SPECIALTY SALES LLC

WORKING WITH NATURE

NUTRA-BOND PLUS

Back to Nutra-Bond main page

Caterpillar
Compaction Manual

What is compaction?

Compaction can be defined in several ways. But in simplest terms, compaction is the process of mechanically increasing the density of a material. Soil and asphalt, the materials this manual are concerned with, are made denser by reducing the voids between the particles, which make them up. In time, loose material would settle or compact itself naturally. By applying various mechanical forces, we shorten the time required to get compaction from years to hours.

Materials are made more stable by increasing their density.

One or a combination of these forces accomplishes compaction of soil or asphalt: static pressure, impact, manipulation or vibration. These are the compactive forces that will be discussed in this manual.

Why is compaction important?

Denser and more compacted material is able to support heavier loads without deforming (bending, cracking, moving). The subgrade material, which supports a heavy structure, must be very dense or it will compact even more under load, causing the structure to settle. Likewise, asphalt mats must be well compacted or they will lose their original shape when heavy axle loads are placed upon them.

Perhaps the best way to illustrate the importance of compaction is to look at various layers of a typical roadway. Each layer of the roadway is designed to support the weight placed on it. From the subgrade, to the base, to the paved base, to the final riding surface – each layer must be constructed of the right material and be of the proper thickness and density. If one layer is not strong enough, the road will fail.

It is also important to remember that the least expensive element of extending the service life of a road is the compaction process. Increasing the density of the roadway layers during the construction process costs very little in terms of cents per ton of mix or cents per yard of soil. Achieving good density can save significant dollars in future road maintenance and resurfacing costs.

Scope of this document

This document is intended as a user's guide to soil and asphalt compaction principles, testing techniques and on-the-job procedures. The content is slanted toward practical, rather than theoretical, considerations. The chapters are arranged in a reference manual style to help you find the answers to your questions quickly.

Compaction Principles and Measurements

Forces of Compaction

Compaction is the process of compressing a material from a given volume into a smaller volume. This is done by exerting force and movement over a contact area, causing particles within the material to move closer together. The voids between the particles – air, water or a combination of both – are expelled by the combination of force and movement. Four forces are used in compaction: (1) static pressure, (2) manipulation, and (3) impact and (4) vibration.

Static Pressure: In static compaction, weighted loads, applied by rollers, produce shear stresses in the soil or asphalt that cause the individual particles to slide across each other. Compaction happens when the applied force causes individual particles to break their natural bonds to each other and move into a more stable position within the material. Static smooth-wheeled rollers, static sheepsfoot (or pad-foot) and tamping foot rollers work on this principle. Four factors influence compaction performance on static rollers. They are axle load, drum width, drum diameter and rolling speed.

Linear force is the measure of a static roller's compaction potential. It is the vertical force directly below the width of the drum or wheels that creates the shear stresses for compaction. It is calculated by dividing the weight at the drum (axle load) by the drum width. Linear force is expressed as pounds per linear inch (PLI) or kilograms per centimeter (kg/cm). The higher the PLI, the greater the static compaction potential for a given roller.

An important parameter of a static roller's performance is the Nijboer quotient. The quotient is the relationship between axle load, drum width and drum diameter. It is an indicator of the tendency of a roller to shove or literally plow material ahead of the drum. Research has shown that more cracks and larger ridges are formed with small diameters because the surface of the material tends to accept the shape of the drum as it is being compacted. The smaller the drum diameter, the greater the drum's curvature and the more likely it is to produce surface cracking and ridges in the compacted material.

Based on the Nijboer quotient, the following conclusions can be reached. A larger drum diameter can reduce ridge formations. Also, self-propelled rollers with drum drives will not cause cracking of the upper layer of the material being compacted as much as a wheel drive only or towed roller with the same drum diameter. With a non-drum drive compactor, the torque created by bearing friction causes the drum to skid. But a driven drum roller tends to pull the material under the drum rather than push it.

Therefore, drum-driven, static rollers with lower Nijboer quotients perform better on thick lifts of soft material.

Manipulation: Manipulation, the second compactive force, rearranges particles into a more dense mass by a kneading process. The process is especially effective at the surface of the lift material. The longitudinal and transverse kneading action is essential when compacting heavily stratified soils such as clay type soils. It is also the desired process for the compaction of the final wearing surface of an asphalt pavement. Manipulation helps to close the small, hairline cracks through which moisture could penetrate and cause premature pavement failure. Sheepsfoot rollers and staggered wheel, rubber tired rollers are specifically designed to deliver this type of compactive force.

Impact: Impact creates a greater compaction force on the surface than an equivalent static load. This is because a falling weight has speed, which is converted, to energy at the instant of impact. Impact creates a pressure wave, which goes into the soil from the surface. Impacts are usually a series of blows. Impact blows of 5 to 600 blows per minute are considered low frequency ranges and are used on impact hammers and hand tampers. Impact blows of 1400 to 3500 blows per minute are high frequency and are used on vibratory compactors.

Vibration: Vibration is the final and most complex compactive force. Vibratory compactors produce a rapid succession of pressure waves, which spread in all directions. The vibratory pressure waves are useful in breaking the bonds between the particles of the material being compacted. When pressure is applied, the particles tend to reorient themselves in a more dense (fewer voids) state. To understand how vibratory compactors work, it is necessary to know about centrifugal force, amplitude and frequency.

Centrifugal force: In a vibratory compactor, centrifugal force is created by rotating eccentric weight or weights. The mass of the weights, their offset distance from the center of rotation to center of gravity, and speed of rotation all contribute to production of this force. Centrifugal force is a theoretical calculation used to rate machines. The true vibratory force depends on a complex interaction between material being compacted and the machine.

Amplitude: Amplitude is the measure of total peak vertical movement of a vibrating drum per complete cycle. By modifying the amplitude, an operator can vary the force and the movement (acceleration) of the drum on the material. Amplitude adjustments may be necessary when the soil or asphalt mix changes.

The effect of changes in amplitude can be illustrated by the analogy of hammering a nail. In order to hammer a nail, certain drop height and speed are needed. When drop height is reduced, it becomes almost impossible to drive the nail since the impact energy is also reduced.

This principle applies to vibratory compactors. Providing everything else is the same, i.e. drum weight, frequency, etc., a compactor with a higher amplitude produces more compaction energy than a machine with low amplitude.

Frequency: Frequency is a measure of number of complete cycles or revolutions of the weight around the axis of rotation over a given length of time. Frequency is usually expressed in units of vibrations per minute (vpm). The relationship between frequency working speed is important. Machine speed and frequency need to be matched to yield about one impact per inch (25 mm). Higher frequencies permit higher working speeds without "washboarding" (impacts spaced too far apart). Conversely, low frequencies require slower machine speeds.

Back to Top of Page

Dynamics of Vibratory Compaction

Factors Which Influence Vibratory Compaction: Vibratory compaction of soil is a complex process. More than 30 different factors influence the overall compaction effort. Vibratory compaction involves a drum which is moving up and down (amplitude) very rapidly (frequency) and moving forward (working speed) over a non-homogeneous material. All components influencing compaction should be considered as a whole, not as separate entities. It is the combined characteristics of the compactor and of the dirt or asphalt it is attempting to compact that determines the degree of compaction effort.

The characteristics of the material to be compacted plays a part in the dynamics of compaction. Type, gradation, texture, initial density, moisture content, aggregate strength characteristics, layer thickness, subsoil base and its supporting capability all influence compaction. The sum effect of these properties is termed mass stiffness and damping.

The design of the machine is also important to the dynamics of compaction. Influential factors include: frame size, overall weight, wheelbase, ratio of machine weight supported over the front drum to rear drum or tires, and balance of machine weight from left to right of the machine. The list continues with factors like drum diameter, drum width, drum mass, shock isolators, eccentric weight mass, and the distance between the eccentric weight center of gravity and drum axle. Even the weight of fuel and operator have a bearing on the compactive performance of the roller. The manufacturer carefully considers all these factors when the machine is designed.

And, of course, frequency, amplitude and working speed influence compactive effort. The operator can control these variables.

What all these factors mean is that it’s not always easy to set up a roller on a given job to achieve the best compaction results.

The objective in vibratory compaction is to find a point of maximum transmitted force into the material to be compacted. This occurs when the sum of all the components – material characteristics, roller characteristics, amplitude, frequency and speed – is contributing the most to the compactive effort.

Resonance: In vibratory compaction, a condition called resonance is very important. Simply explained, resonance is a natural condition where an object will vibrate at a given frequency when a given force is applied. Unlike materials have unlike resonance. Because a compactor is made of and the soil or asphalt is composed of different materials, they all have different resonances.

When a vibratory compactor is operating and one component reaches its resonant frequency, it may be dampened by a neighboring component with a radically different resonance. At times, the drum is at optimum resonance while the machine yoke, with a different resonance, may be vibrating in a manner to dampen the compactive effort. The drum and the soil or asphalt can create this same condition. The uncoupled resonances work against each other, slowing the compaction process. When the vibration of all the components of the machine and the material to be compacted are coupled, that is when the compactive effort will be at its maximum. The state when the resonances are working together is called harmonic convergence.

Harmonic convergence in a vibratory compaction situation actually has several peaks as centrifugal force is increased. If compactive effort were graphed, it would show that as centrifugal force is increased, the compactive effort would have several peaks and valleys. Typically there is a moderate first harmonic convergence, then uncoupled resonance works to quickly drop off the compactive effort. Resonant factors will converge again and peak quickly a second time. Usually, at this second point, is where the harmonic convergence delivers maximum compactive effort.

Trial and Error Method: In conclusion, there is no easy way of predicting the level of compactive harmony between a roller and the matter it is asked to compact. The best method is trial and error. Obviously, the user will select a compactor of the right size (drum width, weight, etc.) to match the productive requirements. But achieving the maximum compactive effort is usually accomplished by experimentation with the variables that the operator can control – frequency, amplitude and rolling speed. The use of test strips and laboratory analysis is the best way of analyzing the performance of a roller.

Measuring Compaction Density of Bituminous Material

Once an asphalt mix is compacted, an accurate measure of the density is important. The nuclear gauge is becoming more popular for checking density because it is a quick and nondestructive test. Other common test procedures require a sawed or cored sample. Often, nuclear density values are correlated with core sample values to determine differences that occur due to aggregate chemical composition, rough surfaces or depth of measurement.

Field-Tests: Until the late 1960's, most agencies did not impose density requirements for asphalt pavements and little field-testing was done. Instead, they relied on method-type requirements that specified types of compaction equipment and procedures. But as the agencies ran into problems with the method specifications, they began to call for end result specification.

Core Samples: Many relied on density determinations from cores for compaction control. Typically, 4-inch diameter cores were removed from the compacted pavement and tested for density in the laboratory. Coring is accurate and direct, but has some disadvantages. The procedure is relatively slow and expensive. More importantly, the test results frequently are not available until the mat at the job site has cooled well below temperatures suitable for further compaction. Waiting for the lab results can result in rework or long delays in the paving process. Furthermore, sampling frequencies tend to be low, and a few core samples represent large volumes of material. Also, coring disturbs the pavement and requires patching.

Nuclear Density Gauges: Because of the disadvantages of core sampling, many agencies have turned to nuclear gauge testing as their primary means of density measurement.

Nuclear gauges are much faster than core sampling and can determine density at a given location within minutes. Speed makes the devices suitable for acceptance testing (target density) and to some extent for use in a contractor's process control (design specifications). The density can be measured while the pavement is still hot enough to permit additional compacting, if necessary.

The disadvantage of nuclear gauges is that they measure density indirectly. That is, the test output is a radiation count that must be referenced to a previously established calibration curve of count versus density. Therefore, nuclear density gauges require calibration at the job site so they are correlated with core densities they will be measuring.

Nuclear gauges operate by a simple concept known as backscatter gauging. Gamma rays are emitted by a radioisotope source contained in the gauge body. The radiation travels out from the source and penetrates the pavement, where gamma rays are scattered and/or absorbed. A counter in the device established the number of gamma rays that return. The returning rays are proportional to the density.

Several characteristics of the backscatter gauge are critical. First, a gauge is more sensitive to the material nearest the surface than to material farther down. Typically, 80% to 95% of the gauge count comes from the top 2 inches; little comes from below 4 inches. This feature is not important in full depth, multi-layer asphalt pavement construction, but IS important in thin (1 to 2 inches) overlay construction. Although nuclear gauges operating in the backscatter mode get most of their count from the top 2 inches, they still get 5% to 20% from the 2 to 4 inch range. As a result, the density of the underlying material will significantly affect the reading from a thin overlay.

The second important characteristic is the gauge's sensitivity to surface roughness. On a coarse-textured mat, the gauge body rests on the high points of the surface and, therefore, can include considerable air space in the volume being measured. If the surface roughness of a given pavement were equivalent to uniform 0.05 inch air gap under the gauge, the reading would be reduced by about 4 lbs/cu ft. Gauge users frequently compensate for rough surfaces by filling the texture with fine sand.

The third characteristic is the gauge's sensitivity to the chemical composition of the asphalt mixture – that is, the aggregate composition. Given two pavements of the same density, one with a siliceous aggregate and the other a calcareous aggregate, a backscatter gauge could show as much as a 5 lbs/cu ft difference between the displayed density values.

Finally, as with any other test method, the user must be concerned with precision – how reputable are a gauge's readings at a given location. For nuclear gauges, precision is better when the returning gamma rays are counted for a longer period of time. Typically, a one-minute count would have a precision of +/- 0.5 lbs/cu ft. A four-minute count would be accurate to +/- 0.25 lbs/cu ft.

Compaction Specifications: Target densities are established by the specifying agency before the job begins to insure that the mat is adequately and consistently compacted. Generally, target density is set on the basis of either relative or absolute measures.

A relative measurement may use a percentage of a laboratory standard. For example, a specification may require a minimum of 95% of the density obtained from a Marshall (AASHTO Test Method T-245) result. In this method, four or more uncompacted mix samples are taken from the trucks delivering mix to the job site each day. These samples are compacted under conditions similar to those found in the field. The mix temperature should approximate paver temperature without reheating and the number of compactive blows should be the same as were used in the mix design.

Another example of relative target density measure is a nuclear density specification. This usually requires the density to be 98% of the average density obtained on a control strip. The control strip, or test section, is constructed at the beginning of each lift or course. The same production equipment to be used on the job is used on the control strip. Rolling pattern and mix temperature should also be the same. The control strip is part of the job itself and should be at least 500 feet long and the same width and thickness as the paving project.

The control strip is compacted until no increase in density is obtained or until the mix cools to 185ºF. Nuclear density tests are then randomly taken. These readings are averaged and compared to a laboratory compacted sample. If the average readings indicate adequate density in relation to laboratory sample, the target density is usually set at 98% of the control strip readings. If adequate density is not met, a new control strip is constructed incorporating necessary changes in equipment, mix temperature and/or modified rolling patterns.

The other type of specification is an absolute measure of a voidless mix or a percentage of the maximum theoretical density. AASHTO Test Method T-209 determines this. Usually, the target density is a minimum of 92% of the maximum theoretical density. This means that the maximum air void content is 8%.

Summary: A common misconception is that obtaining the proper density during construction is not important because the traffic loads will eventually compact the mix. This may be true for wheel paths, but traffic does not provide a uniform density across the pavement and will produce ruts proportional to the amount of consolidation that occurs due to insufficient density.

The single most important property for asphalt pavement, then, is optimum density. Achieving this requires good mix design and good construction techniques. Nuclear density tests as well as core samples can be used as a measure of density. Whether a relative density procedure or an absolute density procedure is used, a target density must be established and must be met.

Back to Top of Page

Methods of Measuring Soil Compaction

The value of compacting base and subbase soils has long been understood. But it was not until 1933 that R.R. Proctor of the Los Angeles Bureau of Water Works developed a standardized method for determining the optimum water content and the corresponding maximum dry density. The Proctor Test used a manually operated ram to compact three layers of the soil in a confined mold.

Laboratory Tests

Today, the procedures of the Proctor Test have been adopted and further standardized by the American Association of State Highway and Transportation Officials (AASHTO). The Standard AASHTO procedure (T-99) uses a 5.5 lb. (2.5 kg) hammer dropped freely from a height of 12 inches (3054 mm). Again, the soil is compacted in three layers by 25 hammer blows in a 4 inch (102 mm) diameter mold. This test imparts a total of 12,400 ft. lbs. of compactive effort to the soil sample.

Modified compaction tests also have been introduced by AASHTO in connection with structures requiring heavier bearing strength to support extremely heavy loads or to limit settlement. According to the Modified AASHTO procedure (T-180), a 10 lb. (4.5 kg) hammer is dropped from a height of 18 inches (457 mm). The soil sample is compacted in five layers with 25 blows per layer. The compaction energy is 4.5 times larger than the Standard AASHTO test, producing 56,200 ft. lbs. of effort.

For a given soil sample, either that Standard of Modified AASHTO is performed five times. The same procedure is used each time the test is run, but the moisture content is varied for each.

The series is begun with the soil in a damp condition somewhat below the probable optimum moisture content. After the first sample is compacted in the mold, its wet unit weight is taken and a portion of the sample is placed in a drying oven. When the sample is completely dry, it is weighed again. The difference between the wet and dry weight yields is the moisture content that is expressed as a percent of the dry weight.

A second sample with increased moisture content is compared and the weighing and drying process is repeated. Additional samples with increasing moisture content are processed until the wet unit weight decreases or the soil becomes too wet to work.

The dry density and moisture content values for each sample are then plotted and a smooth curve is formed. The highest point on the curve represents the maximum dry density and the optimum soil moisture content for that sample. In other words, that is the absolute laboratory compaction for the amount of compactive effort used on this particular soil.

Laboratory tests determine the moisture content at which maximum density can be attained. It is recognized that this density cannot readily be achieved in the field by conventional compaction equipment. Therefore, field target densities are specified as a certain percent of the maximum laboratory dry density. Generally, required field densities will fall in a range of 90%-95% of Standard AASHTO. Likewise, the moisture content must be within a range of the laboratory determined optimum moisture content.

Field Tests

Periodic field-testing is done to insure that the two important elements – target density and moisture content – are being maintained throughout the particular construction job. These tests can also indicate the effectiveness of the compaction equipment and construction methods being used.

The most common field testing methods are the Nuclear Method, the Sand-Cone Method and the Water Balloon Method.

Nuclear Method: Nuclear density meters emit radiation into the soil being tested and counters measure both moisture content and density. The test is quick and can be performed without disturbing the material.

There are two basic methods of measuring density – backscatter and direct transmission. The direct transmission method gives the best accuracy, least composition error and least surface roughness error. It can be used for testing over a range of depths from two to twelve inches. The most important aspect of the direct transmission method is that the operator has direct control over the depth of measurement.

The backscatter method eliminates the need to create an access hole in the compacted soil because the unit rests on the surface. However, accuracy is less and composition errors are likely. This method works best in shallow depths – two to three inches.

Still another method offers an improvement in composition error and can be used in either the direct or the backscatter mode. This is known as the air-gap method. The testing device is raised above the test surface to lessen the composition error, but accuracy will still not match the direct transmission method.

The limitations for nuclear testing equipment are the precautions that must be observed when handling radioactive material, and the fact that false readings are sometimes obtained from organic soils or materials high in salt content.

Sand-Cone Method: The sand-cone method is a multi-step procedure which is more time consuming than the nuclear density method, but has had proven accuracy. It is sometimes used in conjunction with the nuclear method to verify the calibration of the nuclear density meter.

First, a test site away from operating equipment (so vibrations do not disturb the test) is selected and leveled. The unit's base plate is laid on the compacted surface and material is excavated through the hole in the plate to a depth of about six inches (150 mm).

This wet material is weighed, dried in an oven and weighed again to determine the moisture content.

The volume of the hole is measured by filling it with dry, free-flowing sand from a special sand-cone cylinder. Since the density of the sand is known, the volume of the hole can be calculated.

The density (wet unit weight) of the compacted sample is found by dividing the weight of the material by the volume of the hole. Dry unit weight can be found by dividing the wet unit weight by one plus the moisture content (expressed as a decimal). For example, if the moisture content is 9%, the wet unit weight would be divided by 1.09 to find dry density.

Water Balloon Method: The water balloon method is also called the Washing Densometer Test. The test's first three steps – excavating a sample, weighing it and drying it – are the same as performed in the sand-cone method. In this manner, moisture content is calculated.

However, in place of the sand-cone step to measure the volume of the excavated hole, a Washington Densometer is used. The Densometer, a fluid-filled device, is placed over the hole, and a balloon attached to the base plate is placed in the hole. A valve is opened on the side of the Densometer and calibrated fluid is forced into the balloon. As the balloon is filled, it takes on the shape of the hole. The Densometer is calibrated so the tester can read the volume of fluid and thus the volume of the hole.

The density (wet unit weight) is found by dividing the weight of the excavated sample by the volume of the hole – just as with the sand-cone method. Dry unit weight also can be calculated by dividing the wet unit weight by one plus the moisture content.

Limitations to the water balloon method are, again, the length of time needed to get results and the fact that accuracy depends on the ability of the balloon to conform to any irregularities along the sides of the hole.

Types of Specifications

Before the contractor can bid or assign compaction equipment to a particular job, he must determine what limits have been put on material placement, preparation and compaction.

There are general types of specifications used by sponsoring agencies to establish minimum standards of compaction for embankments, bases or asphalt courses. They are: Method Only, Method and End Result, Suggested Method and End Result, and End Result.

Method Only Specification: When Method Only specifications are used, the sponsoring agency describes in detail the type of equipment to be used, the number of passes, the roller speed, layer thickness and other details like moisture content. It states nothing about results. It is the least satisfactory specification for the contractor because it forces him to obtain equipment for use on materials when other equipment may yield cost savings and better results. There is no assurance that satisfactory results will be obtained.

Method and End Result Specification: This specification is even more restrictive. A typical example of this specification would call for the contractor to achieve 95% AASHTO with a minimum number of passes on a specific lift thickness using a certain roller. It limits the contractor’s use of his experience and new compaction techniques. More importantly, it requires the contractor to obtain an end result using equipment that may be incapable of getting density on specific soil type or mix design.

Suggested Method and End Result Specification: This is a better arrangement and is becoming more popular. It offers the contractor better flexibility while assuring quality results. The experienced contractor has the latitude to make use of his experience and initiative, while the less experienced contractor is provided helpful guidelines.

End Result Specification: Here, only the desired end result is specified. This gives the contractor the full choice to set the equipment to do the job and to enhance the productivity of other equipment. This specification requires strict testing procedures. However, it permits the development of compaction technology that speeds the compaction process and reduces cost.

Back to Top of Page

Soil Compaction

What is soil?

Soils are deposits of disintegrated rocks that have been slowly broken down by physical and chemical processes. The physical processes include freezing and thawing, rolling, grinding and blowing. The resulting gravels, sands and silts are essentially miniature boulders.

Chemical processes form clay soils. Long term weathering action and rainfall play an important part in creating clays. Clay differs from sand and gravel in that it consists of tiny flat particles with plate-like structures that come from a variety of rocks.

Plant growth also contributes to soil formation. When plants die, their residue becomes part of the soil. Soils with high organic matter content are usually too spongy and weak to be used for structural purposes.

Soil Groups

Although soils may very widely in physical and chemical make-up, five fundamental groups are recognized.

1. ***Gravel:*** Individual grains vary in size from .08 to 3.0 inches (2.0 to 76.2 mm) in diameter and have a rounded appearance.
2. ***Sand:*** These are small rock or mineral fragments smaller than .08 inch (2.0 mm) in diameter and semisharp.
3. ***Silt:*** Fine grains appearing soft and floury when dry. When moist, silt pressed between the thumb and forefinger will have a broken appearance.
4. ***Clay:*** Very fine textured soil that forms hard lumps or clods when dried. When moist, clay is very sticky and can be rolled into a ribbon between the thump and forefinger.
5. ***Organic:*** This matter consists of either partially decomposed vegetation (peats) or finely divided vegetable matter (organic silts and clays).

Properties of Soil

Engineers use a number of terms when defining the characteristics and properties of various soils. Understanding these terms is essential to understanding soil compaction principles and techniques.

Capillarity: Capillarity is the ability of a soil to absorb water upwardly or laterally. This is a desirable characteristic for base material used as a layer between he subgrade and the pavement of a roadway. It allows water to drain out of the subgrade. Capillary water is held in the soil by small pores or voids. It is considered free water; it can be removed only by lowering the water table or by evaporation. Without a capillary base, trapped water would soften and expand the subgrade, resulting in an inadequately supported surface and premature deterioration of the roadway.

Compressibility: Compressibility is the rate of the soil's reduction in volume when a force is applied to it. Soils with high compressibility have particles that easily reorient themselves to reduce the space available for air or water voids. Clay soils usually have higher compressibility than granular soils. Therefore, compacted clay has less capillarity and is less suitable then granular soils for base material.

Elasticity: Elasticity is the tendency of a soil to return to its original, or near original, shape after a compressive load is removed. This is an undesirable characteristic for soils that must bear fluctuating loads. Roads with highly elastic bases or subgrades soon fail due to constant flexing under load/no load conditions. Elastic soils usually are chemically stabilized to reduce their elasticity before they are compacted and used to support a load. Organic soils have very high elasticity.

Permeability: Permeability is the ease with which water flows *through* a soil. This is not the same as capillary, which is the soil's ability to *absorb* water. Soil texture, gradation and the degree of compaction influence a soil's permeability. Usually, coarse-grained soils are more permeable than fine-grained soils because they have larger voids between their particles.

Plasticity: Plasticity refers to a soil's compressibility and degree of cohesiveness. The measure of plasticity is expressed as the Plasticity Index (PI). Soils, such as most clays, that have high PI values, are quite compressible and have a high degree of cohesion. A soil with a zero PI is cohesionless and non-plastic. The soil's moisture content also affects its PI.

Settlement: Settlement is the process by which poorly compacted soil particles reorient themselves into an uneven mass. Settlement is usually due to inadequate or uneven compaction. The resulting uneven surface elevation is directly related to the volume of voids settling out over time.

Shear Resistance: Shear resistance is the resistance the soil's particles have to sliding across each other when a compactive force is applied. The shearing strength of soil is the result of internal friction (resistance to sliding over each other) and cohesion (attraction to each other). Irregularly shaped particles have higher shear resistance than smooth shaped particles. The higher the shear resistance, the more compactive force is required to achieve the needed density. Clay has low shear resistance.

Shrinkage/Swelling: Visible shrinkage or swelling is an indication that the soil is fine-grained, such as clay. The cycle of shrinking and swelling results from the release and buildup of moisture within the soil. This type of soil provides a poor foundation since constant changes in volume can cause structural failure in buildings or pavements dependent on stable support.

Moisture Content

Water is present in all soils in their natural state. It appears in one of three ways.

1. ***Gravitational water*** is free to move downward due to the force of gravity. It can drain naturally from a soil.
2. ***Capillary water*** is held in a soil by small pores or voids. It is considered free water but can be removed only by lowering the water table or by evaporation.
3. ***Hygroscopic water*** is present in the soil after gravitational and capillary water is removed. This water is held by individual soil grains in the form of a very thin film having physical and chemical affinity for the soil grains. It is also called "air-dry" moisture content. This water would have to be removed by baking the soil in an oven to get the true weight of the soil.

The effect of the soil's moisture content on compaction was discussed in Chapter Two. For each type of soil, there is optimum moisture content at which maximum density can be reached with the smallest amount of compactive force. The Proctor Test done in a laboratory and various field tests are used to calculate moisture content.

The way that moisture content affects soil compatibility can best be understood by examining soil limits.

Soil Limits

Certain limits of soil consistency – Liquid Limit, Plastic Limit, Plasticity Index, Shrinkage Limit – were developed by A. Atterburg, a Swedish soils scientist. Sometimes called the Atterburg Limits, these are the basis for differentiation between highly plastic, slightly plastic and non-plastic materials.

Liquid Limit (LL): This is the moisture content at which a soil passes from a plastic to a liquid state. This means that there is enough moisture in the soil to overcome internal friction and cohesion.

A simple test has been developed to determine a soil's liquid limit. Take a moist sample of soil and place it in a small bowl, flattening the sample somewhat. Make a deep groove in the sample and tap the bottom of the bowl 10-20 times, watching the groove. It the faces of the groove remain the same distance apart, pick up the sample, add more water to it, and repeat the process. When the faces of the groove move together, the sample has become somewhat liquid and has reached its liquid limit.

High LL values are associated with soils of high compressibility. Typically, clays have high LL values; sandy soils have low LL values.

Plastic Limit (PL): This condition exists when a soil changes from a semi-solid to a plastic state. It occurs when the soil contains just enough moisture that a small amount of it can be rolled into a 1/8" (3.2 mm) diameter thread without breaking.

The PL of a soil is important. It represents the moisture content at which particles will slide over each other and still possess appreciable cohesion. It is the point at which best compaction occurs with pure clay soils. The strength of the soil decreases rapidly as the moisture content increases beyond the plastic limit.

Plasticity Index (PI): This is the numerical difference between a soil's plastic limit and liquid limit. Soils having high PI values are quite compressible and have high cohesion. Soil has little or no cohesion when the moisture content is at the liquid limit, but has considerable cohesion when the moisture content is at the plastic limit. Therefore, the PI offers a means of measuring the compressibility and cohesion of a soil. The PI also indicates permeability. The higher the PI, the lower the permeability, and vice versa. On many jobs, the specifications call for material with a certain gradation, a maximum LL and a maximum PI.

Shrinkage Limit (SL): As the soil is dried below the plastic limit, it shrinks and gets brittle until all the particles are in contact and can shrink no more. This point is called the shrinkage limit. The SL is the best moisture at which to compact many non-plastic (sandy) soils. Soils containing enough clay to raise the PI are best compacted somewhere between the SL and PL limits.

Back to Top of Page

Soil Classification

There are a number of different agency soil classification systems in use today. They all use the terms gravel, sand, silt and clay, but with slightly different numbering or lettering systems. In this manual, we'll introduce two of the most commonly used systems without going into technical detail.

AASHTO Classification System: The American Association of State Highway and Transportation Officials system of soil classification is the most widely used and is based on field performance of soils for highway construction. It is also known as the Bureau of Public Roads Soil Classification. The system divides materials into seven major groups with a number of subgroups.

<u>AASHTO SOIL GROUP DESCRIPTIONS</u>

A-1-a Mostly gravel with or without well-graded fines
A-1-b Mostly sand with or without well-graded fines
A-2-4 Granular material with silty fines
A-2-5
A-2-6 Granular material with clayey fines
A-2-7
A-3 Poorly graded sand with almost no fines or gravel
A-4 Mostly silty fines
A-5 Uncommon soil type with silty fines usually elastic and hard to compact
A-6 Have either silty or clayey fines with low liquid limit
A-7-6

AASHTO CLASSIFICATIONS

General Classification	Granular Materials (35 % or less of total sample passing No. 200)							Silt-clay materials (More than 35% of total sample passing No. 200)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve analysis % passing:											

No. 10 No. 40 No. 200	50 max 30 max 15 max	50 max 25 max	51 min 10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No.40: Liquid limit Plasticity index	6 max		N/P	40 max 10 max	41 min 10 max	40 max 11 min	41 min 11 min	40 max 10 max	41 min 10 max	40 max 11 min	41 min 11 min
Group Index	0		0	0		4 max		8 max	12 max	16 max	20 max

The chart lists the sieve analysis as well as the liquid limit and plasticity index for the fractions passing the No. 40 sieve. A group index based on a formula that considers particle size, LL and PI is given at the bottom of the chart. The group index shows the suitability of a given soil for embankment construction. A group index number of "0" indicates a good material while a group index of "20" indicates a poor material. Laboratory tests are conducted to determine the AASHTO classification of a soil sample.

Unified Soil Classification System: The U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation use this system. It uses texture as the descriptive term. The symbols and modifiers are listed below.

SYMBOLS:

G – Gravel, smaller than 3" (76 mm), larger than ¼" (6 mm)
S – Sand, smaller than ¼" (6 mm) but large enough to see
M – Silt fine-grained soils, individual grains
C – Clay, grains too small to see with the naked eye

MODIFIERS (Sand & Gravel):

W – Well graded having large, medium and small grains
P - Poorly graded having uniform sized grains
C – Clayey
M – Silty

MODIFIERS (Silt & Clay):

L – Low plasticity
H – High plasticity

Again, a laboratory based on sieve analysis and tests for the plasticity index and liquid limits establishes these classifications.

Soil Classification in the Field
When complete laboratory facilities are not available, some simple field tests can be used to classify various soils. The tests are used to determine gradation, plasticity and dispersion.

Gradation: To test the gradation of dry soil, spread a sample of the soil on a flat surface. Use a piece of stiff paper or cardboard as a rake to sort the larger soil particles to one side. Estimate the percentage of particles larger than ¼" (6 mm) and the percentage of fines (too small for the individual grains to be seen by the unaided eye). Also, estimate whether the larger particles are uniform in size (poorly graded) or have large, medium and small sizes (well graded).

If the soil is wet, break a lump apart with a pencil and make percentage estimates as in the dry soil method. To find the percentage of fines, put 1/8" of water in a clear glass and then add enough soil to fill the glass to the ¼ level. Add water until the soil is just covered. Mark this level with a rubber band. Fill the jar ¾ full with water and stir the mixture vigorously. Let settle about a minute and a half and mark the height of the soil that has settled out. The difference between the two marks represents the percentage of fines.

Plasticity of Fine Grained Soils: There are several field tests you can perform to estimate a soil's plasticity.

A. ***Shaking Test –*** Pick up a lump of fine-grained soil and knead it together, working out as many large grained particles as possible. Add water gradually and knead the soil until it begins to get sticky. Hold the ball of soil in the palm of one hand and tap the back of that hand with the fingers of the other hand. If the ball gets shiny and wet on the surface, it is mostly fine sand or silt. Clays have little or no reaction to this test and simply get messy.
B. ***Toughness Test*** – Take about half the ball of soil and knead it between thumb and forefingers to dry it out. Then, attempt to roll the soil sample into a 1/8 "thread" or "worm." If a worm cannot be formed at all, the soil is definitely a silt or fine sand. Highly plastic soils take a long time to dry out. They get hard and waxy and considerable pressure is required to form a worm that just breaks at the 1/8" (3 mm) diameter.
C. ***Dry Strength Test –*** Take the other half of the ball of soil and knead it into a ball. Set it aside to air dry. When the soil is dry, crush it and select a jaggy, pointy fragment. Try to crush this fragment between the thumb and forefinger. Silt will turn to powder with little effort. A clay will be like a rock and almost impossible to crush with the fingers.
D. ***Hand Washing --*** After handling silts and sands, the fingers will feel dusty and rubbing the fingers together will almost clean them. Water flowing gently from a faucet will rinse off the soil. When clays are handled, a crust will form on the fingers that cannot be rubbed off when dry. Water will not rinse it off. The hands must be rubbed together under water to cleanse them.

Dispersion: In addition to the field tests just described, the dispersion test can be used to determine percentages of soil grain sizes as well as an indication of how difficult it will be to compact the soil. All that is needed is a clear glass, water and representative soil sample.

Fill the glass 1/4 to 1/3 with the material. Then fill the container with water to within ½ inch (13 mm) of the top. Stir the mixture well and observe how the material settles out.

The material will settle in three distinct layers; sand at the bottom, silt next and finally clay. Besides showing various groups, the results will show whether the soil is well or poorly graded. Although the silt and clay particles are smaller than the eye can see, gradation changes can be observed by color differences. Also, the longer it takes a layer to settle, the smaller the particles will be.

There are several things that can be learned from the dispersion test. It will show the basic materials and gradation of each, and the settling time will indicate the fineness of the particles. In most cases, a single particle size (poor gradation) and a small particle size will mean more difficult compaction than a mix where there is a good gradation of all particle sizes.

Summary of Identifying Clues: For the various soil types, there are distinct reactions to the field tests.

- Clays – No reaction to the shaking test, a tough worm that dries out slowly, a crusty dry residue that is hard to remove from hands.
- Silts – Rapid reaction to the shaking test, a weak or crumbly worm, powdery residue that is easily wiped or washed off hands.
- Silt and Clay Mixtures – intermediate or conflicting reactions to hand tests.
- Sand or Gravel with few Fine Clays – Enough clay to soil the hand if a wet sample is kneaded, but not enough to allow a lump of clay to be formed.
- Sand or Gravel with Silt Fines – Any mixture with dusty or fairly gritty fines.
- Clean Sands and Gravels – Water added to these soils sinks in immediately without making any mud.
- Shot or Ripped Rock – Jagged material not having enough smaller material to fill the voids.

Back to Top of Page

Soil Compaction Equipment

Many factors influence the choice of compaction equipment. The type of equipment selected for a project is sometimes chosen based on the contractor's previous experience, by the type of soil or by method specifications. Other considerations are how well a machine will conform to the hauling and spreading operation. Climatic and traction conditions are also important. Standardization of equipment sometimes plays a role in the decision-making process.

There is no one compactor that will do all things on all jobs. Each type has a definite material and operating range on which it is most economical.

Pneumatic Tire Compactors: Pneumatic tire compactors are used on small to medium sized compaction jobs, primarily on bladed, granular base materials. Pneumatics are not suited for high production, thick lift embankment compaction projects.

The compactive forces (pressure and manipulation) generated by the rubber tires work from the top of the lift down to produce density. The amount of compactive force can be varied by altering the tire pressure (the normal method) or by changing the weight of the ballast (done less frequently). The kneading action caused by the staggered tire pattern helps seal the surface.

One advantage that pneumatic compactors have is that there is little bridging effect between the tires. Therefore, they seek out soft spots that may exist in the fill. For this reason, they are sometimes referred to as "proof" rollers.

Another advantage is that pneumatic rollers can be used on both soil and asphalt so a roadbuilding contractor can save by having one compactor for both stages of construction – base and asphalt.

Sheepsfoot Roller: Sheepsfoot rollers got their name from the fact that early Roman roadbuilders used to herd sheep back and forth over base material until the road was compacted. The word "sheepsfoot" became a generic term to describe all types of padded drums. In reality, a sheepsfoot roller is very different from a padded drum or tamping foot roller.

A sheepsfoot pad is cylindrical; usually 8" (203 mm) long. The pad face is circular and will range in size from 7 square inches to 18 square inches. The pads on tamping foot or padded drums are tapered with an oval or rectangular pad shape. The pad face is smaller that the face of the pad, an important difference.

The pads on sheepsfoot drums penetrate through the top lift and actually compact the lift below. When a pad comes out of the soil, it licks up or fluffs material. The result is a loose layer of material on top. When more fill is spread, the top lift will be fluffed and the previous layer will be compacted. A sheepsfoot roller compacts from the bottom up.

Using a sheepsfoot compactor has one definite benefit. Because the top lift of soil is always being fluffed, the process helps aerate and dry out wet clays and silts.

But the disadvantages of sheepsfoot rollers are numerous. The loose top lift material can act as a sponge when it rains and slow the compaction process. The loose material also slows hauling units bringing fill material, so haul cycles are increased.

Plus, sheepsfoot compactors can work only at speeds from 4 to 6 mphs (6-10 km/h), which cancels any benefit from impact and vibration. Pressure and manipulation are the only compactive forces exerted on the soil. Usually 6-10 passes are needed to get density on 8" (203 mm) lifts.

Tamping Foot Compactors: Tamping foot compactors are high speed, self-propelled, non-vibratory rollers. They usually have four steel padded wheels and are equipped with a dozer blade. Their pads are tapered with an oval or rectangular face.

Like the sheepsfoot, it compacts from the bottom of the lift to the top. But because the pads are tapered, the pads can walk out of the lift without fluffing the soil. Therefore, the top of the lift is also being compacted and the surface in relatively smooth and sealed.

Because tamping foot compactors are capable of speeds in the 15-20 mph (24-32 km/h) range, they develop all four forces of compaction: pressure, impact, vibration and manipulation. This increases their compaction ability as well as production. Generally 2 to 3 passes will achieve desired densities in 8"-12" (2030-305 mm) lifts, although 4 passes may be needed in poorly graded plastic silt or very fine clay.

The main disadvantage or limitation to the use of tamping foot compactors is that they are best suited for large projects. They need long, uninterrupted passes to build up the speed that generates high production. They are also considerably more expensive than single drum vibratory compactors.

Vibratory Compactors: Vibratory compactors work on the principle of particle rearrangement to decrease voids and increase density. They come in two types: smooth drum and padded drum. Smooth drum vibratory compactors generate three compactive forces: pressure, impact and vibration. Padded drum units also generate manipulative force. Compaction is assumed to be uniform throughout the lift during vibratory compaction.

Density results from forces generated by a vibrating drum hitting the ground. Compaction results are a function of the frequency of these blows as well as the force of the blows and the time period over which the blows are applied. The frequency/time relationship accounts for slower working speeds on vibratory compactors. Working speed is important because it dictates how long a particular part of the fill will be compacted. For vibratory compactors, a speed of from 2 to 4 mphs (3.2 to 6.2 km/h) will provide the best results.

Smooth drum vibratory compactors were the first machines introduced and are most in granular materials, with particle size ranging from large rocks to fine sand. They are also used on semi-cohesive soils with up to 10% cohesive soil content. Lift thicknesses vary according to the size of the compactor but, generally, the lift thickness of granular material should not exceed 24" (607 mm). Whenever large rock is used in the fill, the lifts may be very thick – up to 4’ (1.2 m) are not unusual. One thing to remember when large rocks are in the fill is that the thickness should be about a foot (305 mm) more than the maximum rock size. This permits lift consolidation without having the large rocks project above the fill surface.

When padded drum machines were made available, the material range was expended to include soils with up to 50% cohesive material and a greater percentage of fines. When the pad penetrates the top of the lift it breaks the natural bonds between the particles of cohesive soil and better compaction results. The pads are involuted to walk out of the lift without fluffing the soil and tapered to help clean them. The typical lift thickness for padded drum units on cohesive soil is in the 12" to 18" (305 mm to 457 mm) range.

Back to Top of Page

Soil Compaction Procedures

Before laying out a compaction job, the contractor must consider the job size, fill requirements, rate of placement and specifications. Basically, there are two types of job layouts – the Project Method and the Progressive Method.

Job Layouts

Project Method: Small jobs are best suited for this method. Fill material is moved into the area and spread in lift thicknesses depending on the compactor's capabilities. The, compaction proceeds over the entire area until density is reached. Then, another lift is spread and compacted. This alternating process continues until the correct grade line is achieved.

On this type of project, compactor maneuverability and speed are important because the hauling and spreading equipment sits idle during the compaction phase. If it is possible to break up the job into adjacent fills, the hauling and spreading equipment can be kept working.

Progressive Method: The progressive method is often employed on large jobs, especially in highway construction or in landfills. Here, there is continuous operation of the equipment as material is spread progressively in front of the compactor(s). This goes on for some distance before additional lifts are spread. Therefore, it is necessary for the compactor production rate to match the production rates of the other units.

Machine maneuverability is not as important because the passes tend to be long and straight. But, it is important for the compactor to be very reliable so continuous operation is possible. Also, ease of operation and operator comfort are desirable features due to long periods of operation.

Embankment Applications

An embankment is any fill whose top is higher than the adjoining surface. It could be a building site or a highway. In any job, the embankment is above the original ground.

Rock Fill: Rock is increasingly used as embankment fill in highway construction. It is also used to a greater extent in dam, airport, building and harbor embankment construction. Shot rock often contains so many fines that considerable settling will occur if the fill is not compacted.

Rock fill is usually spread in 18" to 48" (457 to 1219 mm) lifts. How the material is spread before compaction is vital. Tractor spreading in layers creates a uniform fill because the dozer blade does dome reorienting of the rocks and the tracks perform some compaction. Therefore, a relatively dense and even surface is prepared for the compactor.

Heavy compaction forces are needed after spreading to relocate huge stones for density and stability. The largest smooth drum vibratory compactors are selected for this job. Even so, compactors are subject to great stresses on rock fill. The drum should be constructed of thick, high-grade steel. If there is a crushing effect on the surface material, the number of passes may have to be reduced. Or, if the machine is equipped with more than one amplitude, lower amplitude can be used to reduce surface material distortion.

Sand and Gravel: Vibratory compaction with smooth drum machines is especially suitable and economical on sand and gravel. High densities can be achieved in few passes with the lift thickness determined by the size of the compactor.

Free-draining sand and gravel that contains less than 10% fines are easily compacted, especially when water saturated. When high density is required and the lifts are thick, water should be added. This water will drain out of the lift during the compaction process.

If the sand and gravel contains more than 10% fines, the soil is no longer free draining and may become elastic when the water content is high. For this type of soil, there will be an optimum moisture content at which maximum density can be reached. Drying of the wet soil may be necessary to reach the optimum moisture content.

On poorly graded sand and gravel, it is difficult to achieve high density close to the surface of the fill. There is low shear strength in poorly graded soils and the top layer tends to rise up behind the drum. This is not a problem when multiple lifts are being compacted. The previous top layer will be compacted when the next layer is rolled. However, the difficulty of compacting the surface should be kept in mind when testing for density.

Silt: Silts are non-plastic fines that are usually compacted with smooth drum vibratory rollers. They can be spread and rolled in thick lifts.

Like all fine-grained soils, their compactability is dependent on moisture. For best compaction results, the water content should not vary much from the optimum moisture content. If too much water is present, silts rapidly approach the fluid state and compaction is impossible. This means that the lifts may have to be aerated with discs, mixed with drier soil (an expensive procedure) or the borrow pit has to be better drained.

Silty soils that also contain clay may have considerable cohesion. On these soils, padded drum, tamping foot or pneumatic rollers will give the best results.

Clay: Clays have plastic properties that mean that the compaction characteristics are highly dependent on moisture content. When the water content is low, clay becomes hard and firm. Above the optimum moisture content, clay becomes more and more plastic and difficult to compact.

The main problem in clay compaction is very often the need to adjust the water content. The addition of water by using water trucks, discs or soil stabilizers is time-consuming. Water infiltration into the borrow pit may be a better alternative. Drying wet clay can be done only in warm and dry conditions, even using discs and soil stabilizers. Prolonged rolling with sheepsfoot rollers is sometimes done to lower the moisture content.

Even at the optimum moisture content, clay requires a higher compactive effort and a lower lift thickness compared to non-cohesive soils. Padded drum rollers work best because as the pads penetrate the soil, they break the natural cohesive bonds between the particles. Pneumatic tire compactors can be used on clays with a low to medium Plasticity Index.

On projects where high production is a requirement and clay is used as fill, good results can be obtained by using tamping foot compactors in conjunction with vibratory padded drum compactors. Tamping foot compactors equipped with dozer blades are efficient at spreading the fill and breaking large, hard lumps of clay often found in clay borrow material. These machines perform the first passes. Final density is reached by vibratory padded drum compactors.

Base and Sub-base Applications

Bases and sub-bases are the layers constructed on top of an embankment on natural ground surface. They increase in strength as they near the finished surface. The materials used in these layers depend on the type of loads the road or building must support.

Usually very tight specifications are given for base and sub-base materials, for the thickness of the lift and for the required density.

Native Soils: From an economic standpoint it is preferable to use locally available soils. If these soils are suitable, they may be used without chemical treatment or additives. Proper compaction of these soils will substantially increase their load-bearing capacity and control other factors such as permeability, capillary action and shrink and swell.

The choice of compaction equipment will depend on the type of soil. Generally, granular, non-cohesive soils are specified as base and sub-base material. Smooth drum or pneumatic tire compactors are more often used in this application.

Treated Soils: Mixing chemicals with native or imported soils can substantially improve the soil's stability and load-bearing characteristics. This is called soil stabilization.

After lime, cement, salt or asphaltic cement has been mixed into the soil; the soil should be compacted. The type of compactor used will depend on the soil's original, untreated characteristics. Where a large volume of cohesive soil is involved, a tamping foot roller may be more economical than a vibratory compactor. Smaller volumes may be compacted with a pneumatic roller.

Crushed Rock: Job specifications may call for well-graded crushed rock to be used as base and sub-base materials. By using crushed material, gradation can be controlled during the crushing process to match specifications. Crushed rock is generally easier to spread and compact than fine soils and the compaction results are more predictable. However, the expense of crushing and the often longer hauls to the project site offset these advantages.

Crushed rock is usually hauled to the job in end dump trailers and dumped on the grade in front of a motor grader or spreading machine. The base material is then spread and shaped in lifts ranging from 6" to 10" (152 mm to 254 mm). After spreading, compaction is accomplished by smooth drum rollers (static or vibratory) or pneumatic tire compactors.

Back to Top of Page
