an inverted funnel placed over the hole with a uniform fine sand. The volume of the hole and funnel is found by dividing the weight of sand used by its density. The volume of the funnel is then subtracted to yield the hole volume.

Nuclear density devices measure the amount of radioactivity from a calibrated source that is reflected back from the compacted material to determine both material density and moisture content. When properly calibrated and operated, these devices produce accurate results in a fraction of the time required to perform traditional density tests. The increasing size and productivity of earthmoving and paving equipment have greatly increased the need for rapid determination of the soil or asphalt density being achieved. As a result, the use of nuclear density devices is becoming widespread.

Nonnuclear density gauges that measure asphalt density, temperature, and moisture content are also available. Nonnuclear devices are safer, lighter, and easier to transport than nuclear devices. When properly calibrated, such devices claim to be as accurate as nuclear devices.

Responding to the need for rapid measurement of compaction results, *equipment-mounted compaction measurement and control systems* are being offered by a number of compaction equipment manufacturers. In addition to measuring and recording the material density actually achieved, some systems control the energy being delivered by the compactor to avoid over- or undercompaction of the material. Some systems also record the temperature of the asphalt being compacted. Measurement systems which provide a continuous record of compaction results over the entire area covered by the roller are valuable for providing proof of the compaction actually achieved.

5–2 COMPACTION EQUIPMENT AND PROCEDURES

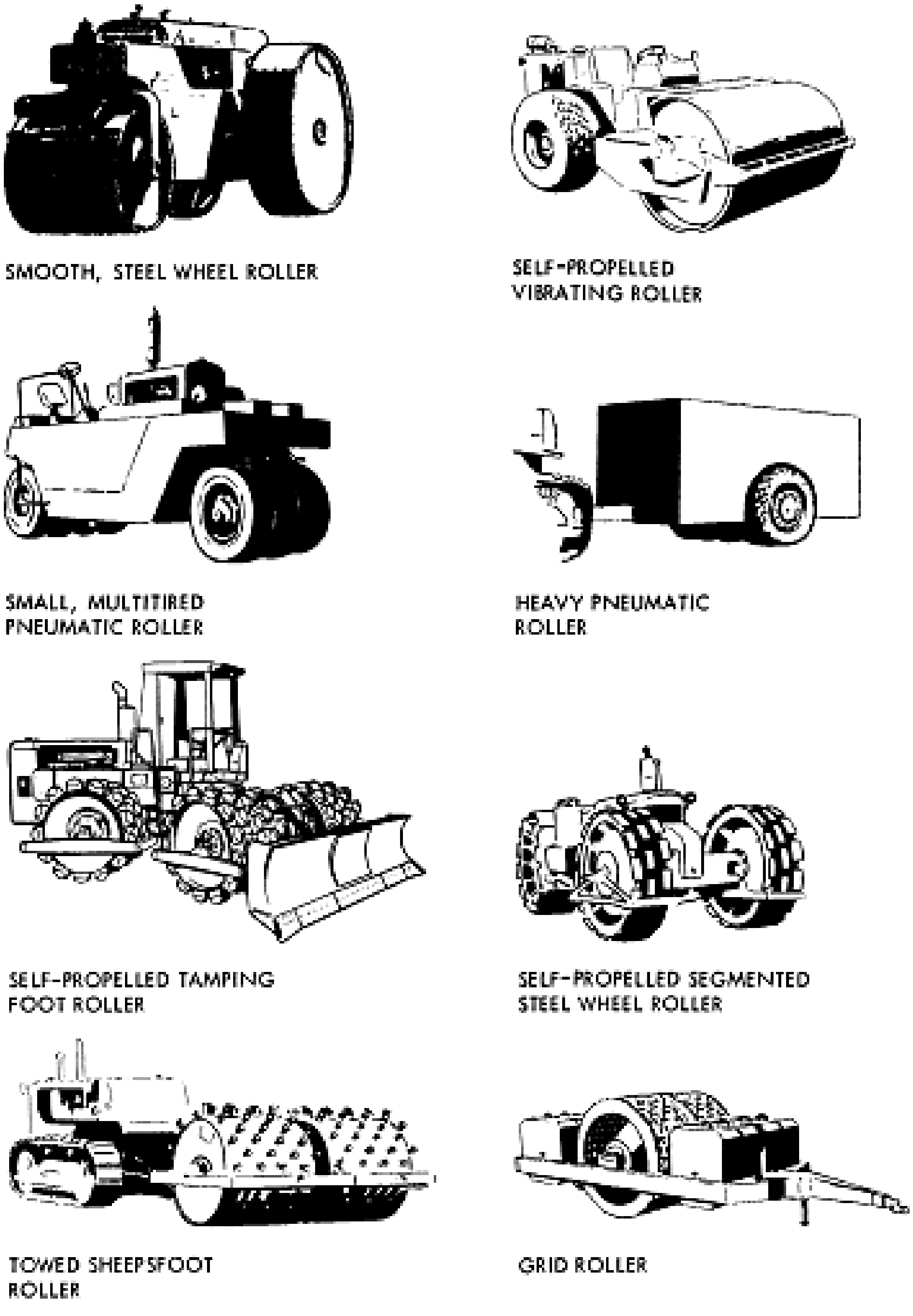
Types of Compaction Equipment

Principal types of compaction equipment include tamping foot rollers, grid or mesh rollers, vibratory compactors, smooth steel drum rollers, pneumatic rollers, segmented pad rollers, and tampers or rammers (see Figure 5–3).

Tamping foot rollers utilize a compaction drum equipped with a number of protruding feet. Tamping foot rollers are available in a variety of foot sizes and shapes, including the sheepsfoot roller. During initial compaction, roller feet penetrate the loose material and sink to the lower portion of the lifts. As compaction proceeds, the roller rises to the surface or "walks out" of the soil. All tamping foot rollers utilize static weight and manipulation to achieve compaction. Therefore, they are most effective on cohesive soils. While the sheepsfoot roller produces some impact force, it tends to displace and tear the soil as the feet enter and leave the soil. Newer types of tamping foot rollers utilize a foot designed to minimize displacement of soil during entry and withdrawal. These types of rollers more effectively utilize impact forces. High-speed tamping foot rollers may operate at speeds of 10 mi/h (16 km/h) or more. At these speeds they deliver impacts at a frequency approaching vibration.

Grid or *mesh rollers* utilize a compactor drum made up of a heavy steel mesh. Because of their design, they can operate at high speed without scattering the material being compacted. Compaction is due to static weight and impact plus limited manipulation. Grid rollers are most effective in compacting clean gravels and sands. They can also be used to break up lumps of cohesive soil. They are capable of both crushing and compacting soft rock (rock losing 20% or more in the Los Angeles Abrasion Test).

Vibratory compactors are available in a wide range of sizes and types. In size they range from small hand-operated compactors (Figure 5–4) through towed rollers to large self-propelled rollers (Figure 5–5). By type they include plate compactors, smooth drum rollers, and tamping foot rollers. Small walk-behind vibratory plate compactors and vibratory rollers are used primarily for compacting around structures and in other confined areas. Vibratory plate compactors are also available as attachments for hydraulic excavators. The towed and self-propelled units are utilized in general earthwork. Large self-propelled smooth drum vibratory rollers are often used for compacting bituminous bases and pavements. While vibratory compactors are most effective in compacting noncohesive soils,



SMOOTH, STEEL WHEEL ROLLER

SELF-PROPELLED VIBRATING ROLLER

SMALL, MULTITIRED PNEUMATIC ROLLER

HEAVY PNEUMATIC ROLLER

SELF-PROPELLED TAMPING FOOT ROLLER

SELF-PROPELLED SEGMENTED STEEL WHEEL ROLLER

TOWED SHEEPSFOOT ROLLER

GRID ROLLER

Figure 5–3 Major types of compaction equipment. (Reprinted by permission of Caterpillar Inc. © 1971)

Figure 5–4 Walk-behind vibratory plate compactor. (Courtesy of Wacker Corp.)

they may also be effective in compacting cohesive soils when operated at low frequency and high amplitude. Many vibratory compactors can be adjusted to vary both the frequency and amplitude of vibration.

Steel wheel or *smooth drum rollers* are used for compacting granular bases, asphaltic bases, and asphalt pavements. Types available include towed rollers and self-propelled rollers. Self-propelled rollers include three-wheel (two-axle) and two- and three-axle tandem rollers. The compactive force involved is primarily static weight.

Rubber-tired or *pneumatic rollers* are available as light- to medium-weight multitired rollers and heavy pneumatic rollers. Wobble-wheel rollers are multitired rollers with wheels mounted at an angle so that they appear to wobble as they travel. This imparts a kneading action to the soil. Heavy pneumatic rollers weighing up to 200 tons are used for dam construction, compaction of thick lifts, and proof rolling. Pneumatic rollers are effective on almost all types of soils but are least effective on clean sands and gravels.

Segmented pad rollers are somewhat similar to tamping foot rollers except that they utilize pads shaped as segments of a circle instead of feet on the roller drum. As a result, they produce less surface disturbance than do tamping foot rollers. Segmented pad rollers are effective on a wide range of soil types.

Figure 5–5 Vibratory tamping foot compactor. (Courtesy of BOMAG (USA))

Rammers or *tampers* are small impact-type compactors which are primarily used for compaction in confined areas. Some rammers, like the one shown in Figure 5–6, are classified as vibratory rammers because of their operating frequency.

Compaction in Confined Areas

The equipment available for compaction in confined areas such as trenches and around foundations includes small vibratory plate compactors (Figure 5–4), tampers or rammers (Figure 5–6), walk-behind static and vibratory rollers (Figure 5–7), and attachments for backhoes and hydraulic excavators.

Figure 5–6 Small vibratory rammer. (Courtesy of Wacker Corp.)

Figure 5–7 Walk-behind vibratory roller with remote control. (Courtesy of Wacker Corporation)

Figure 5–8 Compaction wheel mounted on hydraulic excavator. (Courtesy of American Compaction Equipment, Inc.)

Compactors which mount on the boom of backhoes and excavators include compaction wheels and vibratory plate compactors. Such compactors are highly maneuverable and are especially useful for compacting the material in deep excavations such as trenches. Due to their long reach, these compactors often eliminate the safety hazard involved in having a compactor operator down in the trench.

Compaction wheels (Figure 5–8) are small compactors similar in design to tamping foot rollers. They are normally mounted on the boom of backhoes or hydraulic excavators.

Vibratory plate attachments (Figure 5–9) are small vibratory plate compactors which are powered by the hydraulic system of the equipment to which they are attached.

Characteristics of typical compactors for confined areas are given in Table 5–2.

Selection of Compaction Equipment

The proper selection of compaction equipment is an important factor in obtaining the required soil density with a minimum expenditure of time and effort. The chart in Figure 5–10 provides a rough guide to the selection of compaction equipment based on soil type.

Figure 5–9 Vibratory plate compactor attachment for excavator. (Courtesy of Ingersoll-Rand Tramac)

Table 5–2 Compactors for confined areas

Type	Weight [lb(kg)]	Power [hp(kW)]	Freq [vpm]	Force [lb(kN)]	Width [in.(cm)]
Rammer/tamper	108–235	3–5	550–700	1850–5900	4–16+
	(49–107)	(2–4)		(8.2–26.2)	(10–41)
Vibratory plate	99–1335	3–14	2580–6325	1320–15000	12–32+
	(45–606)	(2–10)		(5.9–66.7)	(30–81)
Vibratory roller	1000–3400	7–24	1800–4200	3400–16000	4–43
	(454–1542)	(5–32)		(15.1–71.2)	(10–109)
Excavator Attachments					
Compaction wheel	600–5155	NA	NA	NA	4–46
	(272–2338)				(10–117)
Vibratory compactor	825–2250	NA	1700–2400	6400–22000	19–35*
	(374–1021)			(28.5–97.9)	(48–89)

+Extensions available

*Narrow trench attachments available

Material	Steel wheel	Pneumatic	Vibratory	Tamping foot	Grid
Rock	●	○	●	●	●
Gravel, clean or silty	●	◓	●	●	●
Gravel, clayey	●	◓	◓	●	◓
Sand, clean or silty	○	○	●	○	◓
Sand, clayey silt	○	◓	◓	●	○
Clay, sandy or silty	○	●	◓	●	○
Clay, heavy	○	●	◓	●	○

● Recommended
◓ Acceptable
○ Marginal

Figure 5–10 Compaction equipment selection guide.

Compaction Operations

After selecting appropriate compaction equipment, a compaction plan must be developed. The major variables to be considered include soil moisture content, lift thickness, number of passes used, ground contact pressure, compactor weight, and compactor speed. For vibratory compactors, it is also necessary to consider the frequency and amplitude of vibration to be employed.

The general concepts of optimum moisture content as related to compaction effort and soil density have been discussed in Section 5–1. However, it must be recognized that

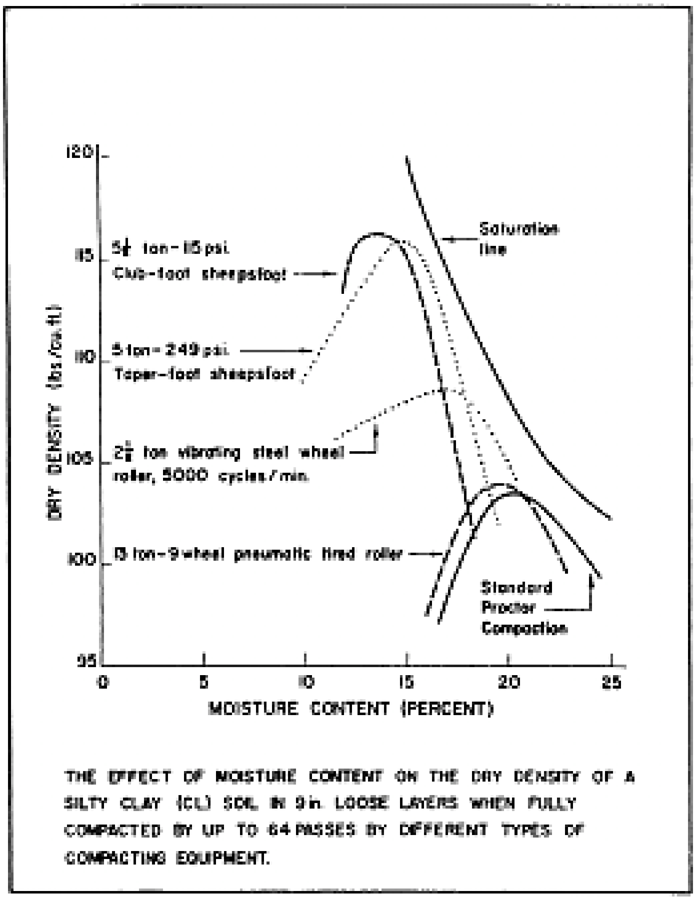


Figure 5–11 Variation of optimum moisture content with roller type. (From reference 6)

the compactive effort delivered by a piece of compaction equipment will seldom be exactly the same as that of either the standard or modified compaction test. As a result, the field optimum moisture content for a particular soil/compactor combination will seldom be the same as the laboratory optimum. This is illustrated by Figure 5–11, where only one of the four compactors has a field optimum moisture content close to the laboratory optimum. For plastic soils it has been observed that the field optimum moisture content is close to the laboratory Standard Proctor optimum for pneumatic rollers. However, the field optimum is appreciably lower than laboratory optimum for tamping foot rollers. For nonplastic soils, the field optimum for all nonvibratory equipment appears to run about 80% of the laboratory Standard Proctor optimum. The vibratory compactor appears to be most effective in all types of soil when the field moisture is appreciably lower than laboratory optimum.

Lifts should be kept thin for most effective compaction. For all rollers, except vibratory rollers and heavy pneumatic rollers, a maximum lift thickness of 5 to 8 in. (15 to 20 cm)

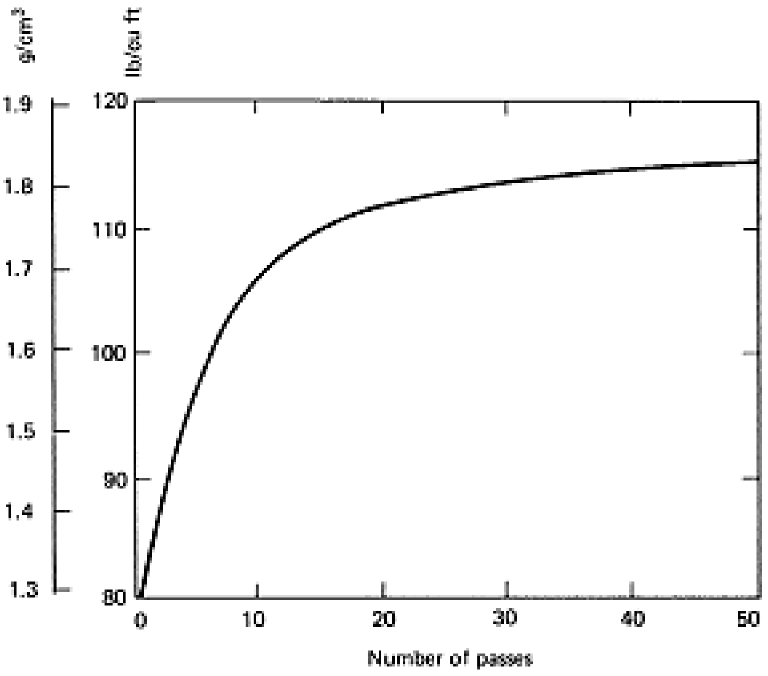


Figure 5–12 Typical effect of number of passes.

is suggested. Lift thicknesses of 12 in. (30 cm) or more may be satisfactory using heavy pneumatic rollers. However, precompaction with a light roller may be required to prevent rutting when heavy pneumatic rollers are used on thick lifts. The maximum lift thickness for effective vibratory compaction depends on the static weight of the compactor. Appropriate lift thicknesses for clean granular soils may range from 8 in. (20 cm) for a 1-ton compactor to 48 in. (122 cm) for a 15-ton (13.6 t) compactor. Heavy vibratory rollers have successfully compacted rock using lift thicknesses of 7 ft (2.1 m).

The compaction achieved by repeated passes of a compactor depends on the soil/compactor combination utilized. For some combinations (such as a tamping foot roller compacting a clayey gravel), significant increases in density may continue to occur beyond 50 passes. However, as shown in Figure 5–12, the increase in density is relatively small after about 10 passes for most soil/compactor combinations.

Ground contact pressure may vary from 30 lb/sq in. (207 kPa) for a pneumatic roller to 300 lb/sq in. (2070 kPa) or more for a tamping foot roller. Within these ranges it has been found that total roller weight has a much more pronounced effect on the compaction achieved than does contact pressure. Thus increasing the foot size on a tamping foot roller while maintaining a constant contact pressure will increase both the soil density and the surface area covered in one pass. Likewise, increasing the weight of a pneumatic roller at constant tire pressure will increase the effective depth of compaction. The use of excessive ground contact pressure will result in shearing and displacement of the soil being compacted.

If a tamping foot roller fails to "walk out" to within 1 in. (2.5 cm) of the surface after about five passes, it usually indicates that either the contact pressure or the soil moisture content is too high.

Tests have shown little relationship between compactor travel speed and the compaction achieved, except for vibratory compactors. In the case of vibratory equipment, travel speed (at a fixed operating frequency) determines the number of vibrations that each point on the ground surface will receive. Therefore, when using vibratory equipment, tests should be performed to determine the compactor speed that results in the highest compactor productivity. For conventional equipment the highest possible speed should be utilized that does not result in excessive surface displacement.

For compaction wheels, typical lift thickness ranges from 24 to 48 in. (61–122 cm) for excavators to 18 to 30 in. (46–76 cm) for backhoes. Compaction to 90% relative density is usually achieved in 5 to 6 passes of the wheel. It is recommended that a minimum cover over pipe of 3 ft (91 cm) be maintained for excavators and 2 ft (61 cm) for backhoes.

Estimating Compactor Production

Equation 5–1 may be used to calculate compactor production based on compactor speed, lift thickness, and effective width of compaction. The accuracy of the result obtained will depend on the accuracy in estimating speed and lift thickness. Trial operations will usually be necessary to obtain accurate estimates of these factors. Typical compactor operating speeds are given in Table 5–3.

$$\text{Production (CCY/h)} = \frac{16.3 \times W \times S \times L \times E}{P} \qquad \textbf{(5–1}\boldsymbol{A}\textbf{)}$$

$$\text{Production (CCM/h)} = \frac{10 \times W \times S \times L \times E}{P} \qquad \textbf{(5–1}\boldsymbol{B}\textbf{)}$$

where P = number of passes required
W = width compacted per pass (ft or m)
S = compactor speed (mi/h or km/h)
L = compacted lift thickness (in. or cm)
E = job efficiency

The power required to tow rollers depends on the roller's total resistance (grade plus rolling resistance). The rolling resistance of tamping foot rollers has been found to be approximately 450 to 500 lb/ton (225–250 kg/t). The rolling resistance of pneumatic rollers and the maximum vehicle speed may be calculated by the methods of Chapter 4.

Job Management

After applying the principles explained above, trial operations are usually required to determine the exact values of soil moisture content, lift thickness, compactor weight, and vibrator frequency and amplitude that yield maximum productivity while achieving the specified soil density. The use of a nuclear density device to measure the soil density actually being obtained

Table 5–3 Typical operating speed of compaction equipment

Compactor	Speed mi/h	Speed km/h
Tamping foot, crawler-towed	3–5	5–8
Tamping foot, wheel-tractor-towed	5–10	8–16
High-speed tamping foot		
First two or three passes	3–5	5–8
Walking out	8–12	13–19
Final passes	10–14	16–23
Heavy pneumatic	3–5	5–8
Multitired pneumatic	5–15	8–24
Grid roller		
Crawler-towed	3–5	5–8
Wheel-tractor-towed	10–12	16–19
Segmented pad	5–15	8–24
Smooth wheel	2–4	3–6
Vibratory		
Plate	0.6–1.2	1–2
Roller	1–2	2–3

during compaction is strongly recommended. Do not use boom-mounted compactors such as compaction wheels to trim trench walls, pull backfill into the trench, or to lift heavy objects.

Traffic planning and control is an important factor in compaction operations. Hauling equipment must be given the right-of-way without unduly interfering with compaction operations. The use of high-speed compaction equipment may be necessary to avoid conflicts between hauling and compacting equipment.

5–3 GROUND MODIFICATION

The process of giving natural soils enough abrasive resistance and shear strength to accommodate traffic or design loads is called *ground modification* or *soil stabilization.* Methods available include mechanical methods, hydraulic methods, reinforcement methods, and physiochemical methods. Some techniques falling under each of these categories are shown in Table 5–4.

Mechanical Methods

As you see, the compaction process discussed in the preceding sections of this chapter is a form of mechanical stabilization. Additional mechanical stabilization methods include dynamic or deep compaction and vibratory compaction.

Table 5–4 Soil stabilization methods

Mechanical	Hydraulic	Reinforcement	Physiochemical
Compaction	Drainage	Confinement	Admixtures
Deep compaction	Preloading	Inclusions	Freezing
Vibroflotation	Electroosmosis	Minipiles	Grouting
		Soil nailing	Heating
		Stone columns	

Dynamic compaction, or *deep compaction,* involves dropping a heavy weight from a crane onto the ground surface to achieve soil densification. Typically, drop weights of 10 to 40 tons (9–36 t) are used with a drop height of 50 to 100 ft (15–30 m) to produce soil densification to a depth of about 30 ft (9 m). The horizontal spacing of drop points usually ranges from 7 to 25 ft (2–8 m).

Vibratory compaction, also called *vibroflotation* and *vibrocompaction,* is the process of densifying cohesionless soils by inserting a vibratory probe into the soil. After the probe is jetted and/or vibrated to the required depth, the vibrator is turned on and the device is slowly withdrawn while the soil is kept saturated. Clean, granular material is added from the surface as the soil around the probe densifies and subsides. The process is repeated in a pattern such that a column of densified soil is created under each footing or other load. The process is quite effective on granular soils having less than 15% fines and often allows bearing capacities up to 5 tons/sq ft (479 kPa) or more. In such cases, vibratory compaction will usually be less expensive than installing piles. However, the process can also be used in conjunction with pile foundations to increase pile capacity. A related technique for strengthening cohesive soils is called *vibratory replacement, vibroreplacement,* or *stone column* construction. The process is similar to vibratory compaction except that the fill added as the probe is withdrawn consists of crushed stone or gravel rather than sand. The resulting stone column is vibrated to increase its density and interaction with the surrounding soil. Stone column capacities of 10 to 40 tons (9–36 t) are typically developed.

Hydraulic Methods

Saturated cohesive soils are particularly difficult to densify since the soil grains cannot be forced closer together unless water is drained from the soil's void spaces (see Section 5–1). *Surcharging,* or placing additional weight on the soil surface, has long been used to densify cohesive soils. However, this is a very-long-term process (months to years) unless natural soil drainage can be increased. *Sand columns* consisting of vertical drilled holes filled with sand have often been used for this purpose. A newer technique that provides faster drainage at lower cost involves forcing *wicks,* or plastic drain tubes, into the soil at intervals of a few feet. *Electroosmosis* employs electrical current to speed up the drainage of cohesive soils. It is explained in more detail in Section 10–7.

Reinforcement Methods

These include confinement, inclusions, minipiles, soil nailing, and stone columns. Soil reinforcement is described in Section 10–5. *Stone column* construction, also called *vibratory replacement* or *vibro-replacement,* is a technique for strengthening cohesive soils. The process, described just previously, is similar to vibratory compaction.

Physiochemical Methods

While soil stabilization technically includes all the techniques described above, in common construction usage the term soil stabilization refers to the improvement of the engineering properties of a soil by use of physical or chemical admixtures.

The principal physiochemical admixtures used for soil stabilization include granular materials, portland cement, lime and asphalt. Table 5–5 lists these materials along with the applicable soil, typical percentage employed, and their curing time. Some considerations involved in the use of these admixtures are described below. In addition, it has been found that the addition of fly ash will generally increase the strength of stabilized soil. Also, the addition of 0.5 to 1.5 percent by weight of calcium chloride will increase the early strength of portland cement or lime stabilization.

Granular Admixtures

Soil blending with granular material is often used to produce a well-graded mixture, without excessive fines, which is suitable for compaction.

Table 5–5 Common stabilization materials

Material	Soil	Quantity (% by weight)	Curing Time
Granular admixtures	Various	Varies	None
Portland cement*	Gravel	3–4	24 h
	Sand	3–5	
	Silt/clayey silt	4–6	
	Clay	6–8	
Lime*			
Hydrated	Clayey gravel	2–4	7 days
	Silty clay	5–10	
	Clay	3–8	
Quicklime	Clayey gravel	2–3	4 h
	Silty clay	3–8	
	Clay	3–6	
Asphalt	Sand	5–7	
	Silty or clayey sand	6–10	1–3 days

*May be combined with fly ash.

Portland Cement

The effectiveness of portland cement as an admixture diminishes rapidly as the soil's plasticity index exceeds 15. The soil-cement mixture may need to be placed in multiple lifts to obtain depths greater than about 8 in. (20 cm).

Lime

The use of quicklime results in much faster strength gain than does hydrated lime. However, quicklime is hazardous to handle.

Asphalt

Asphalt admixtures are generally not effective in soils having more than about 30% fines by weight or a plasticity index greater than about 10.

Some techniques for employing physiochemical admixtures include surface mixing, placing layers of admixture in embankments, and deep mixing methods. Some considerations in the use of these techniques include:

- *Surface mixing.* This is probably the most widely used procedure. While the usual depth of mixing is about 6 to 10 in. (15–25 cm), the mixing depth can go as high as 40 in. (1 m) with special mixing equipment.
- *Embankment layers.* One such field application successfully used 2-in. (5-cm) layers of quicklime confined by filter fabric separated by 28 to 48 in. (71–119 cm) of compacted cohesive soil.
- *Deep mixing methods.* These consist of several related techniques which provide in-place (*in situ*) soil treatment. A stabilizing admixture, usually cementitious, is blended into the soil using hollow rotating drill shafts equipped with cutting tools and mixing paddles or augers at the tip. Admixture materials may be in either wet (grout) or dry form. Mixing may occur using rotary action only or may be combined with jet action. Mixing action may take place only near the end of the tool or it may extend some distance along the tool when the shaft is equipped with multiple augers or paddles. An early application of deep mixing involved the *lime column* technique in which lime is augered into a plastic soil to form a strengthened soil column which aids in transferring loads to deeper soils.

5–4 GRADING AND FINISHING

Grading is the process of bringing earthwork to the desired shape and elevation (or grade). *Finish grading,* or simply *finishing,* involves smoothing slopes, shaping ditches, and bringing the earthwork to the elevation required by the plans and specification. Finishing usually follows closely behind excavation, compaction, and grading. Finishing, in turn, is usually followed closely by seeding or sodding to control soil erosion. The piece of

Figure 5–13 Modern motor grader. (Courtesy of John Deere Construction & Forestry Company)

equipment most widely used for grading and finishing is the motor grader (Figure 5–13). Grade trimmers and excavators are frequently used on large highway and airfield projects because their operating speed is greater than that of the motor grader.

In highway construction, the process of cutting down high spots and filling in low spots of each roadway layer is called *balancing. Trimming* is the process of bringing each roadway layer to its final grade. Typical tolerances allowed for final roadway grades are ½ in. per 10 ft (1.25 cm/3m) for subgrades and subbases and ⅛ in. per 10 ft (0.3 cm/3m) for bases. Typical roadway components are illustrated in Figure 5–14.

Finishing is seldom a pay item in a construction contract because the quantity of earthwork involved is difficult to measure. As a result, the planning of finishing operations is usually rudimentary. However, studies have shown that the careful planning and execution of finishing operations can pay large dividends.

Motor Grader

The *motor grader* is one of the most versatile items of earthmoving equipment. It can be used for light stripping, grading, finishing, trimming, bank sloping, ditching, backfilling, and scarifying. It is also capable of mixing and spreading soil and asphaltic mixtures. It is

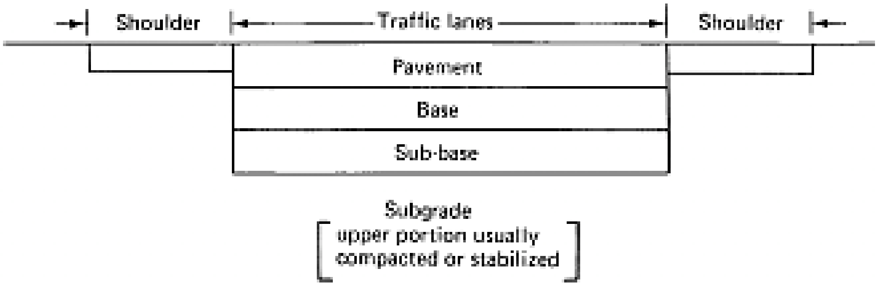


Figure 5–14 Typical roadway components.

used on building construction projects as well as in heavy and highway construction. It is frequently used for the maintenance of highways and haul roads.

The blade of a motor grader is referred to as a *moldboard* and is equipped with replaceable cutting edges and end pieces (end bits). The wide range of possible blade positions is illustrated in Figure 5–15. The pitch of the blade may be changed in a manner similar to dozer blades. Pitching the blade forward results in a rolling action of the excavated material and is used for finishing work and for blending materials. Pitching the blade backward increases cutting action but may allow material to spill over the top of the blade. Blade cutting edges are available in flat, curved, or serrated styles. Flat edges produce the least edge wear, but curved edges are recommended for cutting hard materials and for fine grading. Serrated edges are used for breaking up packed gravel, frozen soil, and ice.

Motor graders are available with articulated frames that increase grader maneuverability. The three possible modes of operation for an articulated grader are illustrated in Figure 5–16. The machine may operate in the conventional manner when in the straight mode (Figure 5–16A). The articulated mode (Figure 5–16B) allows the machine to turn in a short radius. Use of the crab mode (Figure 5–16C) permits the rear driving wheels to be offset so that they remain on firm ground while the machine cuts banks, side slopes, or ditches. The front wheels of both conventional and articulated graders may be leaned from side to side. Wheels are leaned away from the cut to offset the side thrust produced by soil pressure against the angled blade. Wheel lean may also be used to assist in turning the grader.

Graders are available with automatic blade control systems that permit precise grade control. Such graders utilize a sensing system that follows an existing surface, string line, or laser beam to automatically raise or lower the blade as required to achieve the desired grade. Scarifiers are used to loosen hard soils before grading and to break up asphalt pavements and frozen soil. Their operation is similar to that of the ripper described in Chapter 6. However, scarifiers are not intended for heavy-duty use as are rippers. While rippers are available for graders, their ripping ability is limited by the weight and power of the grader. Grader rippers are usually mounted on the rear of the machine.

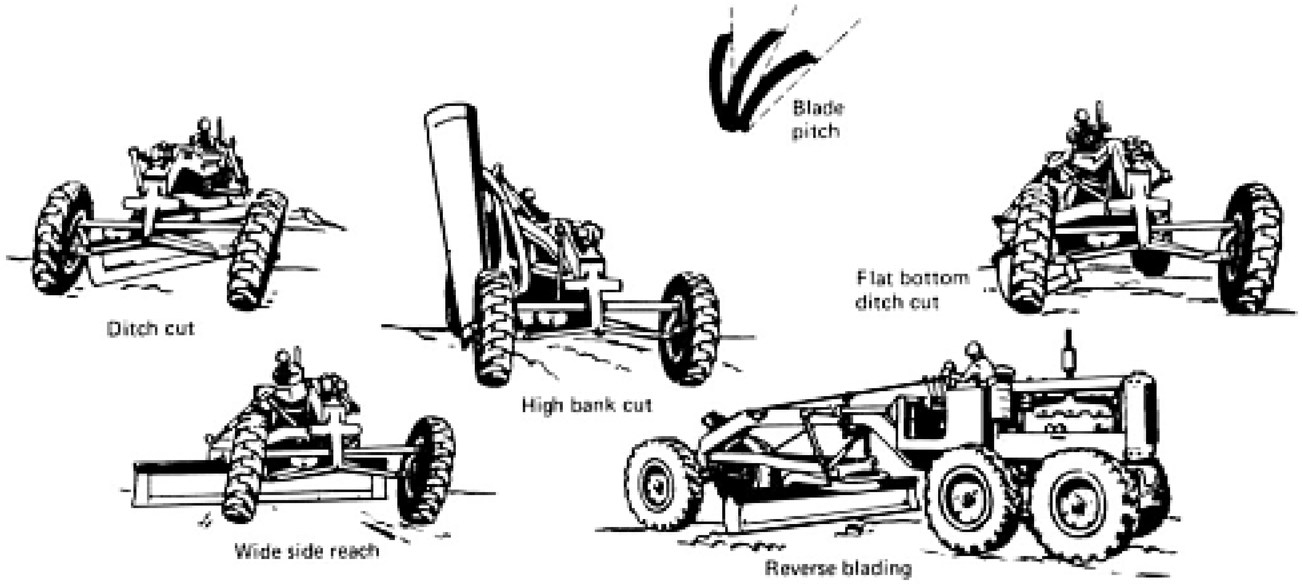


Figure 5-15 Blade positions for the motor grader. (U.S. Department of the Army)

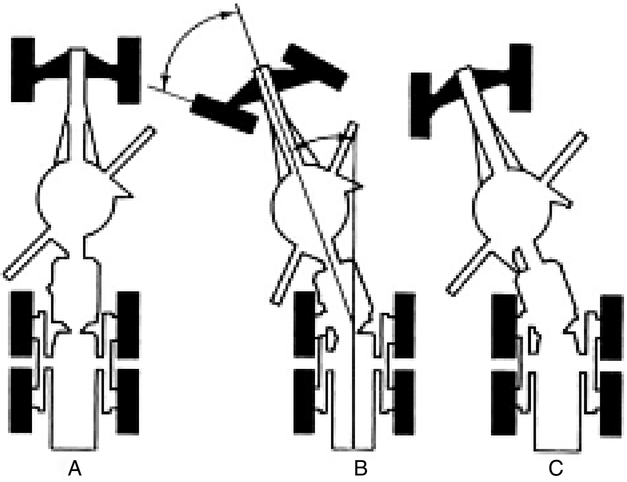


Figure 5–16 Articulated grader positions.

Grade Excavators and Trimmers

Grade excavators or *trimmers* are machines that are capable of finishing roadway and airfield subgrades and bases faster and more accurately than can motor graders. Many of these machines also act as reclaimers. That is, they are capable of scarifying and removing soil and old asphalt pavement. Trimmers and reclaimers are usually equipped with integral belt conveyors that are used for loading excavated material into haul units or depositing it in windrows outside the excavated area. The large grade trimmer/reclaimer shown in Figure 5–17 is also capable of compacting base material, laying asphalt, or acting as a slipform paver.

While grade trimmers lack the versatility of motor graders, their accuracy and high speed make them very useful on large roadway and airfield projects. Their large size often requires that they be partially disassembled and transported between job sites on heavy equipment trailers.

Estimating Grader Production

Grader production is usually calculated on a linear basis (miles or kilometers completed per hour) for roadway projects and on an area basis (square yards or square meters per hour) for general construction projects. The time required to complete a roadway project may be estimated as follows:

$$\text{Time (h)} = \left[\sum \frac{\text{Number of passes} \times \text{Section length (mi or km)}}{\text{Average speed for section (mi/h or km/h)}} \right] \times \frac{1}{\text{Efficiency}} \qquad \textbf{(5–2)}$$

Average speed will depend on operator skill, machine characteristics, and job conditions. Typical grader speeds for various types of operations are given in Table 5–6.

Figure 5–17 Large grade trimmer/reclaimer/paver. (Courtesy of Terex Roadbuilding)

Table 5–6 Typical grader operating speed

Operation	Speed *mi/h*	 *km/h*
Bank sloping	2.5	4.0
Ditching	2.5–4.0	4.0–6.4
Finishing	4.0–9.0	6.5–14.5
Grading and road maintenance	4.2–6.0	6.4–9.7
Mixing	9.0–20.0	14.5–32.2
Snow removal	12.0–20.0	19.3–32.3
Spreading	6.0–9.0	9.7–14.5

EXAMPLE 5–1

Fifteen miles (24.1 km) of gravel road require reshaping and leveling. You estimate that six passes of a motor grader will be required. Based on operator skill, machine characteristics, and job conditions, you estimate two passes at 4 mi/h (6.4 km/h), two passes at 5 mi/h (8.0 km/h), and two passes at 6 mi/h (9.7 km/h). If job efficiency is 0.80, how many grader hours will be required for this job?

SOLUTION

$$\text{Time (h)} = \left(\frac{2 \times 15}{4.0} + \frac{2 \times 15}{5.0} + \frac{2 \times 15}{6.0}\right) \times \frac{1}{0.80} = 23.1 \text{ h} \qquad \text{(Eq 5–2)}$$

$$\left[= \left(\frac{2 \times 24.1}{6.4} + \frac{2 \times 24.1}{8.9} + \frac{2 \times 24.1}{9.7}\right) \times \frac{1}{0.80} = 23.1 \text{ h}\right]$$

Job Management

Careful job planning, the use of skilled operators, and competent supervision are required to maximize grader production efficiency. Use the minimum possible number of grader passes to accomplish the work. Eliminate as many turns as possible. For working distances less than 1000 ft (305 m), have the grader back up rather than turn around. Grading in reverse may be used for longer distances when turning is difficult or impossible. Several graders may work side by side if sufficient working room is available. This technique is especially useful for grading large areas.

PROBLEMS

1. What type of compactor would you expect to be most suitable for compacting a clean sand?
2. Estimate the production in compacted cubic yards (meters) per hour of a self-propelled tamping foot roller under the following conditions: average speed = 5 mi/h (8.0 km/h), compacted lift thickness = 6 in. (15.2 cm), effective roller width = 10 ft (3.05 m), job efficiency = 0.75, and number of passes = 8.
3. List the four principal methods for achieving ground modification or soil stabilization. Provide one example of each.
4. a. What is a compaction wheel?
    b. What is the typical lift thickness for an excavator-mounted compaction wheel?
    c. State the minimum pipe cover that should be used when compacting with an excavator-mounted compaction wheel.
5. List the types of compactors that are available for compaction in confined areas.
6. A highway contractor has opened a cut in a fine silty sand (SM). Because of the cut location and lack of drainage, surface water has drained into the cut, leaving the material very wet. Rubber-tired scrapers are hauling material from the cut to an adjacent fill. The material is being placed in the fill in 8- to 10-in. (20- to 25-cm) lifts and compacted by a heavy sheepsfoot roller towed by a crawler tractor. It is apparent that the specified

compaction (95% of standard AASHTO density) is not being attained. The sheepsfoot roller is not "walking out," and the scraper tires are causing deep rutting and displacement of the fill material as they travel over it. What is causing the compaction problem? What would you suggest to the constructor to improve the compaction process?

7. Twelve miles (19.2 km) of gravel road require reshaping and leveling. You estimate that a motor grader will require two passes at 3 mi/h (4.8 km/h), two passes at 4 mi/h (6.4 km/h), and one pass at 5 mi/h (8.0 km/h) to accomplish the work. How many grader hours will be required for this work if the job efficiency factor is 0.83?
8. Why might the laboratory and field optimum moisture contents vary for a particular soil?
9. The data in the accompanying table resulted from performing Modified Proctor Tests on a soil. Plot the data and determine the soil's laboratory optimum moisture content. What minimum field density must be achieved to meet job specifications that require compaction to 90% of Modified AASHTO Density?

Dry Density		
lb/cu ft	**g/cm^3**	**Moisture Content (%)**
109	1.746	10
112	1.794	12
116	1.858	14
115	1.842	16
110	1.762	18
106	1.698	20

10. Write a computer program to calculate the time required (hours) for a motor grader to perform a finishing operation. Input should include section length, number of passes at each expected speed, and job efficiency. Solve Problem 7 using your computer program.

REFERENCES

1. *Compaction Industry Vibratory Roller Handbook.* Association of Equipment Manufacturers, Milwaukee, WI.
2. *Fundamentals of Compaction.* Caterpillar Inc., Peoria, IL.
3. *Handbook of Soil Compactionology.* Bros, Inc., Brooklyn Park, MN.
4. Hausmann, Manfred R. *Engineering Principles of Ground Modification.* New York: McGraw-Hill, 1990.
5. Nunnally, S. W. *Managing Construction Equipment,* 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2000.
6. Townsend, D. L. *The Performance and Efficiency of Standard Compacting Equipment* (Engineering Report No. 6). Queens University, Kingston, Ontario, 1959.
7. Wahls, H. E., C. P. Fisher, and L. J. Langfelder. *The Compaction of Soil and Rock Materials for Highway Purposes* (Report No. FHWA-RD-73-8). U.S. Department of Transportation, Washington, DC, 1966.