CAT® PAVING PRODUCTS

GUIDE TO SOIL COMPACTION

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FORWARD

Earth materials have always been the world's most abundant construction material. From the days when Romans used earth materials to build roads to modern-day dam construction, proper compaction operations have been linked to the performance of fills and to what is ultimately built on top of those fills. Today, projects such as roadways, embankments, dams, structural fills, and slopes require controlled compaction operations to ensure compliance with engineering quality criteria. When compaction quality is not achieved during construction, repair costs over performance life can exceed initial construction costs.

Earth materials are not just the most abundant construction material, but also the most variable. Particle size and shape, mineralogy, moisture content, mixings and time all contribute to the variability of earth materials. This guide describes sources of variability and focuses on selecting the correct equipment to maintain effective, productive compaction operations. Practices for selecting compaction equipment and earth material placement processes have been based largely on rules-of-thumb or what has worked in the past. However, with accelerated construction schedules and shifts toward results-oriented performance specifications, compaction operations—even though they are a small part of overall construction costs—are increasingly critical for project success.

This guide describes the basics of compaction processes, selection of effective compaction machines, and emerging quality assessment testing technologies with the goals of optimizing compaction time and controlling project costs. Guidance for machine selection is based on material type, target lift thickness, productivity needs and quality assessment criteria requirements (e.g., relative compaction, modulus of subgrade reaction).

This guide is particularly useful for contractors who want to gather and use soil information before projects start so they can develop site-specific bid prices and compaction process plans that focus on getting jobs done right the first time, avoiding costly rework and construction delays.

Compaction measurement technologies, like Cat® Compaction Control, now make it possible to monitor compaction progress in terms of lift thickness, pass coverage, Compaction Meter Value (CMV) and Machine Drive Power (MDP). CMV is a well understood parameter that allows

compaction machines to be measurement devices that provide mechanistic parameter values for soils (e.g., stiffness, strength) based on machine-ground vibration analysis. MDP is a new, innovative technology from Caterpillar that pushes the capabilities of these systems even further.

By measuring mechanistic values of compacted materials in real-time using GNSS (Global Navigation Satellite System) position information, color-coded quality assessment maps can be generated. These maps can be linked to design values to ensure that compacted materials meet established quality criteria. This approach to compaction quality assessment is light years ahead of the old method of visually inspecting for "walkout." Where compaction specifications previously were oriented toward method specifications that dictated the process, results-oriented performance specifications are now possible with 100 percent coverage in real-time using integrated technologies. In fact, intelligent compaction technologies are the basis for rethinking compaction quality assessment by agencies around the globe.

This guide combines experience and knowledge gained from Caterpillar's commitment to improving compaction equipment and operations. Many practicing contractors, engineers, recognized authorities and researchers contributed to this guide. Emerging compaction technologies, especially integrated intelligent compaction monitoring and methods for forecasting operation parameters, will drive the most significant changes in compaction assessment since 1933 when Proctor established standards for moisture control.

Users of this guide will have at their fingertips a practical resource for soil compaction principles, expert information about machine selection, and how to optimize compaction operations. Implementing the information in this guide will reduce risk and improve compaction quality.

David J. White, Ph.D.
Associate Professor
Iowa State University


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INTRODUCTION

Those who want to build must compact.

Caterpillar is pleased to present this *Guide to Soil Compaction*. It is intended as a guide to soil compaction principles, testing techniques and on-the-job procedures. The content provides a practical approach to a rather complex theoretical subject. It is the product of decades of experience in the earthmoving industry, as well as the knowledge contributed by countless individuals who have worked with Caterpillar over the years.

Whether you are a construction professional, a governmental official, an educator or student, or whether you are simply interested in learning more about construction methodology, you'll find this guide to be a valuable resource.

Another valuable resource to consult for earthmoving or compaction applications is your local Cat dealer. Dealer personnel are trained by experts from Caterpillar to assist you, providing the equipment, services and knowledge to keep you at your productive best.


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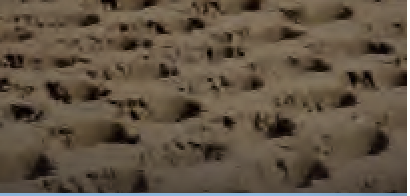
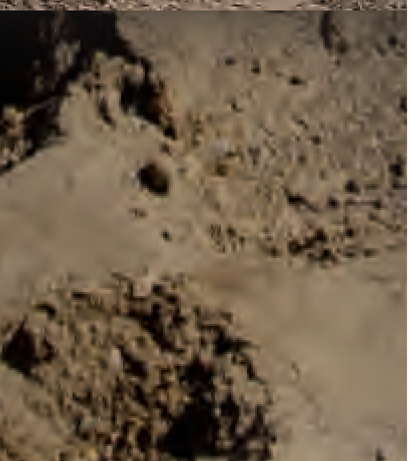




Unit 1
THE BASICS OF SOIL COMPACTION

The ability to analyze soil composition is critical to the process of establishing compaction specifications and then achieving the required load-bearing strength.

[WHAT IS COMPACTION?]

In simple terms, compaction is the process of mechanically increasing the density of a material. Soil is made denser by reducing the voids between the particles that make them up. In time, loose material settles and compacts itself naturally. By applying various mechanical forces, the time required to achieve compaction is shortened from years to hours.

Compaction is a necessary process for nearly every kind of construction project, including roads, railroads, airfields, building sites/ foundations, pipelines, dams, canals, culverts and more. If soil is required to support a structure, compaction usually is necessary to keep the structure stable.

Soil compaction is accomplished by employing one or a combination of forces: static pressure, impact, manipulation and vibration.

[WHY IS COMPACTION IMPORTANT?]

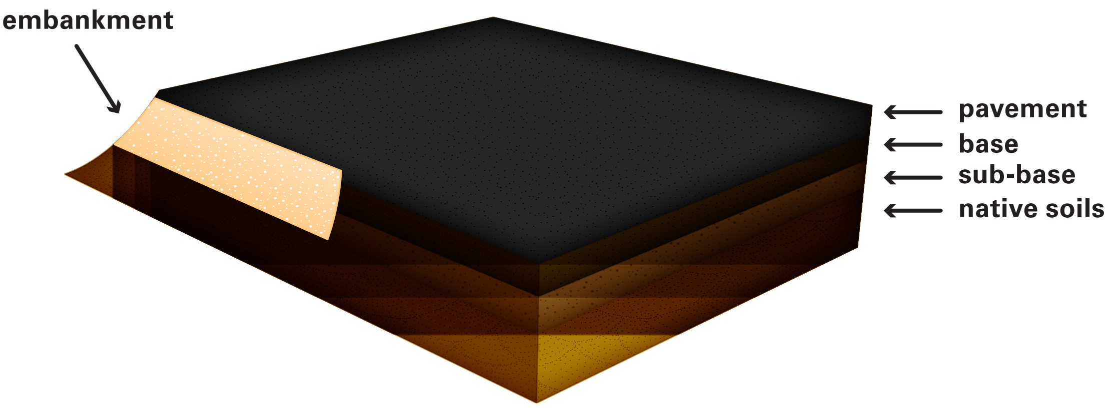
Properly compacted material is able to support heavier loads without deforming (bending, cracking, moving). The substrate material supporting a heavy structure must be very dense or it will compact even more under load, causing the structure to settle. Dense material has less permeability, which reduces the impact of water infiltration. Compaction also levels the surface and reveals structurally weak areas.

A good way to illustrate the importance of compaction is to consider the various layers of a typical roadway. Each layer of the roadway is designed to provide a specific engineering purpose, as well as support the weight placed on it. Each layer must be constructed of the right material to the proper thickness and stiffness. If one layer is not strong enough, the road will fail.

Compaction occurs during all phases of road construction. The quality of compaction has a significant impact on the longevity of the road, as well as a profound effect on the comfort—and possibly the safety—of the public who use it.

The least expensive element in 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 per cubic meter or yard of soil. Meeting density specifications can save significant money in future road maintenance and/or resurfacing costs.

TYPICAL SECTION OF ROADWAY



[WHAT IS SOIL?]

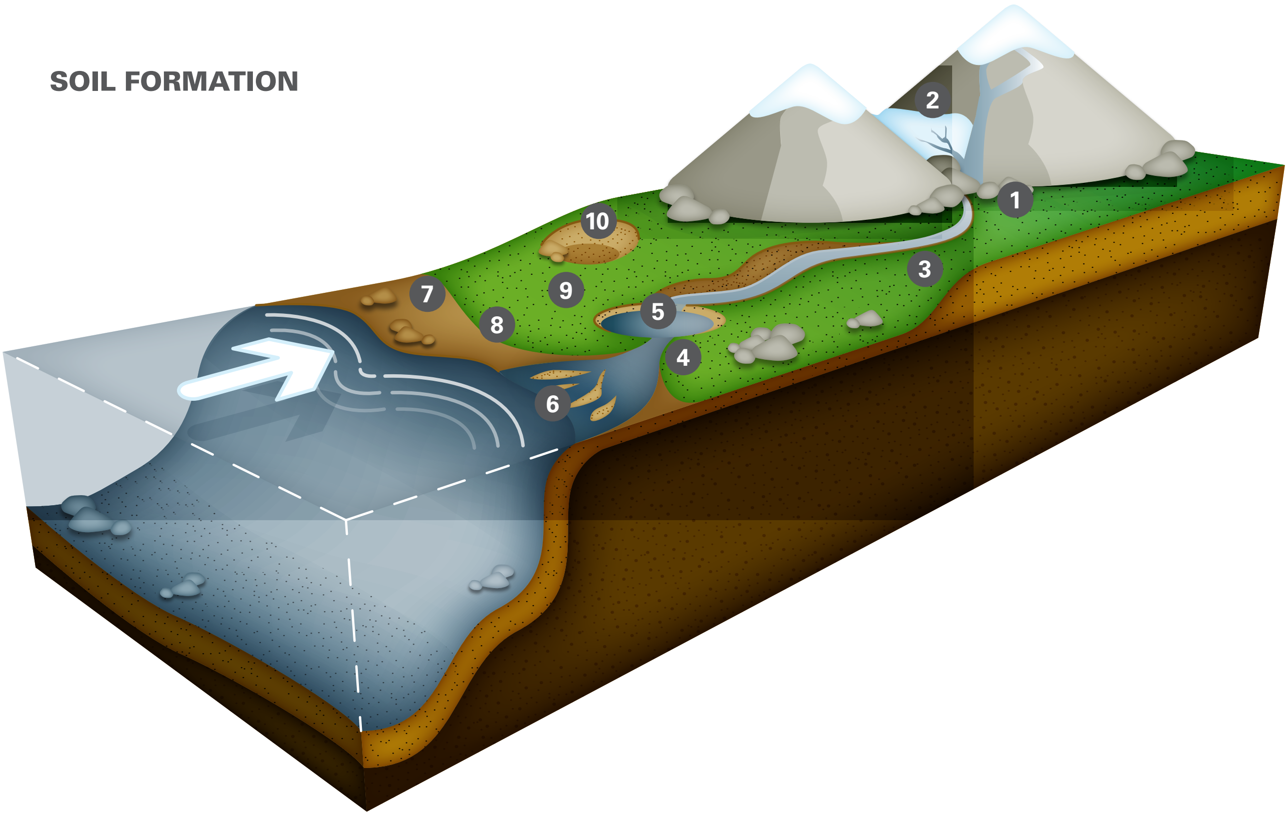
Soils are unconsolidated materials composed of mineral particles that may contain organic substances. Soils are essentially deposits of disintegrated rocks that have been slowly broken down by physical and chemical processes.

The physical processes include freezing and thawing, rolling, grinding and blowing.

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.

Organic matter 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 FORMATION



1. **residual soils**
   broken down pre-existing rock
2. **glacial deposits**
   materials carried or created by ice sheets
3. **glacifluvial deposits**
   materials transported by melt water from ice sheets
4. **river deposits**
5. **lake sediments**
6. **alluvial soils**
   fine-grained soils deposited on plains and in estuaries by flowing water
7. **wave-washed sediments**
8. **wind-blown deposits**
9. **organic soils**
   decomposed vegetation
10. **man-made soils**
    processed by blasting and crushing

[SOIL TYPES]

Although soils may vary widely in physical and chemical make-up, six fundamental types are recognized for engineering purposes: boulder, cobble, gravel, sand, silt and clay.

The six soil types are generally organized by particle size, which is determined utilizing a sieve test. While the precise details of engineering use can vary by country, the sieve sizes are generally defined by systems developed by one of two sources: the International Organization for Standardization (ISO) *[www.iso.org]* or the American Society for Testing and Materials (ASTM) *[www.astm.org]*. The two systems do not agree precisely, but they are very similar. Percentages of soils that are too fine to be sorted with sieves are determined by utilizing a hydrometer test. *(See page 14.)*

SOIL TYPES

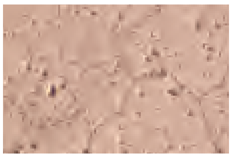
Boulder

Cobble

Gravel

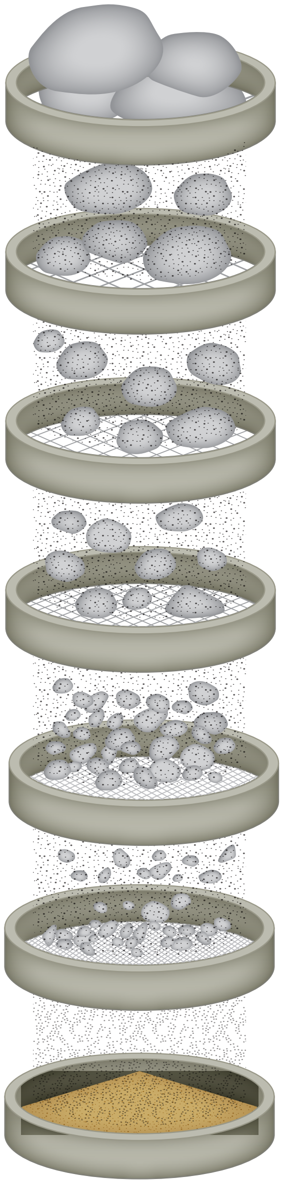
Sand

Silt

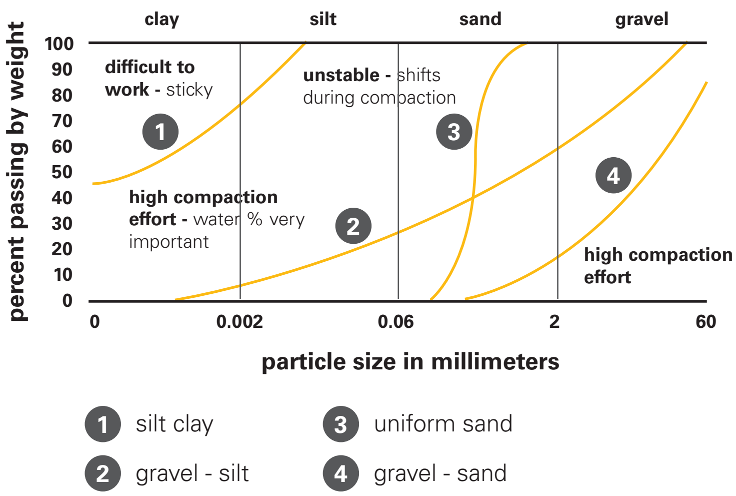


Clay

SIEVE TEST



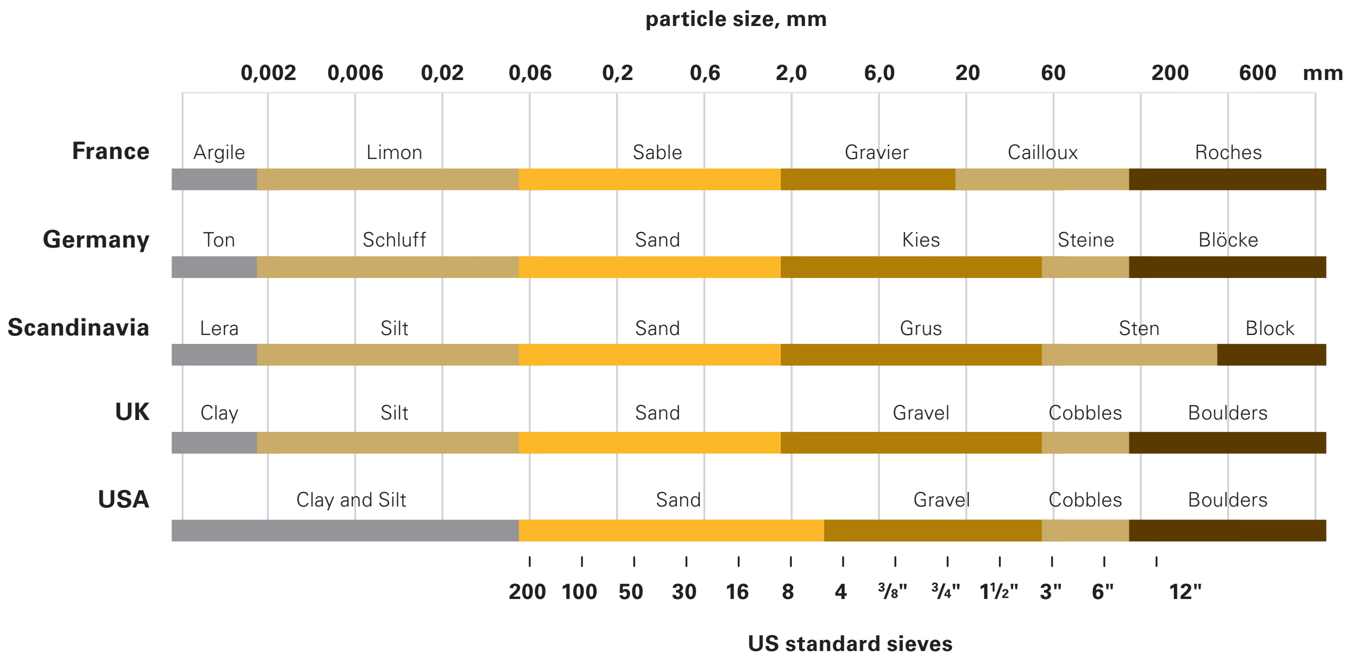
PARTICLE SIZE DISTRIBUTION



Hydrometer Test

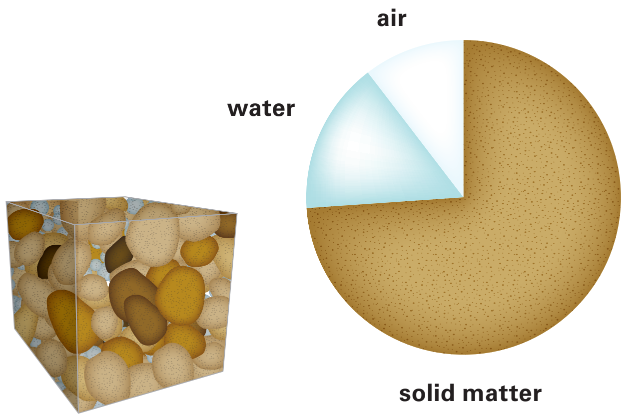
The soil sample is dispersed (suspended) in water in a graduated cylinder. The time it takes for the material to settle to the bottom can identify different grain sizes. A hydrometer reading of the suspension is taken to determine the specific gravity, which allows the percentages of grains for a particular size to be calculated.

SOIL COMPARISON CHART



A soil material is fundamentally a mixture composed of varying percentages of the previously mentioned soil types. It is important to understand that a soil material is not made of solid materials only. A soil material is a mixture of solid matter (any combination of soil types), water and air.

SOIL MIXTURE

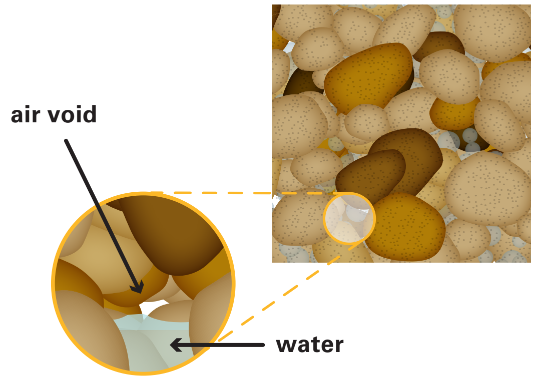


Natural or "native" soils—those that lie naturally deposited in the ground—will vary from one location to the next. For example, a soil material is never 100 percent clay or sand—there are always small percentages of other soil types present. The best soil materials for construction are often composites of specific percentages of choice soil types, depending on the engineering characteristics that are desired.

Geotechnical engineers can design soil mixes to provide these characteristics by specifying the percentages of each soil type. Soil types missing from a native soil are added in proportion and mixed with the natural soils to create an engineered soil. These additive materials are often determined by conducting an economic analysis of soil materials available nearby.

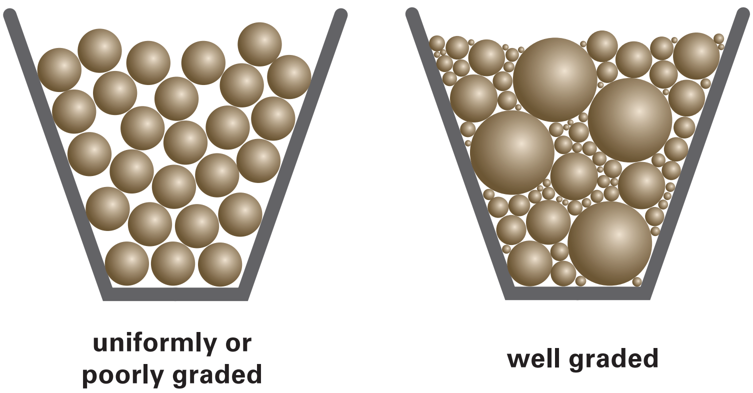
When you examine a soil sample closely, the individual particles are of many sizes and shapes. The spaces between the particles are called "voids." Voids can be occupied by either air or

AIR/WATER VOIDS



water. When a soil material has too much air and water due to abundant voids, the soil will be unstable. The process of compaction rearranges the soil particles to minimize the volume and size of air voids, making the material more dense and stable.

GRADATION



The individual particles of a soil material will vary in size, even if the variance is slight. The range of particle sizes is referred to as "gradation," or sometimes called "particle-size distribution" or "grain-size distribution." Ideally, there are relatively equal amounts of all grain sizes with no predominant size present. A material that possesses this ideal range of sizes is referred to as "well-graded."

Materials that possess particles of nearly identical sizes, such as alluvial sands, are "uniformly graded" or "poorly graded" materials. If one or more sizes are not present in the material, it is called "gap-graded." A well-graded soil will compact easier than a poorly graded soil because the presence of grain-size variability means the smaller grains fit nicely in the voids between the larger grains.

[FOUR TYPES OF SOIL MATERIAL]

While it is sometimes useful to know the exact composition of a soil material, it is more pragmatic to understand how a soil material reacts when various forces are applied to it. To that end, professionals who work with soil classify soil materials into four basic types:

1. **Cohesive**
2. **Semi-cohesive**
3. **Non-cohesive**
4. **Organic**

Each type reacts differently when forces are applied to it. How each reacts dictates its suitability for various engineering purposes in construction, as well as what kinds of means are used to work with each soil. As previously mentioned, organic soil materials are not suitable for construction purposes.

When a soil material is unsuitable for engineering purposes, it is either replaced or various means are employed to improve the characteristics of the soil, a process referred to as "stabilization." These solutions can include chemical stabilization—for example, the incorporation of Portland cement, lime, fly ash or calcium chloride—and mechanical stabilization, which includes adding choice aggregates or utilizing geosynthetics to reinforce the soil.

MATERIAL TYPES

Type of Soil	Appearance / Feel	Water Movement	When Moist	When Dry
Granular soils, fine sands and silts	Coarse grains can be seen. Feels gritty when rubbed between fingers.	When water and soil are shaken in the palm of hand, they mix. When shaking is stopped, they separate.	Very little or no plasticity.	Little or no cohesive strength when dry. Soil sample will crumble easily.
Cohesive soils, mixes and clays	Grains cannot be seen by naked eye. Feels smooth and greasy when rubbed between fingers.	When water and soil are shaken in palm of hand, they will not mix.	Plastic and sticky. Can be rolled.	Has high strength when dry. Crumbles with difficulty. Slow saturation in water.

[THE IMPORTANCE OF MOISTURE CONTENT]

The importance of water to the process of soil compaction cannot be overstated. Every type of soil has physical characteristics that define how the soil reacts to moisture. For every soil material, there is a moisture content that maximizes the engineering properties of the material for a given compaction energy. Generally, the smaller the particle size, the greater the influence of water on compaction.

If a soil possesses too little moisture, the material will be difficult to work with because the particles will lack the lubrication necessary to rearrange them into a more dense state. And, the particles will not be cohesive enough to stay where they have settled.

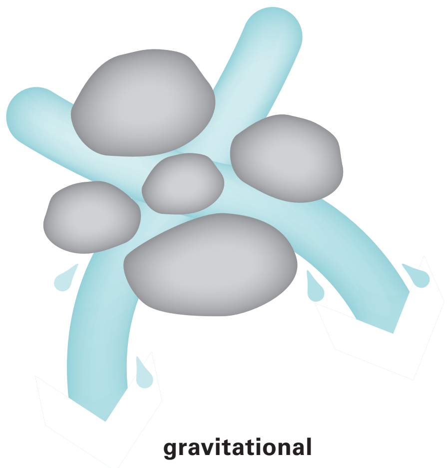
Water is added to enhance cohesion and lubrication. Too much water can cause saturation. When the soil is saturated, voids fill with water, weakening the load-bearing capability of the structure. The particles will also be over-lubricated, allowing them to easily displace.

As a simple example of how water can affect the engineering properties of a soil, imagine trying to construct a sand castle on a beach. The water in the sand gives it enough cohesion to be molded into thick walls and tall towers. Now imagine trying to build the same sand castle in the desert. The arid desert soil lacks cohesion, so it would be difficult to manage more than a few low mounds of sand.

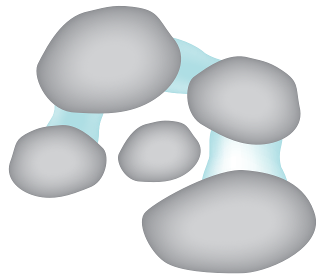
Water has other effects as well. Because it resists compression, it will displace soil materials, causing instability. Frozen water expands, displacing the soil around it. When the frozen water thaws, it occupies a smaller volume, creating space that will allow settling to occur.

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

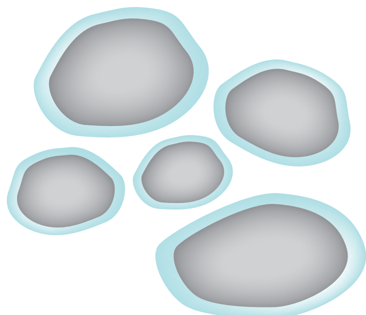
1. Gravitational water is free to move downward due to the force of gravity. It can drain naturally from a soil.
2. Capillary water is held in a soil by small pores or voids. It is considered free water and can only be removed by lowering the water table or by evaporation.
3. Hygroscopic water is present in a soil after gravitational and capillary water are removed. Individual soil grains hold this water 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 determine the true dry weight of the soil.



gravitational



capillary



hygroscopic

Too much moisture over-lubricates the soil and causes particle instability, while too little moisture reduces cohesion and prevents particles from reorienting easily into a denser state. For each soil type, there is an ideal moisture content at which maximum density can be reached with a given amount of compaction energy. The Proctor Test was developed as a way to help define this optimal moisture content for the selected compaction effort.

[THE PROCTOR TEST]

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

Proctor lab test kit

The Standard procedure determines the optimum moisture content of a material that will allow a given applied compaction force to obtain the maximum dry density of the material. This result is used to create a specification for compaction on the worksite. Because conditions in the field do not match the ideal conditions in a laboratory, the target compaction is scaled to a percentage of the dry density determined in the lab. This can range from 90 percent to over 100 percent.

Modified compaction tests have also been introduced in connection with structures requiring heavier bearing strength to support extremely heavy loads or to limit settlement. The Modified compaction test applies about four times more energy than the Standard compaction test and normally results in a lower “optimum” moisture content.

Surpassing 100 Percent Dry Density

How can the target density be over 100 percent? The maximum dry density established by the Proctor Test is not the maximum field density achievable on a particular soil. Proctor Dry Density of 100 percent represents the maximum density achieved in the lab with the particular sample using a specific amount of compaction force and ideal moisture content. Standard Proctor and Modified Proctor use different weights and will achieve different dry densities for the same sample. In the field, the “blows” are coming from a large soil compactor that applies a different amount of force than the hammers from the Proctor tests. It is not unusual to achieve field densities from 100 percent to 115 percent of Proctor maximum dry density. Geotechnical engineers may determine that due to load-bearing requirements and soil characteristics, compaction density over 100 percent of Proctor is warranted.

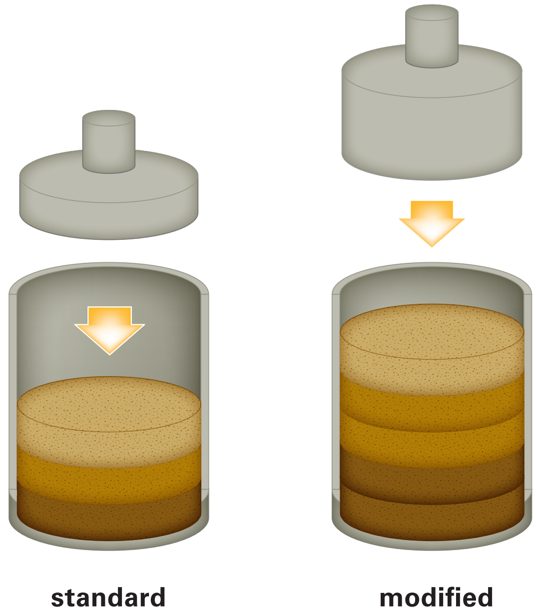
For a given soil sample, either the Standard or Modified Proctor is performed five times. The same procedure is used each time the test is run, but the moisture content is varied for each.

The series starts with the soil in a damp condition somewhat below the probable optimum moisture content. After the first sample is compacted into a cylindrical container, the wet weight is measured 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 weights yields the moisture content that is expressed as a percent of the dry weight.

A second sample with increased moisture content is compacted 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.

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 moisture content for that soil sample.

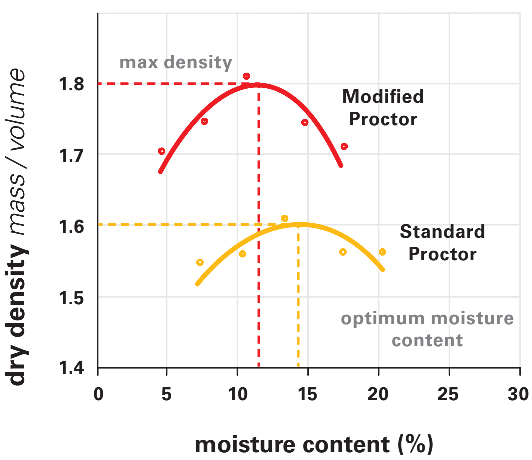
PROCTOR TESTS

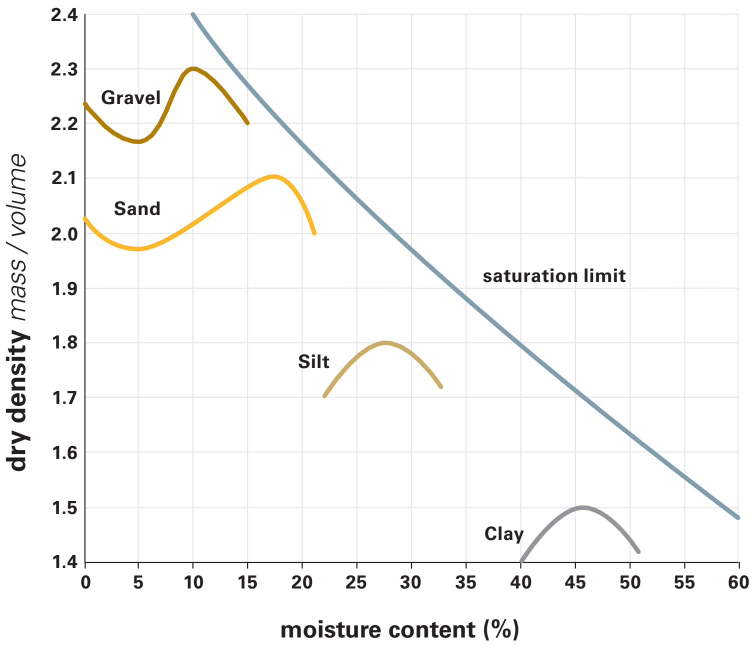


Each layer receives 25 blows from a 2.5 kg (5.5 lb) hammer at a distance of 305 mm (12 in)

Each layer receives 25 blows from a 4.5 kg (10 lb) hammer at a distance of 457 mm (18 in)

PROCTOR CURVES

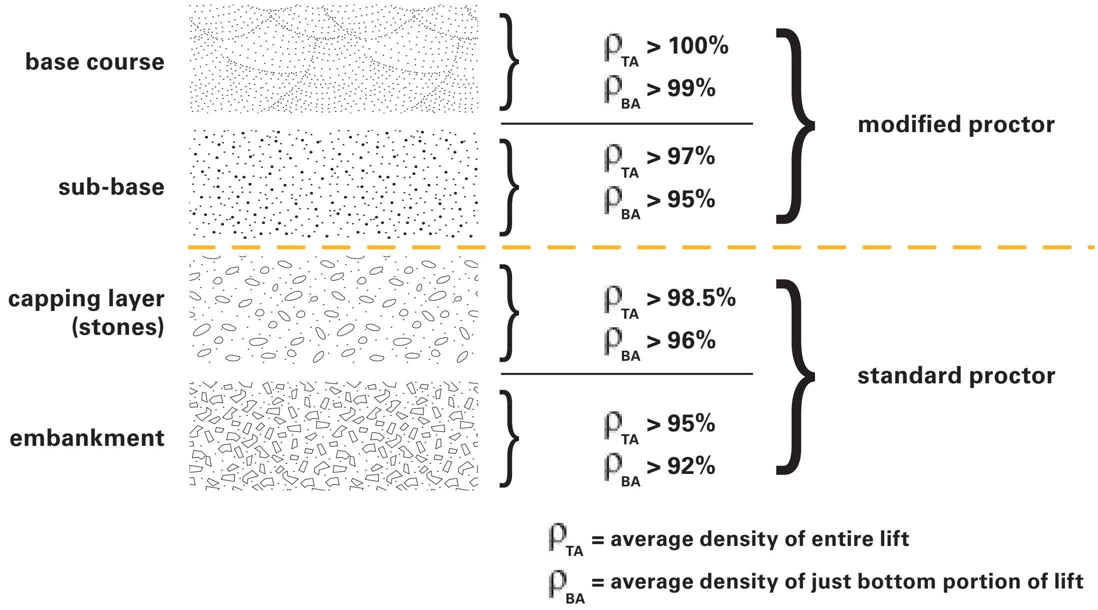




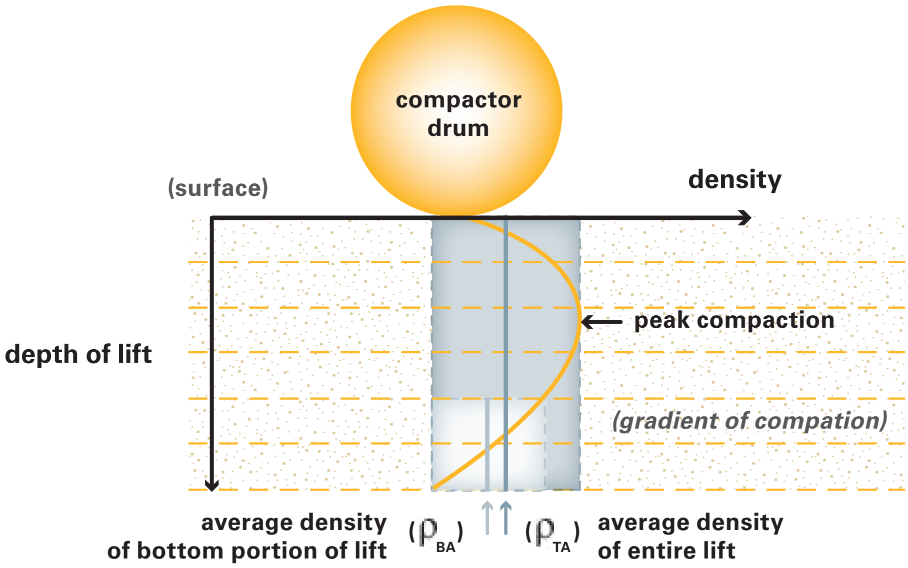
Laboratory tests determine the moisture content at which maximum density can be attained for that particular soil material. Field target densities are specified as a certain percent of the maximum laboratory dry density. Generally, required field densities will be 95 percent of Standard Proctor for embankments and up to 100 percent of Modified Proctor for roadway structures. Likewise, the moisture content must be within a range of the laboratory-determined, optimum moisture content.

DENSITY TARGETS

This example shows how the nearer the material is to the surface, the higher the density.



This illustration of the gradient of compaction compares the average density of the entire lift (ρ_{TA}) with the average density of just the bottom portion of the lift (ρ_{BA}).



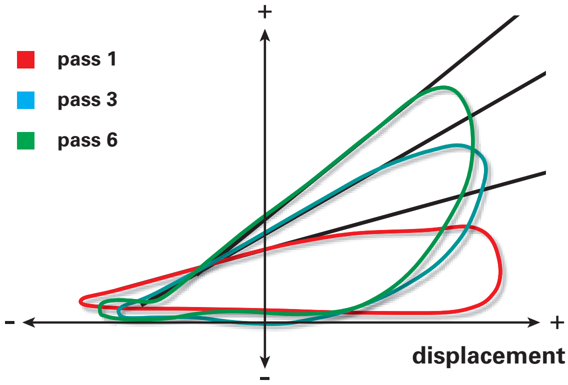
[PROPERTIES OF SOIL]

Engineers typically 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.

Load-Bearing Strength is the critical property of a road structure. Simply stated, it is the capacity of a structure to support the load that it carries. Assessment of load-bearing strength is normally achieved by proof rolling with a loaded dump truck and observing rutting or by plate load tests. In road construction, other properties like modulus, stiffness and density are typically used to provide a working target for load-bearing strength.

Stiffness is the ability of a certain shape of material to resist deflection under load and is calculated as the ratio of stress divided by displacement. Unlike elastic modulus, it is not a quality of the soil material itself. Stiffness is a quality of a certain quantity, shape and composition of a soil material—how much that shape of material deflects under load. For that reason, stiffness has become recognized as a valid way to estimate the load-bearing strength of a soil.

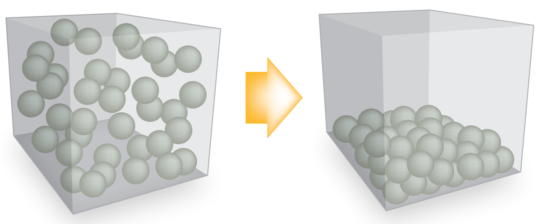
STIFFNESS



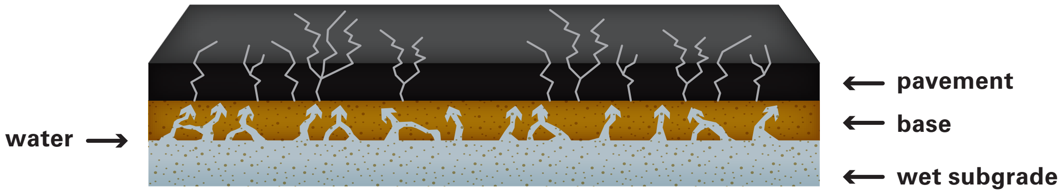
The steeper the slope of the curve, the stiffer the soil.

Density is a calculation of the mass of a material divided by the volume it occupies. Maximum density is the minimum volume a mass of a particular material can occupy. This would be a state with no voids, only a completely solid mass. Soil materials are made denser by compacting them from one volume into a smaller volume. Density has traditionally been the standard property by which engineers estimate load-bearing strength; however, because high density does not correlate to deflection and can cause certain materials to become brittle or degrade, the prominence of density as the primary assessor of load bearing strength has diminished. Regardless, it is still a necessary and trustworthy property to use in making certain assumptions about the support capacity of the road.

DENSITY

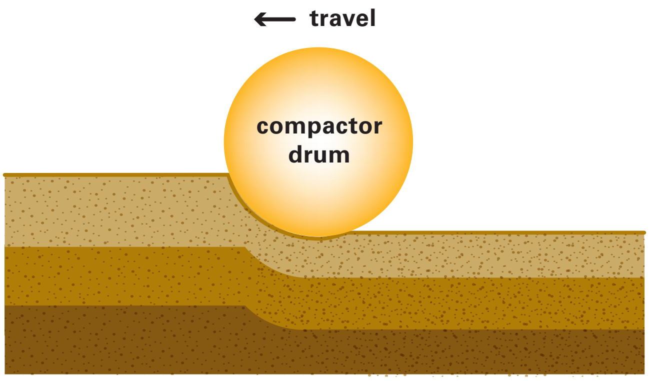


CAPILLARITY



Capillarity is the ability of a soil to force water upward or laterally. A desirable characteristic for base material used as a layer between the subgrade and the pavement of a roadway is to act as a capillary barrier preventing upward capillary movement of water from the subgrade. Granular base also allows water to drain out of the subgrade. Capillary water is held in small pores or voids in the soil. It is considered free water, but it can only be removed by lowering the water table, heavy sustained loading or evaporation. Without a capillary barrier in the base, trapped water would soften and expand the subgrade, resulting in an inadequately supported surface and premature deterioration of the roadway.

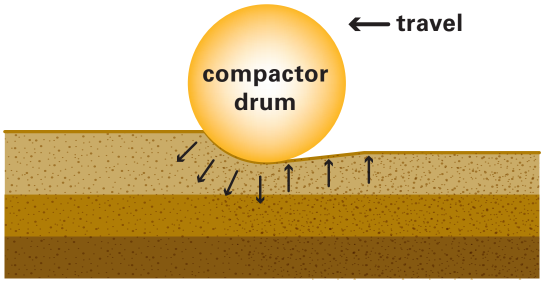
COMPRESSIBILITY



Compressibility is the rate of the reduction in volume of a soil 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. In wet conditions, clay soils usually have higher compressibility than granular soils. But they have less permeability, which makes clay soils very slow to drain and compress. When loads are applied rapidly, for example under moving wheel loads, water pressure builds up in fine-grained soils leading to increased compressibility.

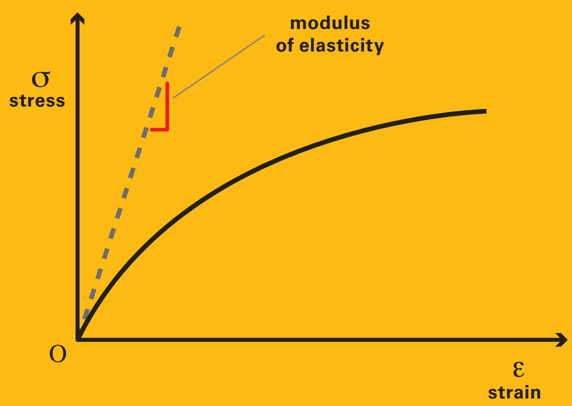
Elasticity is the tendency of a soil to deform and return to its original, or near original, shape after a compressive load is removed. Elasticity can be a desirable characteristic for soils, such as for support of fluctuating loads without accumulation of permanent deformation. However, roads with highly elastic bases or subgrades can perform poorly if the modulus of elasticity is too low, resulting in high strains within in the paving layers. Chemical and mechanical stabilization are often used to control the elastic behavior of soils and base. Organic soils have very high elasticity but low modulus of elasticity.

ELASTICITY

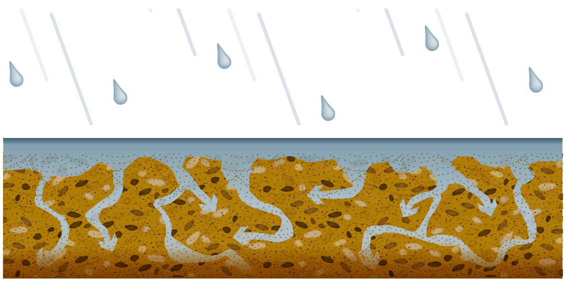


Modulus of Elasticity:

This is a calculation of the ratio of applied stress to the accompanying strain of a soil material. It is considered a quality of the particular soil sample being tested, and can vary with the changing composition of a soil material. The modulus is often used to provide an indication of the load-bearing strength of a soil material. Pavement layer thickness is typically based on an assessment of the underlying modulus of elasticity.

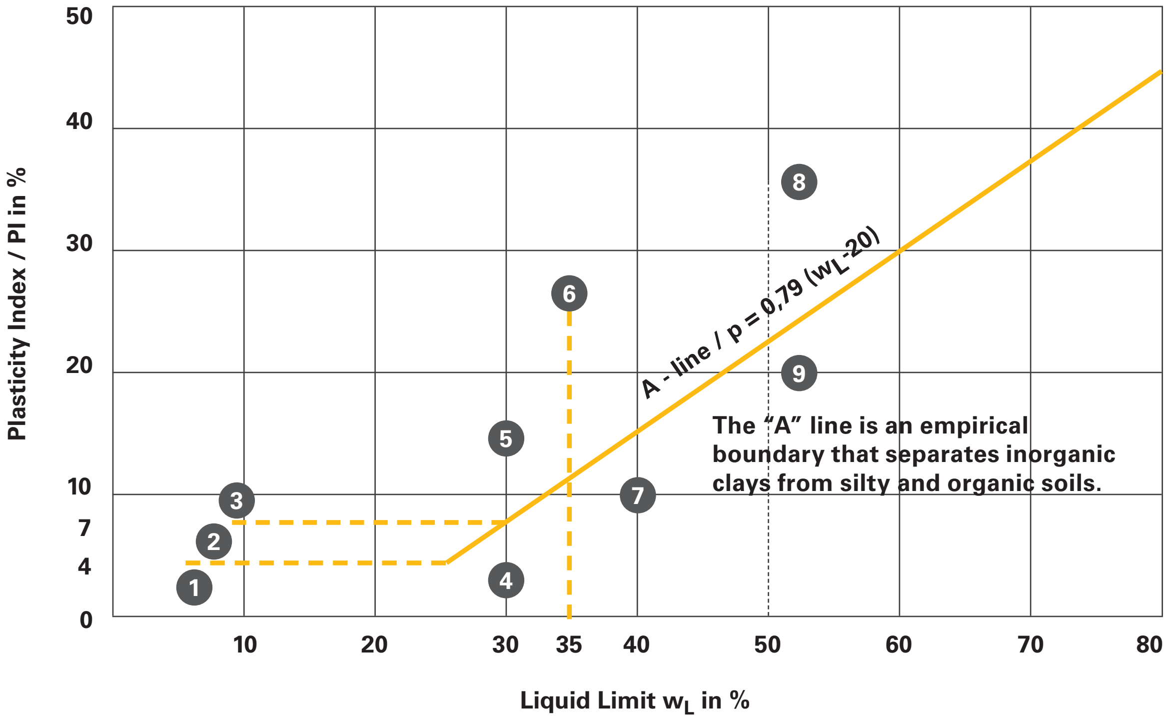


PERMEABILITY



Permeability is the ease with which water flows through a soil. This is not the same as capillarity, which is a soil's ability to absorb water. Soil texture, gradation and the degree of compaction influence a soil's permeability. Permeability is the most variable soil parameter with values varying more than 10 orders of magnitude. Usually, coarse-grained soils are more permeable than fine-grained soils because coarse-grained soils have larger voids between their particles.

PLASTICITY



1. Sand-silt mixtures
2. Intermediate range
3. Sand-clay mixtures
4. Light plastic silts
5. Light plastic clays
6. Medium plastic clays
7. Silts with organic admixtures and organogenic silts and medium plastic silts
8. Distinct plastic clays
9. Clays with organic admixtures and distinct compressible silts

Plasticity refers to the degree of cohesiveness and deformable nature of a soil. The measure of plasticity is expressed as the Plasticity Index (PI). Many clay soils have a high PI value, are quite compressible and have a high degree of cohesion.

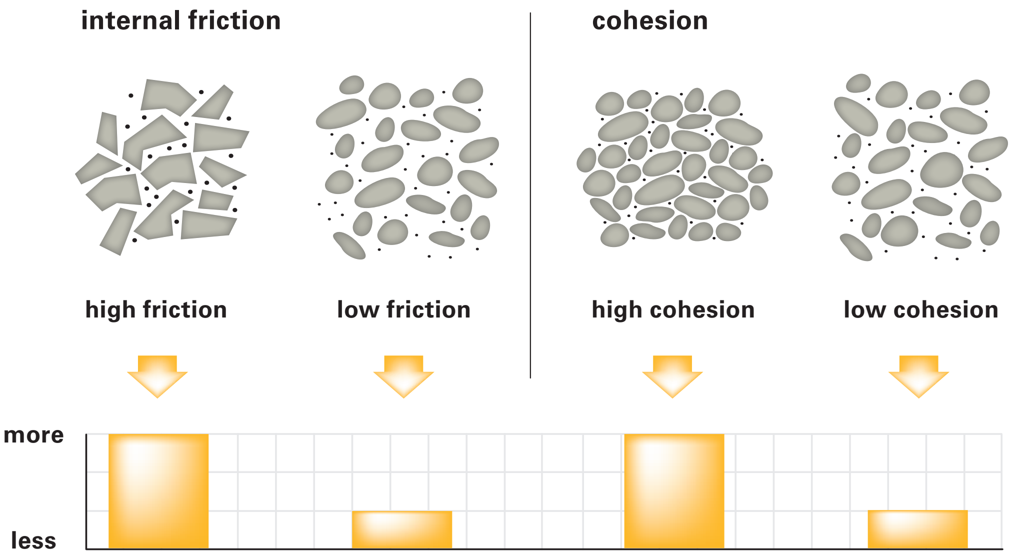
A soil with a zero PI is cohesionless or non-plastic. The moisture content of a soil also affects its PI.

SETTLEMENT

settlement

Settlement is the process of decreasing surface elevation due to the consolidation of fill material. Settlement often is the result of inadequate compaction. Poorly compacted soil particles will, in time, naturally reorient themselves and reduce the space available for air or water. The result is settling, which is directly related to the reduction in the volume of voids.

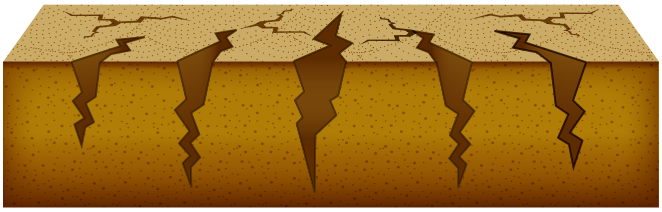
SHEAR RESISTANCE DEPENDS ON ...



Compaction force required to overcome shear resistance

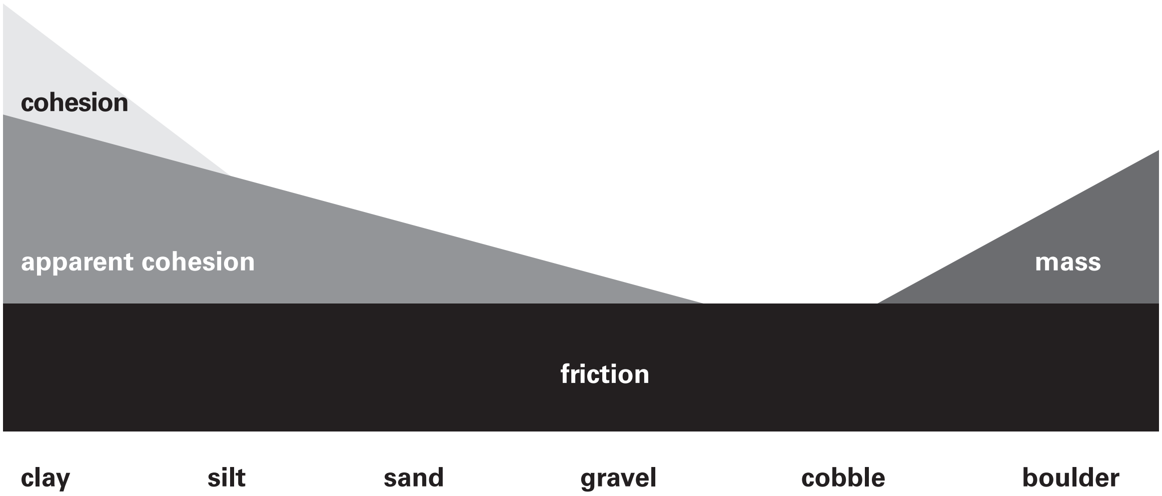
Shear Resistance is the resistance the soil particles have to sliding across each other when a force is applied—for example, vibration or compaction force. The shearing strength of a soil is the result of internal friction (resistance to sliding over each other) and cohesion (attraction to each other). Irregularly shaped particles have higher shear resistance than smooth shaped particles. The greater the shear resistance, the more compactive force is required to achieve density.

SHRINKAGE



Visible Shrinkage or Swelling is an indication that the soil is fine-grained, such as clay. The cycle of shrinking and swelling is a result of the release and build-up 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.

COMPACTABILITY



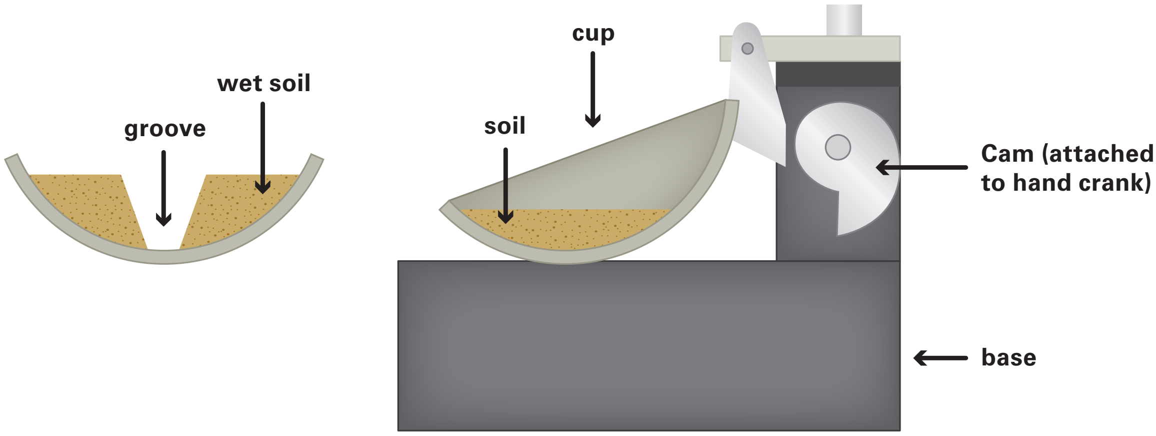
Compactability: During the process of changing a soil from a loose state to a dense state, the ease or rate of compaction is often termed the compactibility. Compactibility can be quantified as the ratio of the difference between the final density minus the initial density divided by the initial density. The higher the compactibility ratio, the easier or more rapid the density will change for the applied compaction effort. Factors that affect compactibility include the soil gradation (well-graded soils tend to have higher compactibility than gap-graded soils), moisture content, shear strength (resistance to deformation), compaction energy and method. Understanding the factors that contribute to increased compactibility will ensure proper equipment selection and efficient compaction operations.

[SOIL LIMITS]

The extent to which moisture content affects the compactability of a cohesive (clay) soil can best be understood by examining soil limits.

Albert Atterberg, a Swedish chemist, first developed certain limits of soil consistency: Liquid Limit, Plastic Limit, Plasticity Index and Shrinkage Limit. Sometimes called the Atterberg Limits, these are the basis for differentiation between highly plastic, slightly plastic and non-plastic materials.

LIQUID LIMIT (LL) TEST



simple liquid limit testing device

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

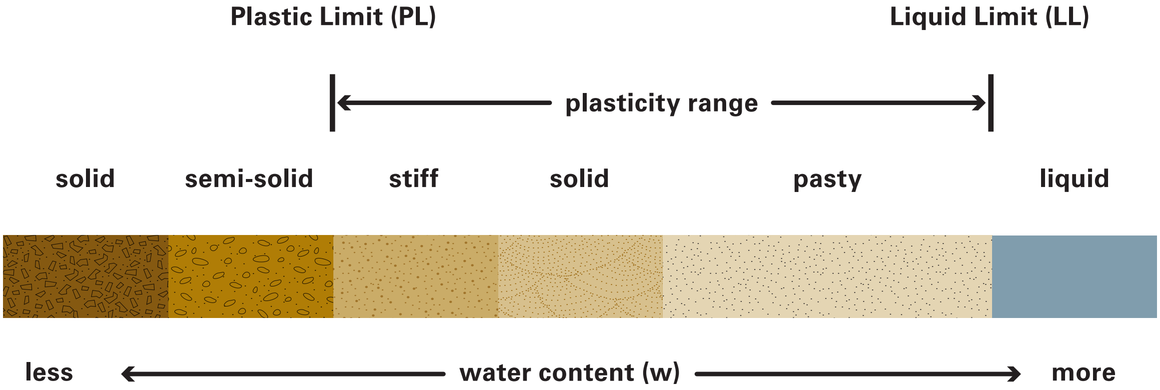
A simple test has been developed to determine the Liquid Limit of a soil. Take a moist sample of a soil and place it in a small bowl, flattening the sample somewhat. Make a deep groove in the sample and tap the bottom of the bowl 10-30 times, watching the groove. If the faces of the groove remain the same distance apart, pick up the sample, add more water, and repeat the process. When the faces of the groove move together on a length of 15 mm (½"), 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 thread approximately 3 mm ($^1/_8$") in diameter without breaking.

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

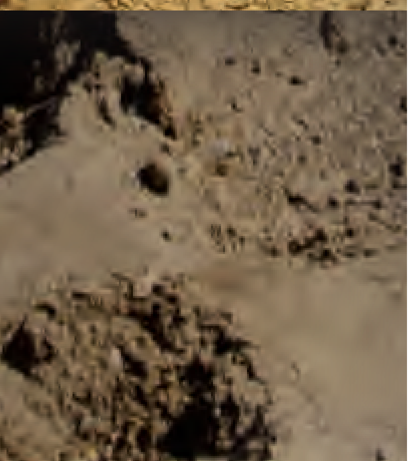
PLASTICITY INDEX (PI)



Plasticity Index (PI)
This is the numerical difference between the Plastic Limit and Liquid Limit of a soil. Soils possessing 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 estimating the compressibility and cohesion of a soil.

The PI also relates to permeability. The higher the PI, the lower the permeability—and the lower the PI, the higher the permeability. On many jobs involving construction with high clay content soils, 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 becomes brittle. At the moisture content that the sample volume change stops, the Shrinkage Limit is determined. 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 the PL.



Unit 2
SOIL TYPES AND CLASSIFICATIONS

Where possible, laboratory soil tests are the best option for classifying soils. When that is not possible, you can conduct one or more field tests to help you identify soils and determine a compaction approach.

[SOIL CLASSIFICATION SYSTEMS]

There are several different soil classification systems in use around the world today. All use the terms gravel, sand, silt and clay, but with slightly different numbering and lettering systems. The purpose of soil classifications is to create standards by which soils and their engineering characteristics can be identified.

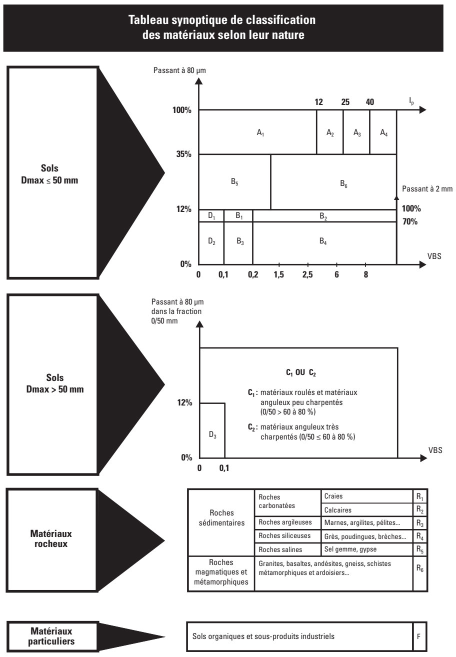
AASHTO Soil Classification System – The widely used American Association of State Highway and Transportation Officials (AASHTO) system of soil classification is based on field performance of soils for highway construction. The system divides materials into seven major groups with some subgroups. The groups are arranged in two major categories: granular materials and silty-clay materials.

AASHTO CLASSIFICATION OF HIGHWAY SUBGRADE MATERIALS
(with suggested subgroups)

General Classification	Granular Materials (35% or less passing #200)							Silt-Clay Materials (more than 35% passing #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 Percent Passing:											
# 10	0-50										
#40	0-30	0-50	51-100								
#200	0-15	0-25	0-10	0-35	0-35	0-35	0-35	36-100	36-100	36-100	36-100
Characteristics of Fraction Passing #40:											
Liquid Limit				0-40	41+	0-40	41+	0-40	41+	0-40	41+
Plasticity Index	0-6		N.P.	0-10	0-10	11+	11+	0-10	0-10	11+	11+
Group Index	0		0	0		0-4		0-8	0-12	0-16	0-20
Usual Types of Significant Constituent Materials	Stone Fragments Gravel and Sand		Fine Sand	Silty or Clayey Gravel and Sand				Silty Soils		Clayey Soils	
General Rating as Subgrade	Excellent to Good							Fair to Poor			

Please see Appendix for full size charts.

French Soil Classification System – This system classifies materials into classes and subclasses based on mechanical analysis of attributes including grain-size distribution, plasticity and sand equivalent.



German Soil Classification System – DIN18196 classifies all soil materials for construction purposes into groups based on particle size according to DIN4022, mass proportions, plasticity and the presence of organic and calcareous components. Generally, coarse particles and fine particles are judged differently as coarse particles have a particle-size distribution criterion and fines have a plasticity criterion.

Hauptgruppe	Korngrößenanteil ≤ 0,06 mm	Korngrößenanteil > 2,0 mm	Gruppe (allgemein)	Gruppe (detailliert)	Kurzzeichen Gruppensymbol
Grobkörniger Boden	≤ 5	< 40	Kies	Enggestufte Kiese	GE
				Weitgestufte Kies-Sand-Gemische	GW
				Intermittierend gestufte Kies-Sand-Gemische	GI
			Sand	Enggestufte Sande	SE
				Weitgestufte Sand-Kies-Gemische	SW
				Intermittierend gestufte Sand-Kies-Gemische	SI
Gemischtkörniger Boden	5 bis 40	< 40	Kies-Schluff	5 bis 15 Gew.-% ≤ 0,06 mm	GU
				15 bis 40 Gew.-% ≤ 0,06 mm	GU*
			Kies-Ton	5 bis 15 Gew.-% ≤ 0,06 mm	GT
				15 bis 40 Gew.-% ≤ 0,06 mm	GT*
		≤ 40	Sand-Schluff	5 bis 15 Gew.-% ≤ 0,06 mm	SU
				15 bis 40 Gew.-% ≤ 0,06 mm	SU*
			Sand-Ton	5 bis 15 Gew.-% ≤ 0,06 mm	ST
				15 bis 40 Gew.-% ≤ 0,06 mm	ST*
Feinkörniger Boden	< 40	–	Schluff	Leicht plastische Schluffe $W_L \leq 35$	UL
				Mittelplastische Schluffe W_L=35 bis 50	UM
			Ton	Leicht plastische Tone $W_L \leq 35$	TL
				Mittelplastische Tone W_L=35 bis 50	TM
				Ausgeprägt plastische Tone W_L=50	TA
Organogener Boden	< 40	–	Nicht brenn- und schwelbar	Organogene Schluffe W_L=35 bis 50	OU
				Organogene Tone $W_L>50$	OT
	≤ 40			Grob bis gemischtkörnige Böden mit humosen Beimengungen	OH
				Grob bis gemischtkörnige Böden mit kalkigen, kieseligen Bildungen	OK
Organischer Boden	–	–	Brenn- und schwelbar	Nicht bis mäßig zersetzte Torfe	HN
				Zersetzte Torfe	HZ
				Mudden (Faulschlamm)	F
Auffüllung[1]	–	–	–	Auffüllung aus Fremdstoffen	A

1 - Eine Auffüllung ist eine unter menschlicher Einwirkung entstandene Schüttung aus natürlichen Böden oder Fremdstoffen.

Unified Soil Classification System – The USCS is a widely used method for classifying soils in construction projects. The U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation developed this system. It uses texture as the descriptive term.

USCS SOIL CLASSIFICATION SYSTEM			
SOIL FRACTION	**SYMBOL**	**SIZE RANGE**	
Boulders	None	Greater than 12"	
Cobbles	None	75 mm (3") to 12"	
1- Course Grained Soils:			
Gravel	G	75 mm (3") to #4 Sieve (4.25 mm)	
Course Gravel		75 mm to 19 mm	
Fine Gravel		#4 Sieve to 19 mm	
Sand	S	#4 Sieve to #200 Sieve (0.075 mm)	
Course Sand			
Medium Sand			
Fine Sand			
2- Fine Grained Soils:			
Fines		Less than #200 Sieve	
Silt	M	Use Atterberg Limits	
Clay	C	Use Atterberg Limits	
3- Organic Soils	O	Use Atterberg Limits	
4- Peat	Pt	Visual Identification	
Gradation Symbols		**Liquid Limit Symbols**	
Well-graded	W	High LL	H
Poorly-graded	P	Low LL	L

United Kingdom Soil Classification System – British Standard (BS) system of classification is a protocol for identifying soil composition. Soil is first classified into either coarse or fine soil based on particle size. Granular soils are classified based on their particle-size distributions. Fine soils are sub-grouped based upon their plasticities.

SOIL GROUPS GRAVEL and SAND may be qualified sandy GRAVEL and gravely SAND where appropriate			SUB-GROUPS and in-laboratory identification GROUP SYMBOL		SUB-GROUP SYMBOL	FINES % < 0.06 mm	LIQUID LIMIT
COARSE SOILS less than 35% of the material is finer than 0.06 mm	GRAVELS More than 50% of coarse material is of gravel size (coarser than 2 mm)	Slightly silty or clayey GRAVEL	G	GW GP	GW GPu CPg	0 to 5	
		Silty GRAVEL Clayey GRAVEL	G-F	G-M G-C	GWM GPM GWC GPC	5 to 15	
		Very silty GRAVEL Very clayey GRAVEL	GF	GM GC	GML, etc. GCL GCI GCH GCV GCE	15 to 35	
	SANDS More than 50% of coarse material is of sand size (finer than 2 mm)	Slightly silty or clayey SAND	S	SW SP	SW SPu SPg	0 to 5	
		Silty SAND Clayey SAND	S-F	S-M S-C	SWM SPM SWC SPC	15 to 35	
		Very silty SAND Very clayey SAND	SF	SM SC	SML, etc. SCL SCI SCH SCV SCE	15 to 35	
FINE SOILS more than 35% of the material is finer than 0.06 mm	Gravelly or sandy SILTS and CLAYS 35% to 65% fines	Gravelly SILT Gravelly CLAY	FG	MG CG	MLG, etc. CLG CIG CHG CVG CEG		< 35 35 to 70 50 to 70 70 to 90 > 90
		Sandy SILT Sandy CLAY	FS	MS CS	MLS, etc. CLS, etc.		
	SILTS and CLAYS 65% to 100% fines	SILT (M SOIL) CLAY	F	M C	ML, etc. CL CI CH CV CE		< 35 35 to 70 50 to 70 70 to 90 > 90
ORGANIC SOILS		Description letter 'O' suffixed to say group or sub-group symbol			Organic matter in significant amount e.g. MHO – organic silt of high LL		
PEAT		Pt – consists predominantly of plant remains (fibrous or amorphous)					

Classification v1.00 Sept 2010

Primary Letter
G = Gravel
S = Sand
M = Silt
C = Clay
O = Organic Soil
Pt = Peat

Secondary Letter
W = Well graded
P = Poorly graded
M = With non-plastic fines
C = With plastic fines
L = Of low plasticity (LL < 50)
H = Of high plasticity (LL > 50)

[SOIL CLASSIFICATION IN THE FIELD]

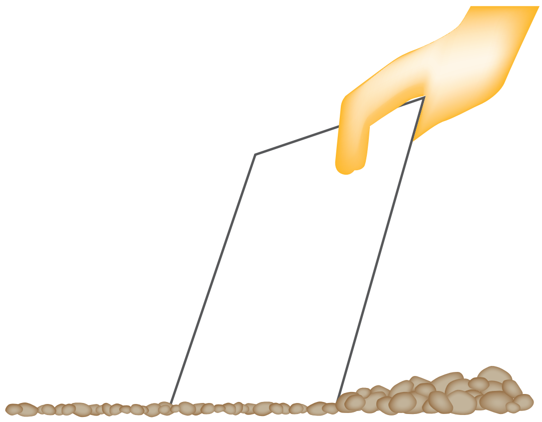
Classification systems require laboratory measurements such as the sieve analysis or the Plasticity Index test. However, some simple field tests can be used to classify various soils when complete laboratory facilities are not available. The tests are used to determine gradation, plasticity and dispersion.

Gradation/Particle Distribution – 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 5 mm (3/16") 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).

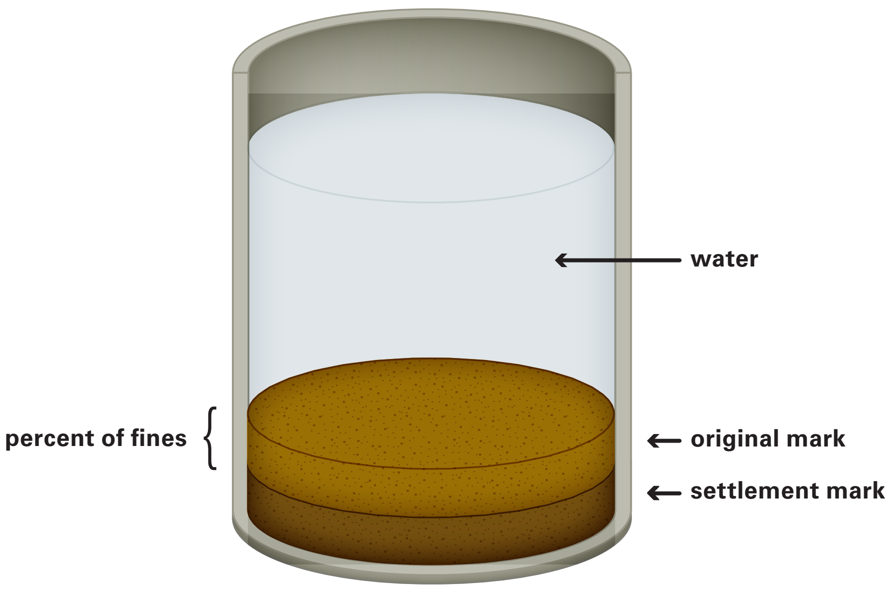
If the soil is wet, break a lump apart with a pencil and make percentage estimates in the dry soil method. To find the percentage of fines, fill a clear glass with 3 mm (1/8") of water. Then, add enough soil to fill the glass 1/4 full. Add water until the soil is just covered.

Mark this level with a rubber band. Fill the jar 3/4 full with water and stir the mixture vigorously. Let it settle about a minute and a half and mark the height of soil that has settled out. The difference between the two marks represents the percentage of fines.

GRADATION TEST

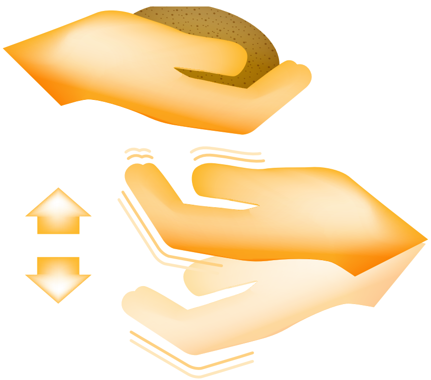


PERCENT OF FINES

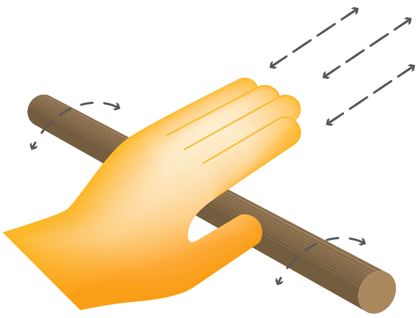


Plasticity of Fine Grained Soils – You can perform one or more field tests to estimate the plasticity of a soil.

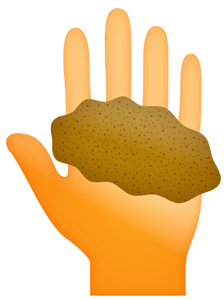
SHAKING TEST



TOUGHNESS TEST



HAND TEST



- **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.

- **Toughness Test –** Take about half the ball of soil and knead it between the thumb and forefingers to dry it out. Then, attempt to roll the soil sample into a 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 a diameter of 3 mm (1/8 in).

- **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 jagged, pointy fragment. Try to crush this fragment between the thumb and forefinger. Silt will turn to powder with little effort. Clay will be like a rock and almost impossible to crush with the fingers.

- **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.

- **Hand Test –** Pick up a handful of soil. Squeeze it; then open your hand. If the soil is powdery and will not retain the shape made by your hand, it is too dry. If it shatters when dropped, it is too dry. If the soil is moldable and breaks into only a few pieces when dropped, it has the correct amount of moisture for proper compaction. If the soil is plastic in your hand, leaves traces of moisture on your fingers and stays in one piece when dropped, it has too much moisture for compaction.

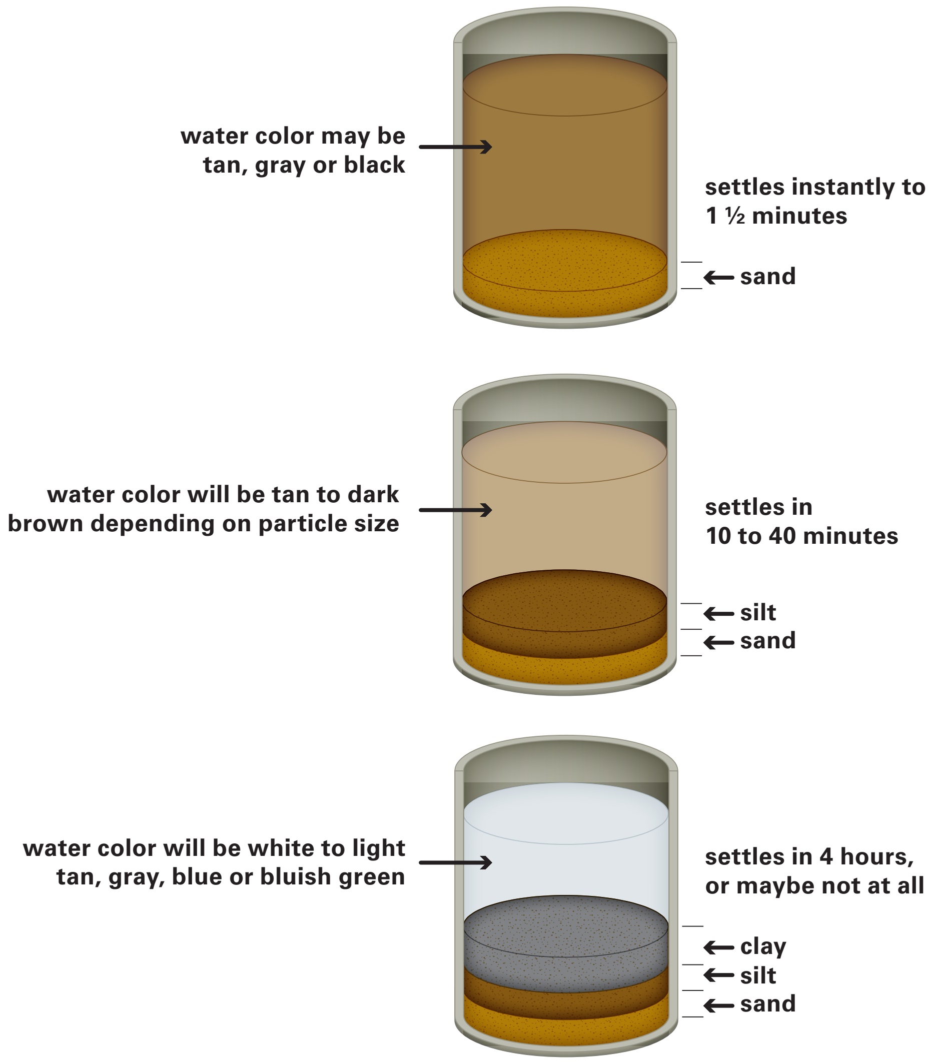
- **Dispersion Test –** In addition to the field tests just described, the Dispersion Test can be used to determine percentages of soil grain sizes as well as an indication of how difficult it will be to compact the soil. All that is needed is a clear glass, water and a representative soil sample.

  Fill the glass 1/4 – 1/3 full with the material. Then, fill the container with water to within 15 mm (1/2 in) of the top. Stir the mixture well and observe how the material settles.

  The material will settle in three distinct layers. The sand at the bottom, silt next and finally, clay. Besides showing the 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.

  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 indicate a less stable construction material than a mix where there is a good gradation of all particle sizes. These materials are difficult to compact because the grains continue to shift under the machine.

DISPERSION TEST



[SUMMARY OF FIELD TESTS]

Soil Types	Description
Clays	No reaction to the shaking test; a rough worm that dries out slowly; a crusty dry residue that is hard to remove from the hands.
Silts	Rapid reaction to the shaking test; a weak or crumbly worm; powdery residue that is easily wiped off or washed off the hands.
Silt and clay mixtures	Intermediate or conflicting reactions to hand tests.
Sand or gravel with 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 immediately without making any mud.
Shot or ripped rock	Jagged material not having enough smaller material to fill the voids.


CAT
CAT

Unit 3
PHYSICS OF COMPACTION

Understanding the physics of compacting different soil types and the effect of different machines and their compactive capabilities is the key to meeting specified soil density in the most cost-efficient manner.

[FACTORS THAT INFLUENCE VIBRATORY COMPACTION]

Vibratory compaction of soil is a complex process. Many different factors influence the overall compaction effort. All of these factors that influence compaction must be considered in total, not independently. It is the combined characteristics of the compactor and of the soil it is acting upon that determine the degree of compaction effort. And, project specifications determine if the compaction effort is adequate. The factors or characteristics influencing vibratory compaction can be divided into three categories:

1. Material and jobsite related characteristics
2. Project specification related characteristics
3. Machine related characteristics

Material and Jobsite Related Characteristics

- **Soil Type –** A given soil type will have unique compaction characteristics; soils that are more difficult to compact call for heavier compactors.
- **Gradation –** The gradation of a material is the range of particle sizes present. Ideally, there are relatively equal amounts of all grain sizes with no predominant size present.
- **Uniformity –** A soil material is a mix of many soil types and particle sizes. Uniformity can be thought of as the degree to which all of the composite materials are well mixed and dispersed evenly throughout the soil. A uniform soil mix is homogenous and will compact consistently; a soil that lacks uniformity will exhibit inconsistent compaction.

  The Uniformity Coefficient (C_u) in soil mechanics is a parameter to describe the particle size distribution (grading curve) of a soil. It provides information on how uniformly the grain sizes of a soil are distributed. In DIN EN ISO 14688-2:2004, C_u is defined as the ratio of the diameter d_{60} during sieving of 60 percent to the diameter d_{10} at 10 percent passing. The ratio represents the slope of the range of the grain size curve between 10 percent and 60 percent of passes (through the sieve).

CALCULATING THE UNIFORMITY COEFFICIENT

$$C_u = \frac{d_{60}}{d_{10}}$$

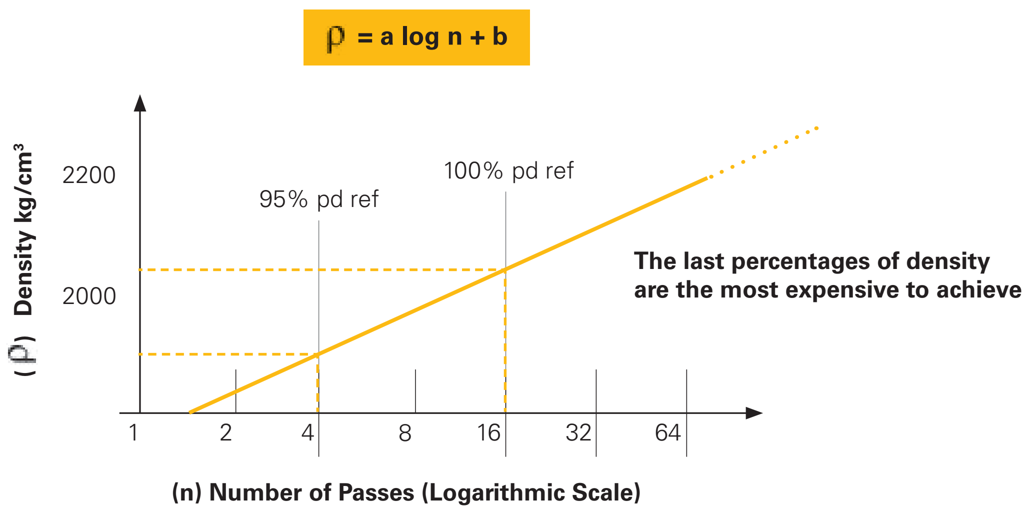
The value of C_u allows the following statements on the soil:

C_u <5 = uniform soil
C_u 5-15 = non-uniform soil
C_u >15 = extremely non-uniform soil

- **Texture –** Individual soil types possess different surface textures, which have an effect on the compaction characteristics of the material. Soil types with coarse texture create high friction between the particles, requiring more energy from the compactor to loosen their bonds, thereby allowing them to reposition in a denser state. Smooth textured particles slide more easily over one another, requiring less effort to compact.
- **Grain Shape –** Like texture, the shape of the particles can also affect compaction of a soil. Jagged shapes tend to have greater friction bonds that require greater effort to compact. Smooth, rounded shapes slide more easily with less compactive effort.
- **Initial Density –** Materials with higher initial density will require less compactive energy than those with lower density. This will affect productivity, as less dense material may require more passes.
- **Moisture Content –** Moisture is the single most important factor to consider when compacting soil. Too little moisture and particles will not adhere to each other. Too much moisture causes particles to displace easily. Every soil type has a moisture content that is ideal for optimal compaction (defined by Proctor Test).
- **Aggregate Strength Characteristics –** Every soil type has a different compressive strength based upon how the aggregate was formed.
- **Subsoil Base and Its Supporting Capability –** A structure is only as strong and resilient as the foundation that supports it. If the subsoil lacks the capability to support a road, it is likely that compaction of the sub-base and base layers will be difficult. Unsuitable soils can be improved by chemical or mechanical stabilization.

THE COST OF DENSITY

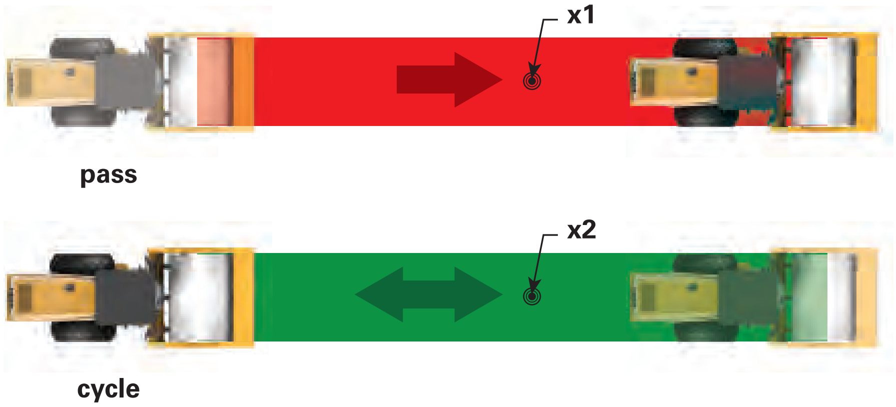
With increasing number of passes, density increases



Project Specification Related Characteristics

- **Compaction Target –** Typically, this is established by the administration of the Standard Proctor or Modified Proctor test and is specified as a certain percentage of the maximum dry weight density resulting from that test—in the example, 95 percent of Standard Proctor. Generally, the higher the compaction target, the more passes are required. It is always the most difficult to achieve the final percentage points of compaction.
- **Lift/Layer Thickness –** When using a compactor of a given size, the layer thickness will influence productivity. A thick layer will require more passes than a thin layer.

COUNTING PASSES



- **Number of Passes –** This refers to the number of times a compactor will pass over an area of ground. Caterpillar defines a pass as a single trip over an area in either forward or reverse direction and a cycle as two consecutive passes over an area, typically one in the forward direction and one in the reverse.

  Knowing the pass count can be important, particularly when an area is identified that is not meeting compaction specifications. If a jobsite receives the same coverage (number of passes), and one area fails but the rest pass, it can help you narrow the number of causes.

In cases where a method specification is used, the number of passes (with an appropriately sized compactor on a lift of specified composition and thickness) will be specified. In those cases, engineers have determined from past experience that this number of passes will be sufficient to meet the compaction target.

Machine Related Characteristics

The design of the machine is important to the dynamics of compaction. Influential factors include: frame size, overall weight, wheelbase, ratio of machine weight supported over the front drum to tires, and balance of machine weight from left to right of the machine. The list continues with factors such as drum diameter, drum length, 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 the operator influences the performance of the compactor. The manufacturer carefully considers all these factors when designing each machine.

Vibratory compaction involves a drum (static weight) that is moving up and down (amplitude) very rapidly (frequency) and moving forward (working speed) over non-homogeneous material.

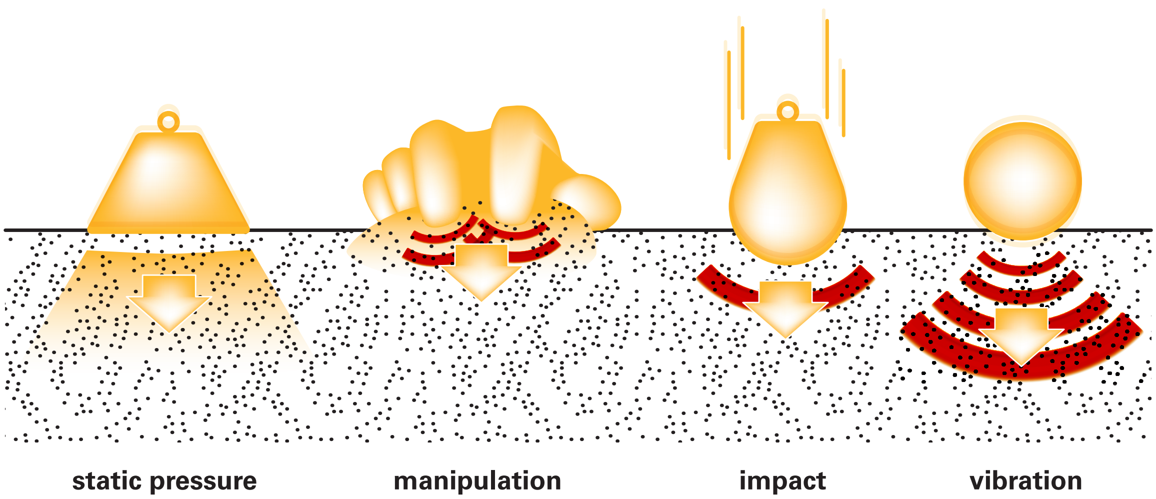
Of course, frequency, amplitude and working speed are variables controlled by the operator. They will be discussed later in Unit 3.

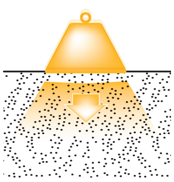
All these variables mean that it's not always easy to set up a compactor on a given job to achieve ideal compaction results. The objective in vibratory compaction is to find a point of maximum transmitted force into the material to be compacted. This occurs when the sum of all the factors—material characteristics, compactor characteristics, amplitude, frequency and speed—is contributing optimally to the compactive effort required for meeting the project specifications.

[FACTORS THAT INFLUENCE VIBRATORY COMPACTION]

Compaction is the process of compressing a material from a certain volume into a smaller volume. This is accomplished by exerting force and movement over a contact area, causing particles within the material to break their natural bonds with each other and 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**
3. **Impact**
4. **Vibration.**

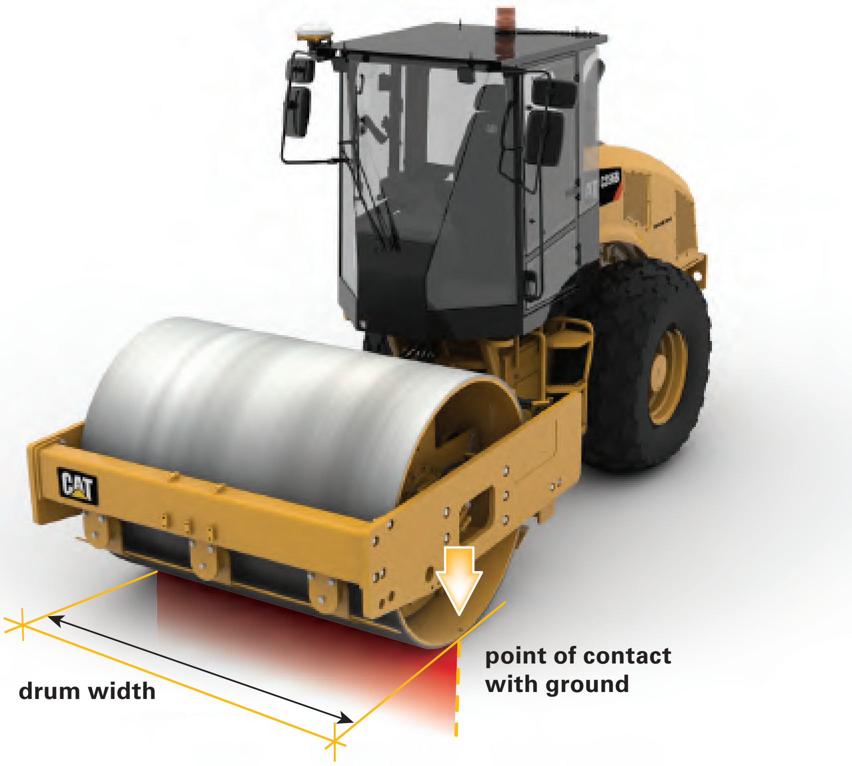




Static Pressure – In static compaction, pressure from the weight of the compactor produces shear stresses in the soil that cause the individual particles to slide across each other. Compaction occurs when the applied force causes individual particles to break their natural bonds to one another and reorient to a more stable position. This compaction force has a greater effect on surface and shallow depth materials. It has a minimal effect on deeper soils.

Static linear load is the measure used by the industry to compare the compaction potential of static, smooth drum compactors. It is the vertical force directly below the width of the drum that creates the shear stresses for compaction. It is calculated by dividing the weight at the drum (axle load) by the drum width. Static linear load is expressed as kilograms per linear centimeter (kg/cm) or pounds per linear inch (lb/in). Compactors with a higher linear load have greater compaction potential and depth of influence.

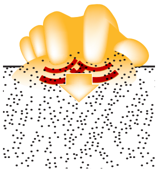
STATIC LINEAR LOAD



Static Linear Load	
Vibratory Soil Compactors	
5 - 8 Ton	**16 - 22 kg/cm (90 - 120 lb/in)**
8 - 12 Ton	**20 - 30 kg/cm (100 - 200 lb/in)**
12 - 15 Ton	**30 - 45 kg/cm (180 - 250 lb/in)**
>15 Ton	**45 kg/cm+ (250 lb/in+)**
Pneumatic Tire Compactors	**1000 - 3200 kg/wheel (2200 - 7000 lb/wheel)**

For static padfoot drum compactors, tamper foot compactors and sheepsfoot compactors, the amount of tip pressure exerted constantly varies as the number and surface area of the tips that are in contact with the ground changes. The depth of penetration can also affect the calculation. The pressure of the pad faces is expressed in kilograms per square centimeter (pounds per square inch).

Static compaction is used in applications where a gentle touch is required, either due to nearby buildings, materials that are fragile or where surfaces have low load-bearing strength. It is also used in situations where too much compaction force could draw free water to the surface.



Manipulation – Manipulation is a compactive force that rearranges particles into a more dense mass by a kneading process. The process is especially effective at the surface of the material lift. The longitudinal and transverse kneading action are essential when compacting heavily stratified soils such as clay-type soils. Sheepsfoot compactors and staggered wheel, pneumatic tire compactors are specifically designed to deliver this type of compactive force.

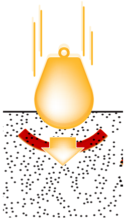
The manipulation force generated by pneumatic tire compactors is a product of two factors: the contact pressure and the wheel load. Adjusting either factor will change the performance of the compactor.

Manipulation compaction is useful to build a well-sealed surface to help the material resist the effects of water and weather.

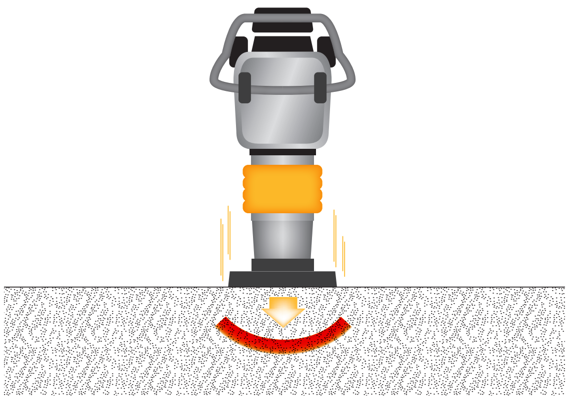
CONTACT PRESSURE FORMULA

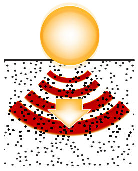
$$\underset{\text{kg/cm}^2 \text{ : bar}}{\textbf{CONTACT PRESSURE}} = \frac{\text{Wheel load (kg)}}{\text{Tire contact area (cm}^2\text{)}}$$

$$\underset{\text{kg}}{\textbf{WHEEL LOAD}} = \frac{\text{Compactor's operating weight}}{\text{Number of wheels}}$$



Impact – Impact creates greater compaction force than the gravitational force of a static load. This is because a mass in motion has velocity, which is converted to energy at the instant of impact. Impact creates a pressure wave that goes into the ground from the surface. Impacts are usually a series of blows. Impact blows of 50-600 blows per minute are considered low frequency ranges and are used on impact hammers and hand tampers. Impact blows of 1,400-3,000 blows per minute are high frequency and are used on vibratory compactors.





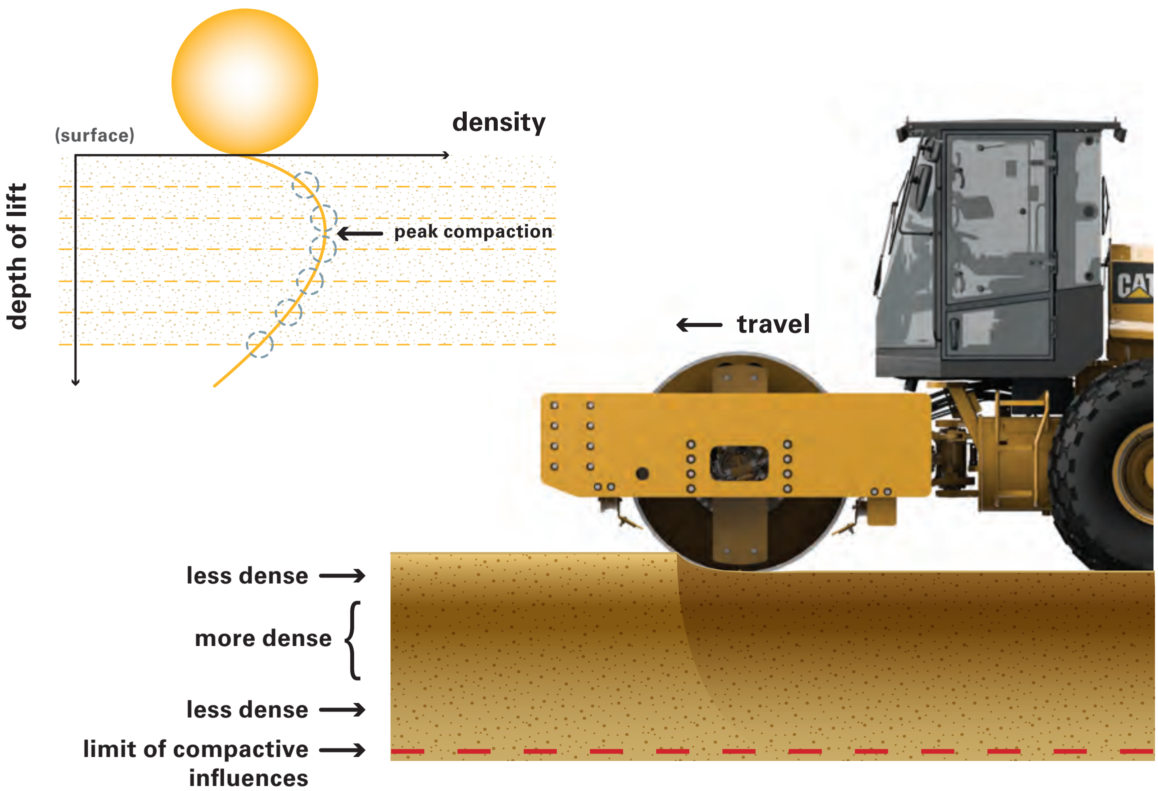
Vibration – Vibration is perhaps the most complex and cost-effective compactive force. More than 90 percent of the compactors sold in today's market are vibratory. This is because vibratory compactors can produce at the same rate as a static compactor that has about three times more mass. Vibratory energy makes a vibratory compactor more efficient than a comparably sized static compactor.

Vibratory compactors produce a rapid succession of pressure waves that spread in all directions. The vibratory pressure waves overcome the shear resistance 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 understand the dynamics of vibratory compaction: amplitude and frequency, as well as static linear load and the ratio of vibrating mass to suspended mass.

As a compactor works, the volume of soil compacted will not be uniformly compacted from top to bottom. A compactor of a certain mass will compact soil to a certain depth, but the degree of soil compaction will vary from the surface to the maximum depth of compactive influence. Generally, the surface soil will be less compact, the middling soils will contain a peak compaction, and the maximum depth soils will again become less compact.

Changing operating parameters can influence the depth of the compaction zones and alter the depth of the peak compaction zone, but it still will not change the fact that the soil will vary in compaction from top to bottom. This phenomenon is called the "gradient of compaction," and this data helps describe the suitability of a certain sized compactor or operating setting for specific compaction applications.

GRADIENT OF COMPACTION



It seems logical that when using a rolling compactor, surface soil should be the most dense– however, the peak density actually occurs below the surface, and decreases as depth lessens the influence of the compactor. This is called the Gradient of Compaction.

[DYNAMICS OF VIBRATORY COMPACTION]

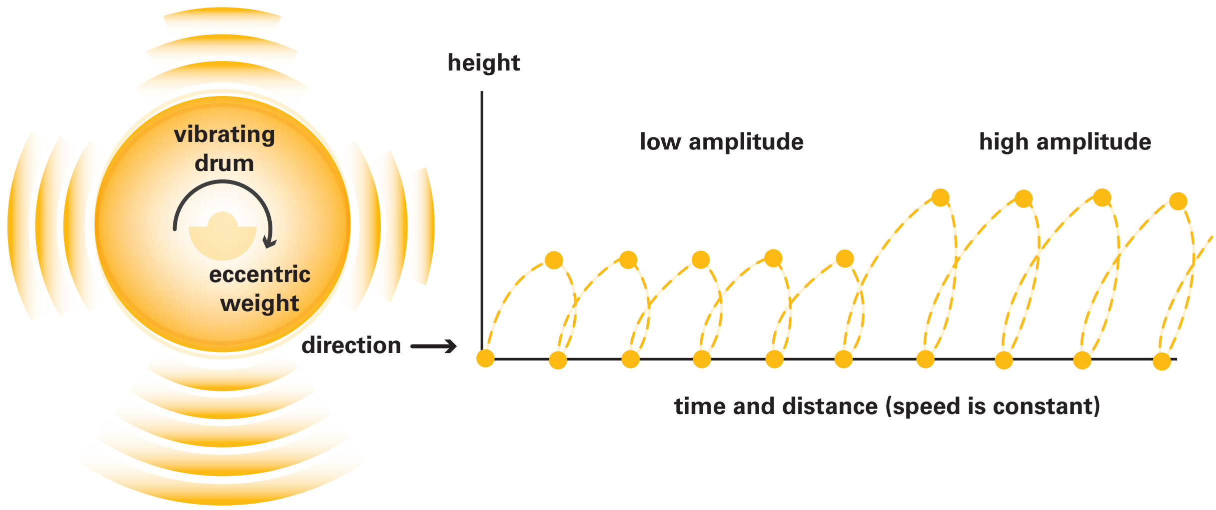
Amplitude – Amplitude is the measure of the distance of vertical movement from rest position to peak position of a vibrating drum. Manufacturers promote this nominal value, which is measured on a suspended drum. The real, working amplitude, however, is the product of the nominal amplitude and the coefficient of amplification, which is a ratio of the transmitted frequency to the resonant frequency of the machine and the ground being compacted. It can be more useful to think of amplitude as the distance the drum travels into the ground as it displaces and compacts soil.

By modifying the amplitude, an operator can vary the force and the movement (acceleration) of the drum on the material.

As soil nears maximum density, there comes a point where the soil can't absorb the compactive energy the vibratory compactor is delivering. At this point, the drum can bounce off the surface and a vibratory cycle can occur while the drum is suspended in the air. This phenomenon is called "de-coupling," or "double-jumping," and is accompanied by a distinct and uncharacteristically vigorous vibration affecting the entire machine. De-coupling can damage the machine and produce undesirable results on the soil being compacted, such as decompaction.

To stop de-coupling, the operator needs to decrease the amount of energy the machine is delivering to the soil by simply reducing the amplitude, which will lessen the amount of compactive force applied to the soil. Alternatively, the operator could work in static mode.

AMPLITUDE



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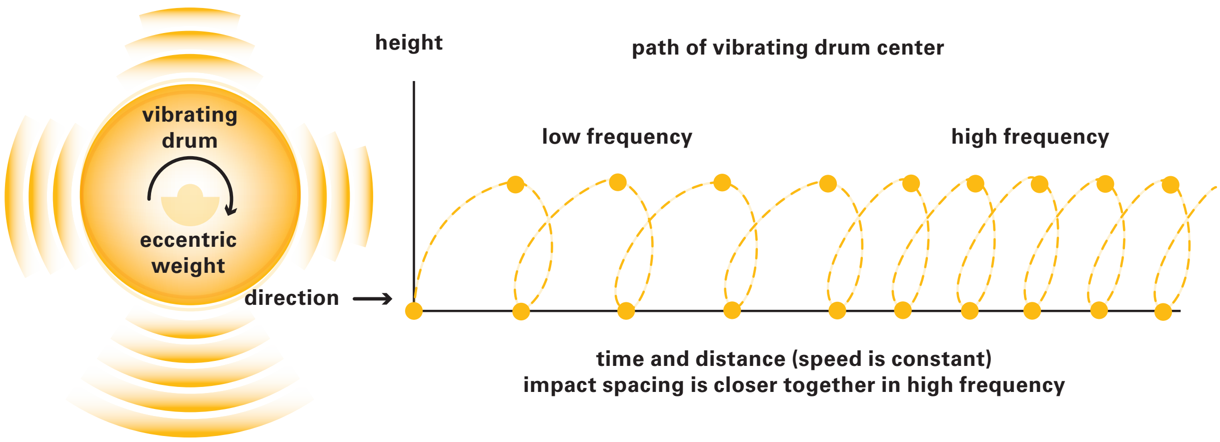


Frequency and Speed – Frequency is a measure of the number of complete cycles or revolutions of the eccentric weights around the axis of rotation over a given length of time. Frequency is usually expressed in units of hertz (Hz) or vibrations per minute (vpm). Typically, frequencies between 23-35 Hz (1380-2100 vpm) are used depending on material and amplitude setting.

The relationship between frequency and working speed is sometimes simplified to a rule of thumb that states that frequency and working speed should be adjusted to yield approximately one impact per 25-30 mm (1-1.2 in). A working speed that is too fast can cause "washboarding" (impacts spaced too far apart), and a working speed that is too slow negatively impacts machine productivity. There is an optimum speed and frequency for each compaction application, but they may not yield one impact per 25 mm (1 in). Maintaining uniform compaction is critical, and utilizing automatic speed control features to ensure balance of speed and frequency can help deliver that consistency.

Ratio of Vibrating Mass Over Suspended Mass – One might assume that if a vibratory compactor of a certain mass and amplitude can compact a certain soil with a certain degree of efficiency, then simply applying more mass and more amplitude would make the compactor more efficient on the same soil. This is not necessarily true.

On a vibratory compactor, the vibrating mass (drum) is isolated from the suspended mass (the rear frame), and the ratio between the two is a critical factor in determining the mass and amplitude the compactor can possess. The ratio is carefully balanced to allow the machine to optimize the amount of energy it can safely impart to the soil.


total operating mass


suspended (non-vibrating) mass


vibrating mass

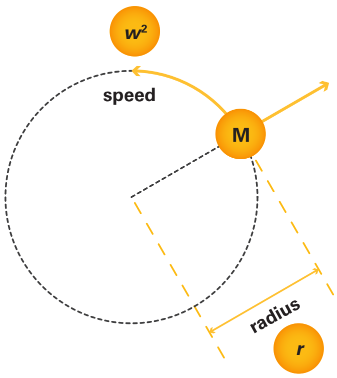
Resonance working against compactive effort

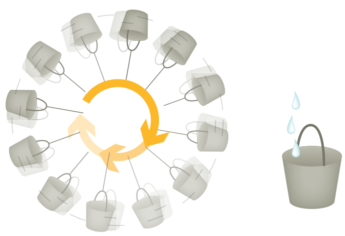
Resonance working together is harmonic convergence

Resonance – When the frequency of imposed vibrations on an object equals the object's natural frequency, the object will vibrate at resonance. In vibratory compaction, resonance is very important.

The interaction between the material being compacted and the vibratory machine causes the material and the machine to vibrate. The eccentric weights rotating inside the drum maintain this vibration at a frequency equal to the rpm of the eccentric weight shaft. At some conditions of the given frequency, the machine and material vibrate at resonance. The conditions that produce resonance depend not only on machine characteristics, but also upon the nature of the material to be compacted and its achieved degree of compaction. The ideal frequency to achieve the most efficient transmission of compaction energy is about 15 percent higher than the resonant frequency.

CENTRIFUGAL FORCE





centrifugal force = Mw^2r

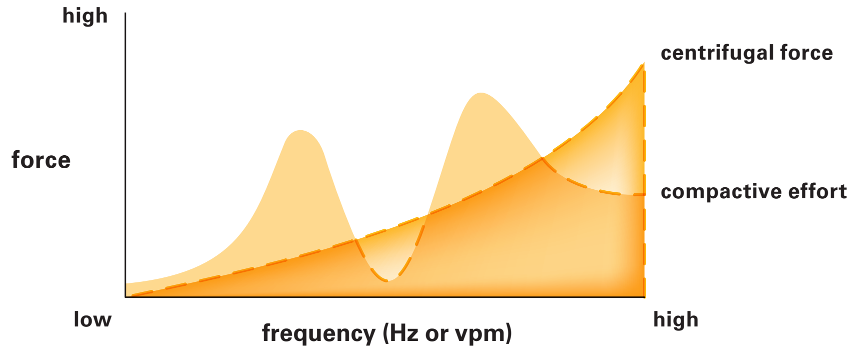
To calculate centrifugal force, the mass (M) of the eccentric weight is multiplied by the radius (r) of the eccentric weight rotation and by the speed of rotation (frequency) squared (w^2). The most significant factor in this equation is frequency.

Centrifugal Force – Vibratory compactors create centrifugal force with an eccentric weight or weights rotating inside a drum. The centrifugal force generated by the drum is analogous to the tug felt when swinging a bucket filled with water. The mass of the weights, their offset distance from the center of rotation to center of gravity, and the speed of rotation all contribute to the production of this force. Centrifugal force is a theoretical calculation and is frequently used to rate the productivity of vibratory soil compactors. But theoretical centrifugal force is not an accurate way to judge the capability of a machine. The true vibrating force depends on a complete interaction between the material being compacted and the machine.

FORCE AND FREQUENCY

This graph shows how theoretical centrifugal force increases as the frequency increases. However, the compactive effort that is actually transmitted to the soil varies as frequency increases. The compactive effort will show multiple "peaks" and "valleys."

Typically, there is a first peak representing a maximum value of the compactive effort, which quickly drops off and is followed by a second peak. Generally, this second peak will produce the higher value, and represents when machine productivity is at its best.



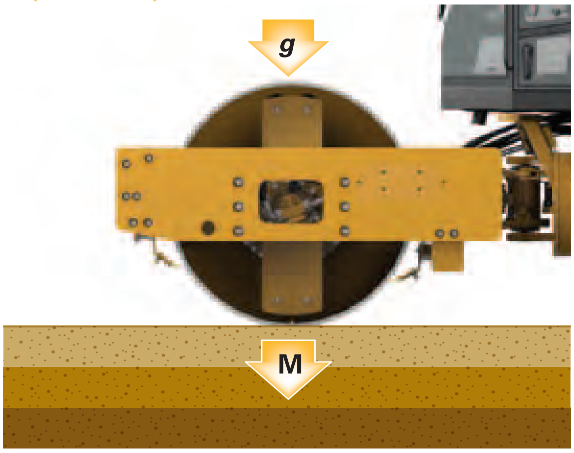
TOTAL APPLIED FORCE (F_{TA})

$$F_{TA} = F_C + F_S$$

Where: F_C is centrifugal force = $1100 (M)(r)\left(\frac{N}{1000}\right)^2$

and: F_S is static drum applied load = $M \times g$

- M — *mass of eccentric weight (kg)*
- r — *moment of eccentricity (m)*
- N — *rpm*
- M — *static drum applied mass (kg)*
- g — *acceleration of gravity* $\left(\frac{\text{meters}}{\text{second}^2}\right)$



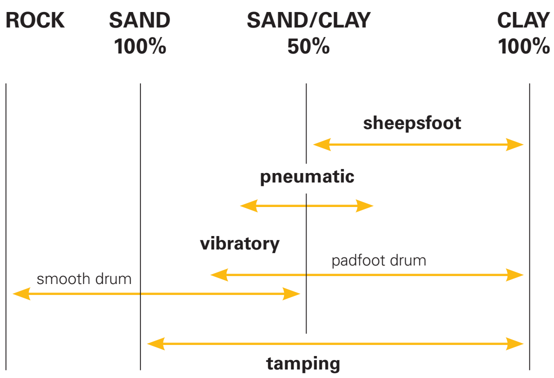
Total Applied Force – Total applied force is regarded as the maximum amount of vibratory energy that a compactor can apply to the ground. It is calculated by adding the static mass of the compactor to the centrifugal force. As with centrifugal force, caution should be used when using this calculation to compare the compactive capabilities of compactors.

[SOIL COMPACTION EQUIPMENT]

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

The application chart provides guidelines for matching equipment to job variables and soil types. There is no single compactor that will do all things in all applications. Each type has a definite material and operating range on which it is most economical. In many cases, there are applications where machines of different sizes and types can achieve the compaction target; but choosing the machine that is most suitable will complete the work most economically and efficiently due to reduced passes, reduced fuel use and less working time.

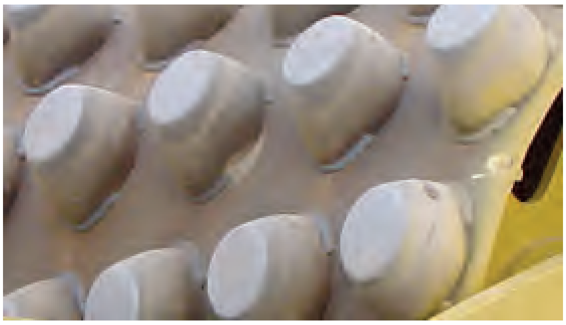
APPLICATION CHART



Vibratory Compactors – Vibratory compactors work on the principle of particle rearrangement to decrease voids and increase density and load bearing strength. They come in two types: smooth drum and padfoot drum. For increased versatility, smooth drum compactors can be equipped with optional padfoot shell kits, which allows the use of smooth drum rollers in padfoot applications, albeit with limited performance.

Smooth drum vibratory compactors generate three compactive forces: static pressure, impact and vibration. Padfoot drum machines generate the same forces, plus they also generate manipulative force. Vibratory compactors provide uniform compaction throughout the lift.

Density is achieved from the forces generated by the vibrating drum hitting the ground. Compaction results are a function of the frequency and amplitude of the blows, as well as the force of the blows and the time period over which the blows are applied.



Oval pads are a good match for cohesive soils and thicker lifts.

Square pads are best suited for semi-cohesive soils and thinner lifts.

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 1-2,5 km/h (0.6-1.6 mph) for rock and clay, and 2-5 km/h (1.2-3 mph) for gravel and sand will provide the best results.

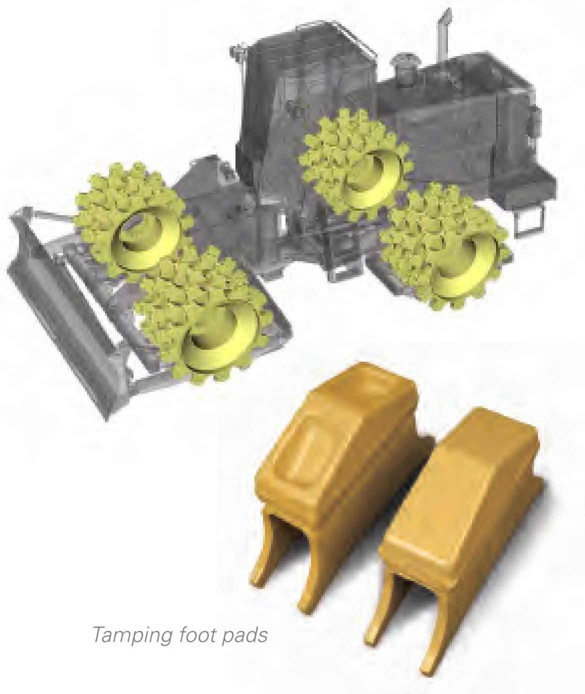
Smooth drum vibratory compactors were the first vibratory machines introduced. They are most effective on granular materials with particle sizes ranging from large rocks to fine sand. They are also used on semi-cohesive soils with up to 50 percent cohesive soil content. Lift thicknesses vary according to the size of the compactor. Whenever large rock is used in the fill, the lifts may be very thick—up to 1,2 m (4 ft) lifts are not unusual. One thing to remember when large rocks are in the fill is that the thickness should be about 300 mm (12 in) more than the maximum rock size. This permits lift consolidation without having large rocks protrude above the surface.

Padfoot drum machines expand the material range to include soils with more than 50 percent 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 achieves better compaction results. The pads are involuted to walk out of the lift without fluffing the soil and tapered to help them stay clean. The typical lift thickness for padded drum units on cohesive soil is in the 150-460 mm (6-18 in) range.

Caterpillar has two pad shapes available: square faced pads and oval-faced pads. Square pads perform well on semi-cohesive soils and thinner lifts of less than 150 mm (6 in). Square pads do a good job of sealing the surface.

Oval pads have less surface area than square pads, so they apply greater ground pressure than square pads. This allows the pad to penetrate deeper into the lift. Oval pads perform better on cohesive soils and thicker lifts of 150-460 mm (6-18 in). Oval pads do not seal the surface as well as square pads.

Caterpillar also offers a padfoot shell kit option for smooth drum compactors. The two-piece shell bolts onto the smooth drum, allowing the compactor to be used on cohesive soils like a normal padfoot drum. Both square pad and oval pad shell kits are available.



Tamping foot pads

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

Tamping foot compactors compact from the bottom of the lift to the top. Because the pads are tapered, they can walk out of the lift without fluffing the soil. Therefore, the top of the lift is also being compacted and the surface is relatively smooth and sealed. Tamping foot compactors are capable of speeds in the 16-32 km/h (10-20 mph) range, but they typically operate in the 10-15 km/h (6-10 mph) range.

Generally, 2-3 cycles (4-6 machine passes) will achieve desired densities in 200-300 mm (8-12 in) lifts although 4 cycles may be needed in poorly graded plastic silt or very fine clay. Tamping foot compactors are effective on all soils except clean sand.

Tamping foot compactors leave a fairly smooth, sealed surface so hauling units are able to maintain a high speed when traveling over the fill. Also, since dozer-equipped tamping compactors do both spreading and compacting, the contractor may be able to reduce the number of track-type spreaders.

Tamping foot compactors are best suited for large projects. They need long, uninterrupted passes to build up speed that generates high production. On lifts greater than 300 mm (12 in) thick, tamping foot compactors are about 2 to 3 times more productive than single drum vibratory compactors. The application, jobsite size and the economics behind decision-making will dictate which kind of machine is best.

Sheepsfoot Compactors – Sheepsfoot compactors derived their name from the fact that early Roman road builders would 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 compactor is very different from a padded drum or tamping foot compactor.

A sheepsfoot pad is cylindrical, usually 200 mm (8 in) long. The pad is circular and will range in diameter from 76-127 mm (3-5 in). The pads on tamping foot or padded drums are tapered with an oval or rectangular shape. And the pad face is smaller than the base of the pad—that's an important difference.

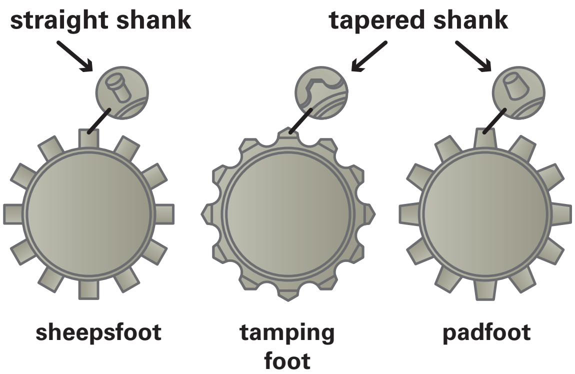
The pads on sheepsfoot drums penetrate through the top lift and actually compact the lift below. When a pad comes out of the soil, it kicks up or fluffs the material. The result is a loose layer of material on top. When more fill is spread, the top lift will be fluffed and the previous layer will be compacted. A sheepsfoot compactor truly 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 compactors 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 that deposit fill material, so haul cycle times are increased.

Plus, sheepsfoot compactors can work only at speeds from 6-10 km/h (4-6 mph), which cancels any benefit from impact and vibration. Pressure and manipulation are the only compactive forces exerted on the soil. Usually, 6-10 cycles (12-20 machine passes) are needed to reach target density on 200 mm (8 in) lifts. Sheepsfoot compactors are no longer widely used.

PAD CONFIGURATIONS



Pneumatic Compactors – Pneumatic compactors are used on small-to-medium size soil compaction jobs, primarily on bladed, granular base materials. Often, they are used as a finishing compactor after a vibratory drum compactor completes compaction of the lift. Pneumatic compactors are best suited for sealing the surface, special applications such as compaction of thin lifts, or special requirements dictated by the job.

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 and smooth the surface.

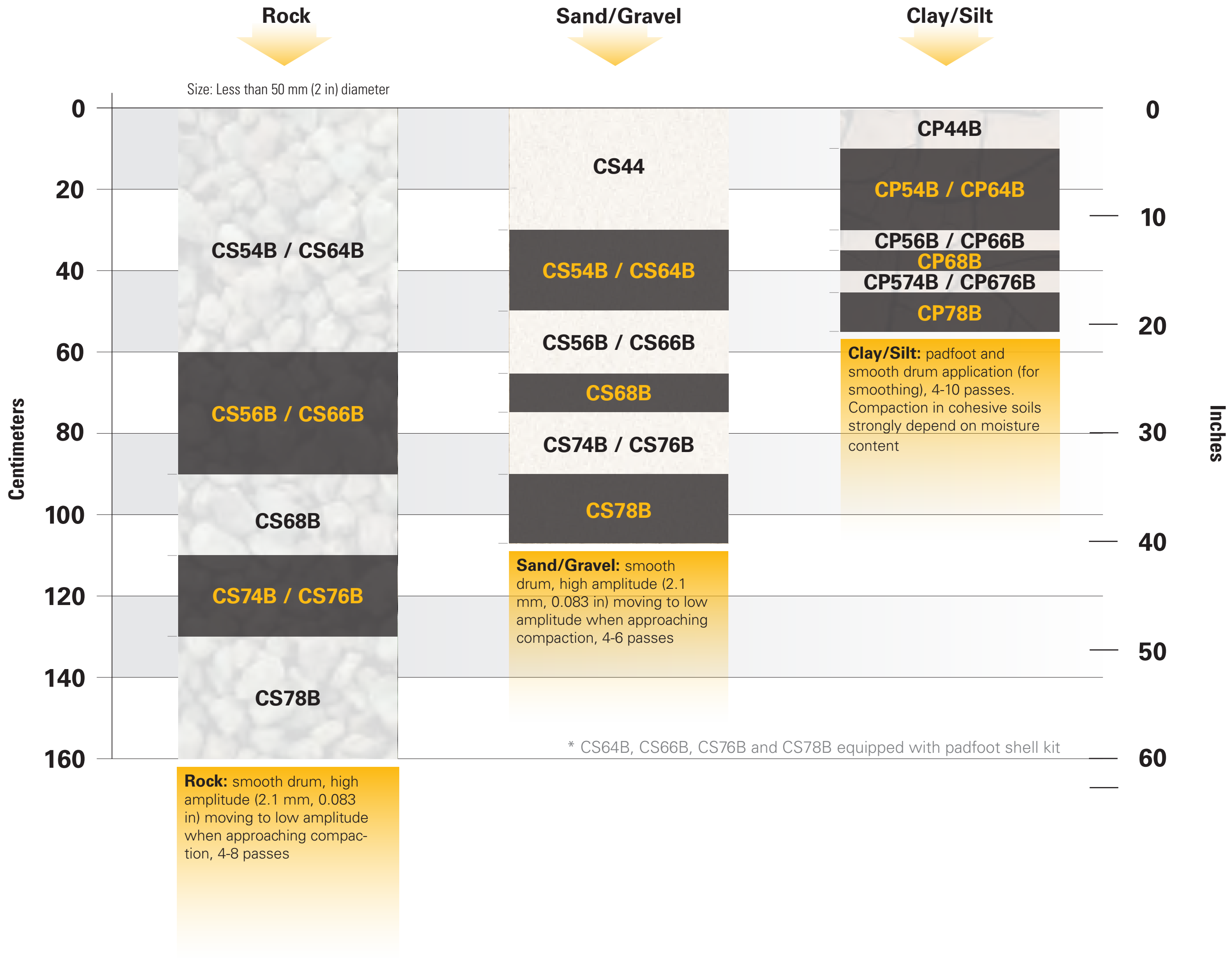
Pneumatic compactors can be used on soil and asphalt, an advantage that allows a road-building contractor to use one compactor for multiple stages of construction.

Rear Vibratory Plates – On non-cohesive material, single drum vibratory soil compactors can be equipped with rear vibratory plates, which provide a surface sealing that cannot be achieved with the single drum compactor alone. This enables the operator to account for the gradient of compaction: the single drum vibratory roller achieves deep compaction, and the vibratory plate compacts and seals the surface.

When the vibratory plates are not needed, the plates should be removed from the machine because their weight can reduce the linear load of the drum, which may mean that additional passes will be required to achieve the compaction target.

COMPACTION DEPTH

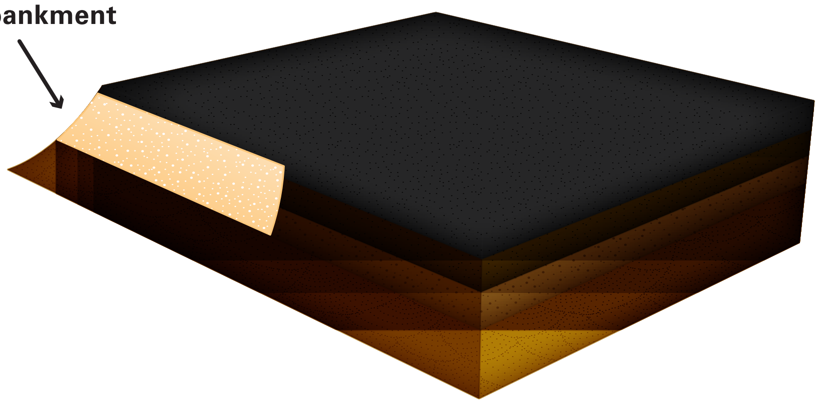
Assumes density specification is 95% of Standard Proctor and can vary substantially due to different soil conditions.




SIXT

Unit 4
APPLICATION AND CONTROL OF QUALITY

Project parameters have a significant impact on the placement of soils and their compaction. Learning to maximize results under wide ranges of conditions will help you maximize efficiencies and avoid rework. Time-tested and new methods of measurement are also beneficial to helping you better manage your compaction projects.



[THE ELEMENTS OF JOBSITE STRUCTURE]

Like any kind of structure, a road is composed of specific components that perform specific functions. Terminology can vary regionally, but these components work together to support the load of the traffic upon it.

Natural or Native Soils – Sometimes called the "substrate," "subgrade" or "basement soil," this is the foundation of a roadbed and consists of the soils and materials that are naturally occurring without human or chemical modification. During the process of building a road, the surface soils are stripped away to provide a level, even grade. The exposed materials at the bottom of the cut are the natural soils. If these existing materials are insufficient to support the load of the road structure, they are modified or replaced with suitable materials. Modification can be mechanical, which includes compaction, reinforcement with geosynthetics or the incorporation of aggregates; or chemical, which includes the incorporation of binders such as Portland cement; or a combination of mechanical and chemical. The goal is to improve the load-bearing capabilities of the material. Ultimately, this foundation must provide adequate support for the structure upon it.

Embankment – An embankment is any fill where the top is higher than the adjoining surface. The roadbed is designed to be a certain width and support the road at an engineered elevation and grade. In some cases, naturally occurring undulations of the terrain may require the use of fill material to provide an adequate subgrade for the roadbed. Embankments are constructed for this purpose by placing and compacting appropriate aggregate materials to build up the terrain until it meets the required elevation.

Sub-base – The primary functions of this layer are to distribute the load of the structure it supports into the substrate and provide a relatively even grade upon which to place the base course. However, the sub-base also can provide a number of additional functions depending on the composition of the substrate materials, such as filtering functions or acting as a barrier against capillary water. Typically, this layer is composed mostly of substrate materials that are modified if necessary and compacted. There can be multiple sub-base layers, as secondary lifts can be added if required to support greater loads. Generally, the aggregates used in the sub-base will be larger than the aggregates used in layers the sub-base supports.

Base – The base layers serve a similar function to the sub-base. They also distribute the load they carry and provide protection from the effects of water and frost. There can be a single base or multiple base layers depending on the load requirements. The base is composed of an engineered gravel mix with a particle size smaller than that used in the sub-base.

Asphalt layers are placed upon this foundation. The quality of the foundation will affect the durability of the asphalt layers placed upon it. For more information about the asphalt layers, consult Caterpillar's companion "Guide to Asphalt Compaction."

[SOIL COMPACTION PROCEDURES]

JOB LAYOUTS

Before laying out a compaction job, the main questions a contractor must consider are:

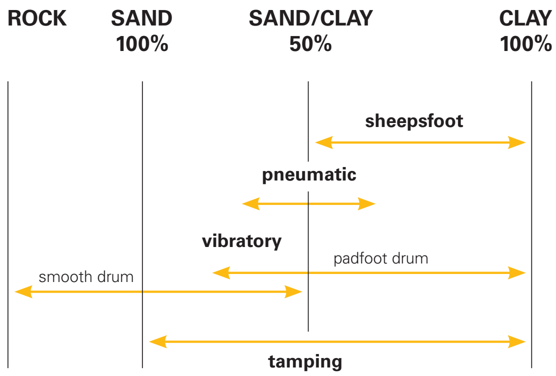
- What is the soil gradation and classification?
- What is the maximum dry density and optimal moisture content?
- What is the compaction requirement (%)?
- What are the compactor settings and speed?
- What is the lift thickness?

A contractor needs to know the material, the requirements and the application for each type of equipment. Once these variables are understood, the contractor can begin to think about the best approach to the job, and may also consider available technologies to apply.

Compactor Application and Sizing – Operating characteristics for the various types of compactors are shown in the accompanying illustration. For comparison, the illustration below shows application ranges where each compactor is most effective. The machines may overlap in these ranges and it is not uncommon to see machines working on materials outside their normal application zone. Therefore, the information presented in these charts should be considered strictly as average application guidelines.

Sitework and Embankment Applications – Sitework refers to a broad range of earthen construction, including: foundation preparation, grading, backfilling and basin filling. It could be a building site, a road, or some other surface or structure.

APPLICATION CHART



OPERATING CHARACTERISTICS FOR SOIL COMPACTION EQUIPMENT

Self Propelled Only

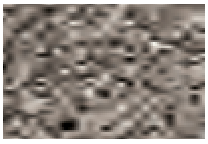
Machine	Sheepsfoot	Pneumatic (15 ton and up)	Tamp Foot	Vibratory
compacted lift thickness - mm (in)	150 - 300 (6 - 12)	150 - 300 (6 - 12)	150 - 300 (6 - 12)	150 - 600 (6 - 24)*
average working speed - km/hr (mph)	6 - 10 (4 - 6)	6 - 19 (4 - 12)	16 - 32 (10 - 20)	2 - 8 (2 - 5)
cycles (1 cycle = 2 machine passes)	6 - 10	3 - 8	4 - 8	2 - 4

**Depends on compactor size and compaction target*

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 450-1200 mm (18-48 in) lifts. How the material is spread before compaction is vital. Tractor spreading in layers creates uniform fill because the dozer blade does some reorienting of the rocks and the tracks provide some compaction. Therefore, a relatively dense and even surface is prepared for the compactor.

Heavy compaction forces are needed after spreading to relocate large stones for density and stability. The largest smooth drum vibratory compactors are selected for this job. Even so, compactors are subjected 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 setting, 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 contain less than 10 percent fines is easily compacted, especially when they are nearly 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.

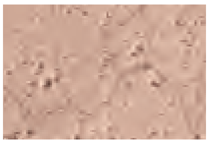
If the sand and gravel contain more than 10 percent fines, the soil is no longer free draining and may become elastic when the water content is high. This type of soil has optimum moisture content where maximum density can be reached. Drying of the wet soil may be necessary to reach the optimum moisture 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.

When moisture content is below the optimum, water may be added to ensure that proper compaction can be reached.

Silt – Silts are non-plastic fines that are usually compacted with smooth drum vibratory compactors. 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 material may need to be drained better. Silty soils that also contain clay may have considerable cohesion. On these soils, padded drum, tamping foot or pneumatic compactors will achieve better results.



Clay – Clays have plastic properties, which means 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.

Often in clay compaction, the main problem is 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 only be done in warm and dry conditions, even using discs and soil stabilizers. Prolonged rolling with sheepsfoot compactors is sometimes done to lower the moisture content.

Even at the optimum moisture content, clay requires a higher compactive effort and a thinner lift thickness compared to non-cohesive soils. Padded drum compactors work best because as the pads penetrate the soil, they break the natural cohesive bonds between the particles. Pneumatic 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 using vibratory padded drum compactors.

When moisture content is too high, opening up the soil speeds drying time.

Base and Sub-base Applications – Bases and sub-bases are the layers constructed on top of an embankment or natural ground surface. These layers serve as the foundation for placement of a surface structure such as a road or a building. They increase in strength as they near the finish surface. The materials used in these layers depend on the type of loads the road or building must support.

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

Natural (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 capacities and control other factors such as permeability, capillary action, and shrink and swell.

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

Treated Soils (Soil Stabilization) – Mixing chemicals with natural or imported soils can substantially improve the soil's stability and load-bearing characteristics. This is called soil stabilization.

After lime or cement has been mixed into the soil, the soil should be compacted with a vibratory compactor. The type of compactor used will depend on the soil's original, untreated characteristics; but generally, a vibratory compactor of 15 tons (33,000 lb) or greater should be used. Where a large volume of cohesive soil is involved, a tamping foot compactor may be more economical than a vibratory compactor. Smaller volumes may be compacted with a pneumatic compactor.

At the beginning of the work, it is recommended that you conduct a stabilization suitability test to ensure that the results are sufficient.

Soil Stabilization improves the engineering qualities of a soil.

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. Plus, the compaction results are more predictable. However, these compaction advantages are offset by the expense of crushing and the often-longer hauls to the project site.

Crushed rock is usually hauled to the job in end-dump trailers and placed on the grade with a motor grader or spreading machine. The base material is then spread and shaped in lifts ranging from 150-250 mm (6-10 in). After spreading, compaction is accomplished by smooth drum compactors (static or vibratory) or pneumatic compactors.

[SOIL COMPACTION TIPS]

Despite its simple appearance, soil compaction can be one of the most difficult elements of any construction project. Many manufacturers offer options on their compaction equipment that allow the operator to adjust machine vibration, frequency and amplitude to meet job specifications.

There is no easy way of adjusting the working parameters of a compactor according to the material it is compacting. Trial-and-error is often he best method. Obviously, the user will need to select a compactor of the appropriate size (drum width, weight, etc.) to match the production 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—then analyzing performance and making adjustments.

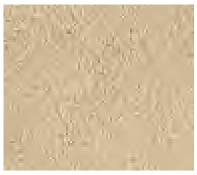
Manufacturers are building more technology into their machines that can assist the operator in maximizing efficiency. But, even with increasing technology and sophistication, to achieve the best soil compaction results you may have to review some basic principles of soil compaction that have proven themselves on construction projects for years. Following are some soil compaction tips to provide basic guidance.

WHICH ROLLER FOR THE APPLICATION?

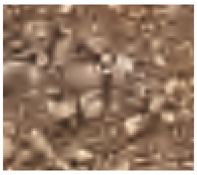
COHESIVE MATERIAL
Thin layers
Single-drum roller (padfoot)

FINE MATERIAL
Water sensitive
Single-drum roller, smooth or padfoot

FRICTION MATERIAL
(sand 0,063-2 mm/0.002-0.07 in)
Free draining if fine content < 7%
Single-drum roller, tandem roller, pneumatic tire roller



COARSE GRAINED, FREE DRAINING
Friction material
Single-drum roller, tandem roller



COARSE GRAINED
(gravel 2-63 mm/0.07-2.5 in)
Free draining
Friction material
Single-drum roller, tandem roller

COARSE MATERIALS
Heavy particles
Large plates, large single-drum roller (>12.7 tons)

	Permeability	Foundation support	Pavement subgrade	Expansive	Compaction difficulty
Gravel	Very high	Excellent	Excellent	No	Very easy
Sand	Medium	Good	Good	No	Easy
Silt	Medium low	Poor	Poor	Some	Some
Clay	None+	Moderate	Poor	Difficult	Very difficult
Organic	Low	Very poor	Not acceptable	Some	Very difficult

Uniformity of Lift, Speed and Rolling Pattern – The structure of buildings and roads depends on soil bases that are not only compacted to specification, but are compacted uniformly as well. Variations in base density can lead to potholes or wheel ruts in roads and foundation settling under buildings. One of the biggest causes of soil density variations is the use of different soil types that are placed side by side.

Because different soil types will compact differently and yield different compaction results, effort should be made during construction to utilize similar material for each lift. If different types of material are required, try to use the same type for each lift—do not use different material in a horizontal spread. This can be critical in achieving uniform compaction results.

Another cause of density variation is inconsistent moisture content. Because it is more difficult to compact soil that is too dry or too wet, the optimum moisture content as determined by the Proctor Test should always be targeted during compaction throughout the entire jobsite. This will help achieve the most uniform and dense results possible.

Lift thickness is usually not tightly controlled, except perhaps for a base course beneath a pavement surface. If all other factors, such as moisture content and material type, are kept constant, uniform lift thickness will lead to uniform density across the jobsite. Neglecting lift thickness could result in failing to meet the job specifications.

Other factors that can affect compaction and are often given inadequate attention are the coverage and pass counts. Parameters such as the number of passes, compactor speed and vibratory settings can be easily controlled. Intelligent compaction technology, such as Cat Compaction Control with GNSS mapping capability, can provide a visual reference to ensure that proper coverage and pass counts are maintained. Uniform coverage is more efficient and will be more successful than randomly compacting the material.

Lift Thickness – Compactor technology is continually advancing and offering more options and variations to the compaction process. However, after equal compaction effort is applied—even with the most advanced compactor—relatively thick lifts of material will be less dense than thinner lifts. There are exceptions to this rule, but a lift thickness should be sought which optimizes production rates based on required density and minimum compactor passes.

The condition of the previous lift or underlying base will also have an effect on achieving compaction. If a sub-layer has not been compacted thoroughly, it will contain areas that are relatively soft. In turn, compaction on the next lift will have varied, undesirable results. Each lift should be uniformly and thoroughly compacted to ensure subsequent lifts can be successfully compacted as well.

Compactive Effort – Compactive effort is the amount of energy imparted to the soil in order to rearrange and compact the soil particles. Varying machine parameters such as weight, width, tire pressure, vibration amplitude and frequency can change compactive effort. Some of these parameters can be adjusted on a single machine. Others, such as width, may require a different machine in order to alter compactive effort. Certain magnitudes of these parameters are necessary for any given project.

Working Speed – In general, travel speed plays an important part in construction productivity; the faster the machine, the faster the job is complete. However, with vibratory compactors, unlike all other types, productivity will generally increase by decreasing the travel speed. There is an optimum economical speed that will allow a compactor to achieve required compaction.

General Rules of Soil Placement and Compaction – Following are general rules that you, your jobsite management and operators should consider at the start of each compaction project.

- When placing a new lift of soil material, spread material over the entire area uniformly. Avoid placing soils that have excessively high moisture content. Spread the material with a slow-moving dozer and shape the appropriate profile. Do not bury saturated layers with new materials.
- Surface cavities or areas with visible segregation should be remedied by adding well-graded material of the same composition.
- Immediately after spreading is complete, compact the soil, starting from outside and working toward the middle of the area.
- Embankment/shoulder areas must be compacted as well; compact the shoulder from the outside edges and work toward the middle areas. Smooth and seal the surface.
- When working with materials that are susceptible to weather, all placed soil should have a side slope of about 6 percent to prevent the accumulation of surface water.
- When poor weather occurs, compact each lift by working a single drum-width strip until it is fully compact. Then move over to the next strip, repeating the process and working your way across the lift until the entire area has been compacted. Be sure to smooth and seal the surface at the end of the day to prevent further water penetration.
- When compacting a flexible base, it is advantageous to use low amplitude with high frequency if the base is adequately rigid. Use high amplitude and medium-to-low frequency when the base is being compacted together with the first lift.
- Using a combination of static and vibratory compaction—vibratory first followed by static—may yield the best results.

[COMPACTION MEASUREMENT METHODS]

Density has been the traditional method of quantifying soil compaction in the lab, and density has also been the most common historical method to set and measure compaction requirements in the field. Laboratory tests (such as Proctor) determine the moisture content at which maximum density can be attained. Field target densities are specified as a certain percent of the maximum laboratory dry density.

Generally, required field densities will be 95 percent of Standard Proctor for embankments and up to 100 percent of Modified Proctor for roadway structures. Likewise, the moisture content must be within a range of the laboratory determined optimum moisture content.

Point-by-point field-testing has long been required to ensure that the two important elements—target density and moisture content—are being maintained to specification throughout a particular construction job. These tests can also indicate the effectiveness of the compaction equipment and construction methods being used. Recently, machine-integrated compaction measurement methods have become more accepted as a means to determine the quality of compaction on the jobsite.

Many authorities are now requiring what is referred to as "intelligent compaction," which is the augmentation of machine-integrated compaction measurement systems with mapping systems that tie measurements to their locations on the site, as well as provide data for later analysis and documentation.

THE EVOLVING HISTORY OF COMPACTION MEASUREMENT

historic methods

- Process Control/Method Specifications
- "Point-by-point" testing
  - *Troxler/Nuclear Gauge*
  - *Penetrometers*
  - *Deflectometers*
  - *Plate Load Tests*

Relatively accurate

Typically samples less than 1% of total work area

machine-integrated compaction measurement

- Accelerometer
- Machine Drive Power (MDP)

Realtime indications of stiffness or load bearing strength to operator

Difficult to correlate with historic point-by-point measurements

Variability of measurement in certain soil types or applications

intelligent compaction

- Adds satellite mapping capabilities
- Augments machine-integrated compaction measurement by correlating measurements and machine data with the exact location they were taken
- Provides detailed maps to visualize work completed
- Provides data for analysis and documentation

The following highlights some of the most common methods. Keep in mind that each testing method measures soil properties differently (e.g. density, strength, etc.) and as such, attempts to correlate between the tests should be done with a physical understanding of the differences. Further, the very nature of the point-by-point test procedure requires assuming that the results of the point test are valid across untested neighboring areas or the entire jobsite.

Field Measurement Methods (historic) – *Measurements related to Soil Density:* Two basic methods are utilized to measure soil density in the field:

1. **Measure the response of soil to radioactive particles with a device called a Troxler or "nuclear density gauge."** These devices have become the most common method of measuring soil density in the field, but they have the disadvantage of requiring a license to use and periodic monitoring and testing of the nuclear radiation source in the device. Paperwork and permits are often required to transport the devices.

   The device provides an indication of moisture content at a depth of about 50 mm (2 in) and density at a depth of 300 mm (12 in) or less by emitting neutron and gamma ray radiation, respectively, into the soil being tested. The test is quick and can be performed without disturbing the material. Best results are obtained in homogeneous soils.

   There are three basic procedures of measuring density with a nuclear gauge—direct transmission, backscatter and use of the "air gap method."

   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 50-300 mm (2-12"). 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 compromised and composition errors are likely. This method works best in shallow depths of 50-75 mm (2-3 in).

A Troxler, or nuclear density gauge

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

   Some 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 with high salt and/or radioactive content. Ground vibrations from construction equipment can also be a source for errors in the measurements.

The sand cone method has proven accuracy.

2. **Excavate and weigh a volume of soil and measure the volume of the hole from which the soil was excavated.** Weighing a soil sample is direct so long as an accurate scale is available. Measuring the volume of the hole where the soil sample was excavated is not as straightforward, but a couple of procedures have been developed and used with reasonable accuracy. The following describe two examples:

   Sand-Cone Method – The sand-cone method is a multi-step procedure that is more time consuming than the Troxler or nuclear density gauge method, but it has proven accuracy. It is sometimes used in conjunction with the nuclear method to verify the calibration of the nuclear density gauge. This method focuses on measuring the volume of sand required to fill the void from which the soil sample was removed. Sand easily flows into a void and has consistent density, meaning the sand will not have changed density significantly when transferred from a container into the soil void.

   Water Balloon Method – The water balloon method is also called the Washington Densometer Test. The first three steps of the test—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, the Washington Densometer is used. The densometer, a fluid-filled device, is placed over the hole. 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 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 can also be calculated by dividing the wet unit weight by one plus the moisture content.

   Limitations to the water balloon method are: the length of time needed to obtain results and the fact that accuracy depends on the ability of the balloon to conform to irregularities in the sides of the hole.

A Dynamic Cone Penetrometer in use.

Measurements related to Soil Strength and Soil Stiffness – Soil density has been the historical measurement for soil compaction, both to set requirements and to qualify results. However, there is a growing trend to use measures of soil compaction more directly related to the engineering requirements, which are most often soil strength. There are several strength measurements used in the field, some of which (but not all of which) will be described in this guide. The strength measurements used in the field fall into three basic categories:

1. **Resistance of the Soil to Penetration –** The most commonly used soil penetration measurement is a *Dynamic Cone Penetrometer (DCP)*. The test is a measurement of the force/energy or shear/frictional strength required to penetrate a small cone into the soil with a fixed-weight hammer that drops a known distance. This device can be used to estimate the California Bearing Ratio and bearing values in newtons per square millimeter (pounds per square inch) to a depth of 1830 mm (72"). Improper use of the drop hammer, or incorrectly counting hammer blows and the change in depth per blow (or series of blows), will cause measurements to be erroneous. Use in rocky soil also produces questionable results.

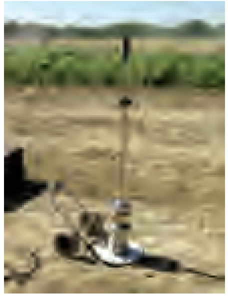
   The common size cone used has a 20 mm (¾ in) base area with a 60-degree included tip angle. The cone is penetrated by a falling weight striking a plate that then imparts the dynamic force to the cone, causing it to penetrate the soil. Data is recorded as the penetration distance per blow. In harder soils, several blows will be needed to penetrate the cone and the number of blows and distance of penetration is recorded.

The DCP has the advantage of measuring soil strength to greater depths than other methods. A cone can be penetrated 1 m (39") and beyond, although the friction of the soil on the cone penetrometer shaft can influence readings— particularly beyond a meter of depth. The DCP will not work on very hard materials, such as a lime-stabilized soil after curing. It is physically intensive and can be tiring after repeated use.

2. **Response of Soil to a Falling Weight –** The underlying principle is: stiffer soils will cause more rebound when a weight is dropped onto the surface. One such device is the Light Falling Weight Deflectometer (LWD). A heavier version is the Falling Weight Deflectometer (FWD).

   Light Falling Weight Deflectometer (LWD) measures soil stiffness or elastic modulus of the surface of construction layers by dropping a fixed weight a known distance onto a base plate equipped with accelerometer(s) and other sensors. By detecting the deflection or motion of the base plate, the dynamic modulus of elasticity of the soil is calculated in megapascals (MPa) to a depth of about 150 mm (6 in). Use requires the ground surface to be smooth and flat. Tests show that deflectometers from different manufacturers will produce differing results for the same soil condition.

   Falling Weight Deflectometer (FWD) is a larger version of the handheld device discussed previously. The FWD is trailer mounted and not as easy to transport, but it uses the same principles to strike a much larger plate, creating a larger zone of influence and measuring to greater depths. Whereas the LWD can measure to a depth of 150 mm (6"), the larger FWD version is capable of energy that may easily transmit 1 m (39") into the soil, more closely resembling the impact created by a vibratory compactor.



A light falling weight deflectometer

3. **Resistance of Soil to a Static Weight –** This method is similar to the falling weight tests because it measures the stiffness of the soil from the soil surface, but different because it uses a static pressure rather than a dynamic force. Because the purpose of soil compaction is to produce a stiff soil, you need to use a lot of force to effectively deflect the soil with a static pressure. To measure soil stiffness requires a plate size approximately equal to the desired depth of measurement—this means a plate closer to 30 cm (12") in diameter is needed rather than a plate in the centimeter- or inch-size range.

   Plate Load Test – Several plate load test devices are available with various plate diameters. The larger the diameter of the plate, the more force needed to create measurable downward motion of the plate into the soil. As the plate is loaded, the deflection for a given force is measured and plotted. This gives the soil modulus (stiffness) and indicates soil load-bearing capability. Large plate load tests require several thousand pounds of force to drive the plate—typically 300 mm (12 in) diameter—downward into the soil. Available construction equipment often is used as the load source. Plate load test measurements are directly used in pavement thickness design.

Preparing a plate load test

A proof roller

Other Field Measurements – Finally, other field measurement methods that measure compaction, but do not specifically fall into the categories outlined previously, are utilized. These methods have been used for many decades on their own or in conjunction with other tests to further assess the capability of a soil to support a load. Many are still in use today.

1. **Proof Roller –** Proof rolling has been commonly utilized in North America as an alternative method to spot testing in order to directly identify how the compacted surface will respond to an applied load. The test can identify soft spots and ensure a uniform ability to support a load. The process involves rolling a heavy mass on wheels over a compacted surface and measuring the depth of rutting or deflection. Excessive rutting reveals unsuitable compaction.

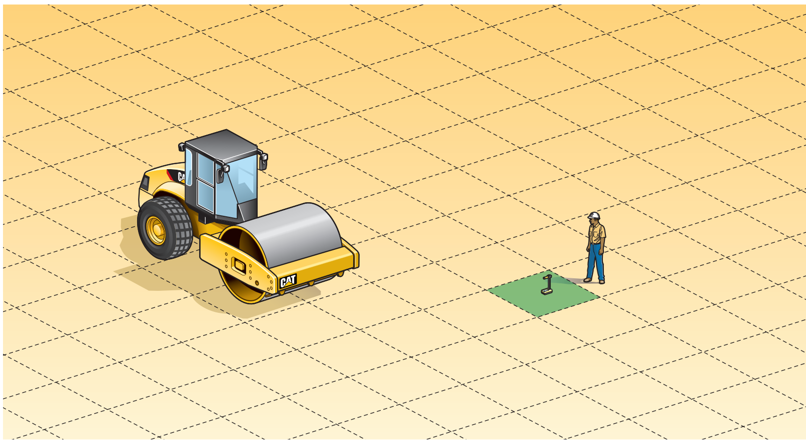
Proof rolling is not as direct a measure of soil strength as some methods previously described, but it may be a more direct measure of compaction quality when the purpose of compaction is simply to increase ground stiffness for structures such as roads and parking lots. If the soil base does not rut under the weight of a loaded proof roller, then it should not deflect under traffic; that is, assuming that the road is well drained and remains stable over time.

Of all the traditional procedures for testing compaction, proof rolling is the method that provides the greatest testing sample size, as it economically tests a much greater footprint than spot-testing single locations can.

2. **Portable Soil Moisture Oven –** The portable soil moisture oven is a device used to provide a measure of soil moisture content to correlate with the load-bearing measurements taken by the other devices. Measurements from the other devices discussed here are not valid without knowing the soil's moisture content.

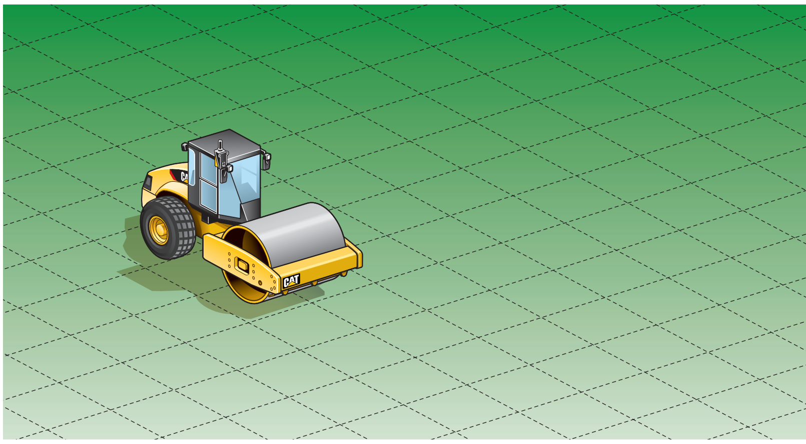
A portable soil moisture oven

Machine-Integrated Compaction Measurement Methods – Traditionally, compaction has been largely an exercise of trial and error. Operators, lacking dependable data about the state of the soil, rely on their experience and senses to judge when compaction is complete. Or, a method specification provides a procedure determined by engineers to produce satisfactory results if followed properly. The compacted soil is then spot-tested for a predetermined area. Any test results found to be insufficient result in rework for that area. Alternatively to spot testing, some areas utilize proof rollers, typically a heavily loaded trailer or a dump truck. As discussed previously, the proof roller is towed over the site and the depth of the wheel ruts indicates areas where compaction is poor.



Traditional measurement systems analyze only a small proportion of the compacted area.

Regardless of the method of checking compaction quality, operators are essentially guessing about the quality of their work as the project progresses. And the method of verifying quality utilizing spot checks and proof rollers tests a proportionally small area of a much larger total area that has been compacted. This leaves open the possibility that many areas may not be adequately compacted, a problem that can become quite costly if it causes a future failure of the building or road.



Machine-integrated compaction measurement analyzes the entire compaction area.

Machine-integrated compaction measurement systems change all of that by empowering operators with data about the state of compaction. Trained operators can use machine-integrated compaction measurement to determine when compaction meets specification, or when an area may have moisture issues. Machine-integrated compaction measurement can alert them to the presence of buried objects that may affect the quality of compaction, such as clay balls, tree trunks or large rocks.

Machine-integrated compaction measurement systems provide a prediction or indication of soil stiffness.

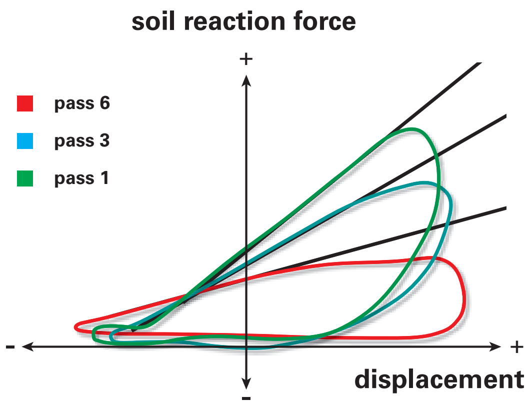
What does machine-integrated compaction technology measure? It is important to understand that these systems do not measure the density of the soil, although the term density is frequently used when discussing results. Because of the variability of compaction work, they do not measure anything directly. What they do is measure a number of factors that provide a prediction or indication about the stiffness of the soil. As previously stated, stiffness is the ability of a certain shape and composition of soil to resist deformation or deflection under the influence of a load. It is a better indication of load-bearing capacity than material density, because certain dense materials can be brittle under load. The material needs to be flexible, but not break.

Two different kinds of measurement technologies are available: accelerometer-based systems and energy-based systems. They make measurements in completely different ways, and correspondingly, what they measure is different as well.

Accelerometer-based Measurement – Accelerometer-based systems are available from most manufacturers. They utilize an accelerometer mounted on the drum to measure the reaction of the soil to being struck by the vibrating drum. Two different methods are employed to make these measurements.

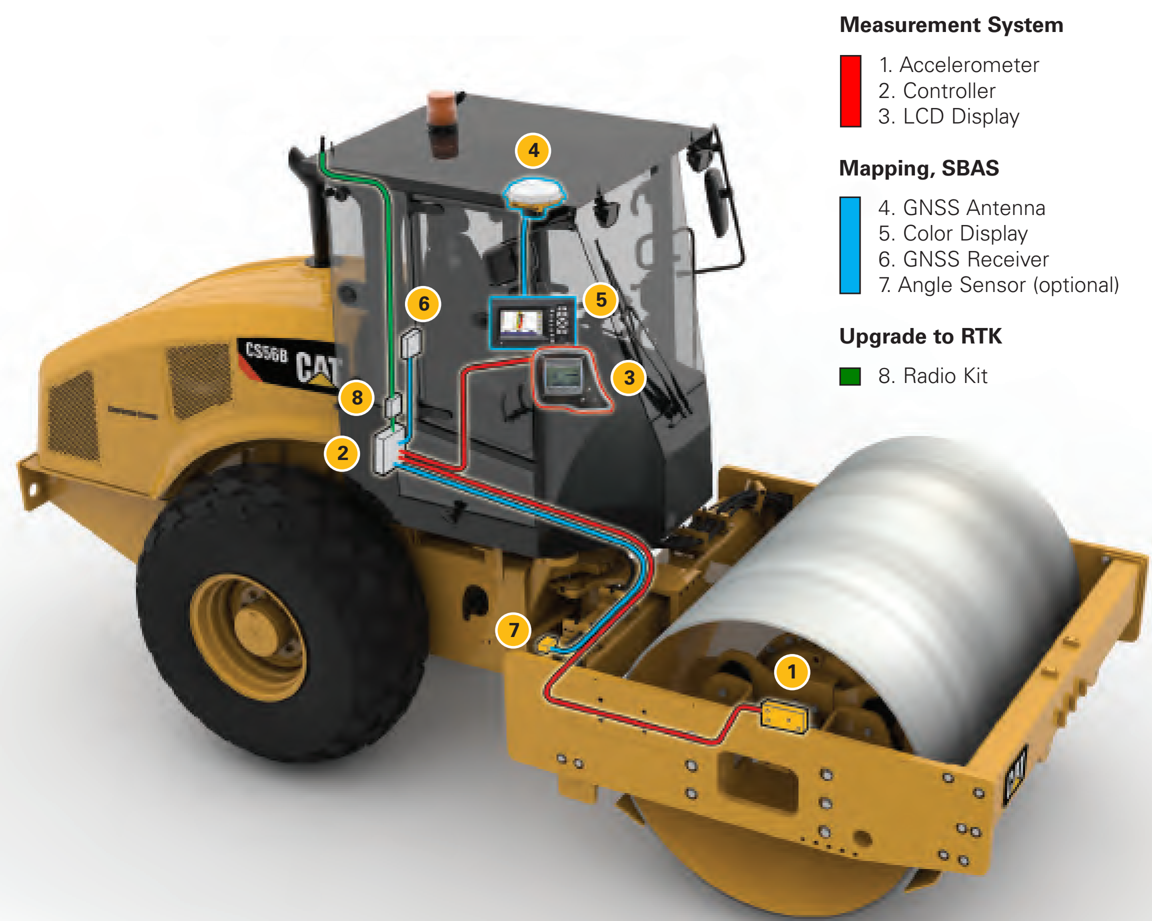
One method is called the Force Displacement method. It uses an accelerometer mounted on the drum axle to measure drum displacement. By measuring the acceleration of the drum and knowing the characteristics of the drum, vibrator and overall machine weight and distribution, a calculation of the force required to achieve a certain displacement is made. The stiffer the soil, the higher the force required to cause the drum to move into the ground a certain depth; or, a constant force will cause the drum to move downward less into the soil as the soil becomes stiffer. Because the contact area of the drum varies with impact into the ground, this method is an estimate and not an exact measurement.

FORCE DISPLACEMENT



The steeper the slope of the curve, the stiffer the soil.

Accelerometers measure the reaction of the soil as it is struck by the vibrating drum.



COMPACTION METER VALUE (CMV)

The second method is called Compaction Meter Value (CMV). Invented by the Swedish company Geodynamik in the 1970s, this method is currently used by Caterpillar as well as several other manufacturers. Rather than attempting to calculate drum displacement, the drum-mounted accelerometer measures the rebound or G-force acceleration at the vibratory frequency and also measures the G-forces at two-times the drum vibratory frequency (this is also referred to as the "first harmonic"). By putting the two values into a formula, a compaction value is calculated that is an indication of soil stiffness, referred to as a Compaction Meter Value (CMV).

Stated another way, the basic principle of measurement focuses on the change of the dynamic response of the compactor as the ground beneath increases in stiffness. Somewhat like a falling weight deflectometer, the accelerometer-based system measures how much the compactor drum is "bouncing" off the ground. Uncompacted soils tend to absorb the vibratory energy, but as the ground stiffens under the compactor with additional passes, energy begins to be reflected off the surface and the drum tends to rebound more rapidly from the vibratory force. Measuring this increased rebound can be translated into an indicator of compaction.

As the soil becomes stiffer, the rebound becomes more pronounced. When the resonant frequency of the ground matches the vibratory frequency of the machine, the soil has reached its maximum stiffness and can no longer accept the compactive energy of the compactor. At this point, the machine will begin de-coupling. Regardless of the measurement method employed, accelerometer-based systems monitor how close the machine is coming to de-coupling. This measurement is called the Resonance Meter Value (RMV) and is used as a gauge of how valid the stiffness measurement is—the closer the machine is to de-coupling, the less valid the measurement.

Accelerometer-based systems measure a deep volume of soil, about 1-1.2 m (36-48 in) deep depending on the composition of the soil and the characteristics of the compactor. This reading is "averaged," so it is not possible to isolate precise stiffness indications at any given depth. But the deep reading is excellent for finding buried objects—in the sub-base, for example—that could affect the quality of the work and the long-term performance of the structure.

One of the drawbacks of accelerometer-based systems is that the drum must be vibrating in order to make measurements. This makes accelerometer-based systems unsuitable for use on cohesive and semi-cohesive soils due to the dampening effect of those materials. For this reason, accelerometer-based systems are ineffective when used on padfoot compactors or in applications when only static compaction is utilized, as the measurements cannot be taken without vibration.

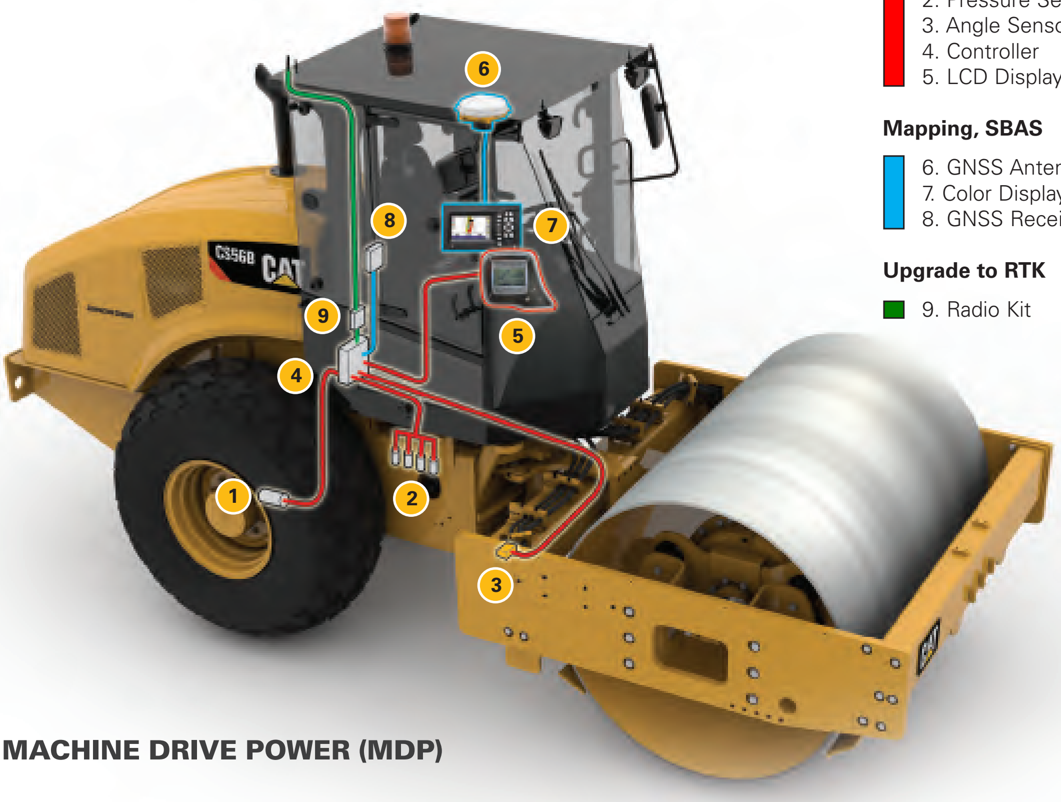
Another drawback of accelerometer-based systems is the depth of measure. As described above, depending on soil type and stiffness of the material being worked, the depth of measurement can be as much as 1.2 m (4 ft) and clearly much deeper/thicker than any one lift being compacted. Thus, you are getting an averaged stiffness value over a number of lifts, or also including the sub-base material stiffness.

CMV - HOW DOES IT WORK?

Vibratory energy is imparted on the soil by the vibrating drum.

The material vibrates in response, which is detected and measured by the accelerometer.

CMV calculates a theoretical indication of soil stiffness.



Measurement System

1. Speed Sensor
2. Pressure Sensors
3. Angle Sensor
4. Controller
5. LCD Display

Mapping, SBAS

6. GNSS Antenna
7. Color Display
8. GNSS Receiver

Upgrade to RTK

9. Radio Kit

MACHINE DRIVE POWER (MDP)

Energy-based Measurement – The other measurement technology available today measures the amount of rolling resistance the soil compactor encounters as it rolls across the ground. It works on the principle more energy is required to overcome the rolling resistance of loose soils than dense soils. With additional passes, the soil compacts, increasing in stiffness and load bearing strength. As the material offers gradually less resistance, the compactor will require less energy to propel itself over the compacted area. The rolling resistance, and the amount of energy necessary to overcome it, can therefore be correlated with the stiffness of the material. Only Caterpillar currently offers energy-based compaction measurement technology, called Machine Drive Power (MDP).

Energy-based measurement has many advantages. Using Machine Drive Power is similar to proof rolling: the less a wheel sinks into the ground, the less energy is required to move the wheel across the ground. As such, a strong correlation exists between MDP and rut depth from proof rolling tests. There is also a high correlation between MDP and soil stiffness, but perhaps the greatest advantage to energy-based measurement is that it is a more tangible and direct calculation and indication of a soil's ability to support a load. If the ground is sufficiently stiff enough to minimize energy transferred from the compacting machine, then it is sufficiently strong to meet the requirements for soil compaction. This relationship, which can be measured for both vibratory and non-vibratory compactors, is the underlying reason to compact soils.

Because the energy-based method of compaction measurement does not require the measurement of vibratory energy in the calculation of soil stiffness, it works well on all soil types including cohesive and non-cohesive soils. It works as well on a padfoot drum compactor as it does on a smooth drum compactor. It functions when the vibratory system is active or inactive. For these reasons, energy-based systems are much more versatile and can be used for more applications than accelerometer-based systems.

Further, energy-based systems do not measure as deep as accelerometer-based systems, about 30-60 cm (12-24 in) deep depending on the soil composition and the characteristics of the compactor. This depth is closer to the depth of a typical lift, so it is measuring the soil that it is compacting rather than an average of a few lifts and/or the sub-base material below the lift being compacted. This depth also is more comparable to the testing depth of portable testing devices, which allows contractors to correlate them with greater confidence.

There are some disadvantages to energy-based systems. They do not measure as deep, so they are sometimes not as adept at identifying buried objects or areas of poor compaction in the sub-base as accelerometer-based systems. Also, when operating an energy-based system with the vibratory system engaged, data warning the operator that the machine is about to de-couple cannot be provided.

MDP - HOW DOES IT WORK?

Propelling over soft ground requires more energy.

Propelling over stiff ground requires less energy.

MDP measures the energy necessary to overcome rolling resistance, a more tangible and direct measurement of soil stiffness.

Factors Influencing Machine-Integrated Compaction Measurement Results – As noted earlier, vibratory compaction is a complex process in which many factors influence the overall compaction force required to achieve compaction/density targets. With machine-integrated compaction measurement technology, operators produce data on 100 percent of the surface compacted, compared with less than 1 percent using traditional portable testing devices/methods. This gives the operator the ability to locate poorly compacted areas or hard spots and take steps to remediate them, which leads to a more homogeneous end result and greater quality.

Accordingly, there are a number of factors that influence machine-integrated compaction measurement results and their correlation to known field test data, regardless of the technology used.

The impact of each factor must be understood in order to use machine-integrated compaction measurement technology to its fullest capabilities. Knowing how each factor influences the measurement will help the contractor perform a consistent measurement with the least amount of variation. To this end, it is beneficial to have a broad understanding of three primary factors:

- Proper preparation of the test site
- Test method and data collection
- Machine parameters

Test Site Preparation

Proper preparation of the test site and tight control of test material conditions are of utmost importance. Failure to ensure homogeneity of the material and uniformity of compaction in both subgrade conditions and raw materials can directly impact the quality and accuracy of the test data.

Preparing a test site

1. **Base or Sub-base Construction Using Multiple Materials –** Oftentimes, a variety of materials are used in the construction of the base or sub-base. For instance, a hard, crushed-rock base may abut a base constructed of relatively soft clay. When covered with a thick layer of gravel—perhaps 1 m (39 in)—the CMVs measured over the rock base will be substantially higher than the measurements over the clay base. Testing the surface density with a portable testing device would result in nearly identical values, because the devices cannot measure deeper than the surface gravel. Base stiffness has a profound effect on accelerometer-based measurements, but can also have a limited effect on energy-based measurements.

   A stiffer base or sub-base causes the fill material above it to compact easier and to a higher degree. Because of this, Caterpillar recommends that the lowest level of excavation be mapped or proof-rolled to determine its condition is before new fill material is brought in, spread and compacted. It may be necessary to remedy some areas that are substantially harder or softer than the majority of the worksite. Uniformity of compaction is the goal and it requires a uniformly compacted base or sub-base of uniform bearing stiffness.

2. **Soil Type –** The type of soil being compacted has a big influence on the CMV or MDP results obtained.

   The reason for this is that the internal soil spring rate and damping rates are very different for fine soils and granular soils. This affects how the soil responds to the vibratory input and, in turn, affects how the measurement is made.

3. **Moisture Content –** Any testing or production compaction should be performed over known, acceptable ground conditions. It is not advised to test over a wet "sponge" or water saturated material. Moisture content of the soil is a variable with enormous impact on compaction results, and will be regularly encountered on the jobsite. It is also a primary cause for variation in CMVs for the same soil type. The contractor does have some control over this factor and can either add water with a water truck and mix it in, or till up the soil and dry it out. For the most efficient compaction, every soil has optimum moisture content. For sandy soils, it ranges from 4 percent to 12 percent and for clay soils it ranges from 9 percent to 22 percent.

Measurements from a machine-integrated compaction measurement system—indications of soil stiffness—are affected by moisture in the soil because of how it fills voids between the soil particles. If there is more air in the voids, the compressibility of the air lowers the reading. If there is more water, its relative incompressibility will result in a higher reading. At some point, so much moisture is present that it acts as a lubricant between particles, allowing them to slide over one another. This will lower the CMV value again.

One benefit of using machine-integrated compaction measurement technology is that the moisture content of a soil can be detected indirectly by how well the soil is packing. For example, a compactor running on granular soils will take more passes to reach a target value as the soil dries out: the drier the soil, the more passes it takes. The operator can track this visually on the display screen, and can call for a water truck to come in and treat specific dry areas. On wet soils, the compactive force of the compactor can cause water to migrate from lower layers to upper layers, resulting in decreased readings. The operator can call for a machine to open the ground up, allowing excess moisture to evaporate.

4. **Hidden Objects Buried in the Soil –** When compacting what appears to be a uniform lift of material, sometimes the machine-integrated compaction measurement in a small area will be substantially higher or lower than the surrounding area. The first response may be to check the area using a surface-reading type of instrument, such as a nuclear density meter or a light falling weight deflectometer. This type of check will rarely produce the same measurement variation as the integrated measurement, because these types of devices do not measure to the same depth.

   A likely cause for a localized high machine-integrated compaction measurement reading would be a large rock or piece of concrete buried in the soil, perhaps a few feet down. A localized low reading could be due to a large clay ball or rubber tires buried in granular aggregate. The variations in integrated compaction measurements are real, but they require excavation of the area to determine just what the object may be. This may not be practical.

   A probe using a long rod driven into the ground or a dynamic cone penetrometer may give some insight into the nature of the anomaly without having to excavate. A decision must be made if the variation will cause problems with the finished road surface during later use. Variation in load bearing strength (stiffness) of the supporting soil can cause stress in the pavement, which leads to a shortened life cycle.

WARNING: When working on sites where there is a possibility of the existence of unexploded munitions buried beneath the surface, it is recommended that a metal detector be used prior to excavation and compaction.

Test Method and Data Collection

1. **Correlation With a Known Field Test Method –** Contractors who are unfamiliar with machine-integrated compaction measuring systems naturally want to relate the data/measurements to a known field compaction test methodology. Troxler (nuclear) density and sand cone density tests have been industry standards for years and show some correlation, but they do not measure the same soil properties or soil depths that the machine-integrated measurement systems do.

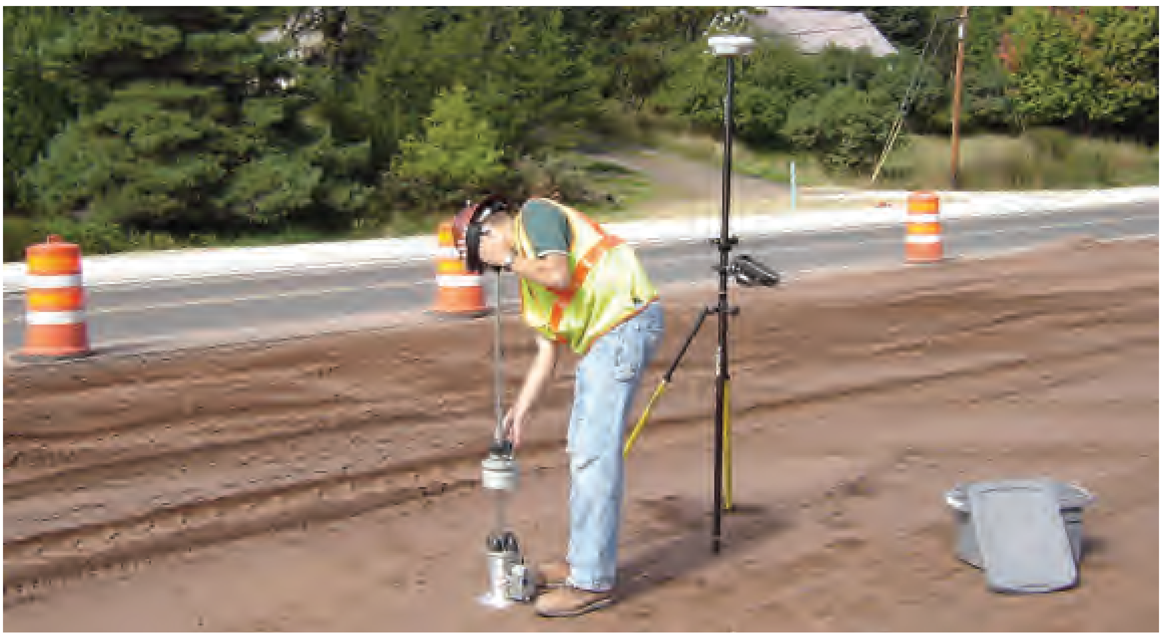
   The field compaction test method utilized can directly impact the level of correlation with a machine-integrated compaction measurement value. The effective volume of soil measured by the machine-integrated compaction measurement technology (either CMV or MDP) is substantially greater than that of a typical field measurement method. None of the known field compaction test measurement devices measure to the same depth, volume of soil or even necessarily the same soil properties.

   Due to the portability and relative ease of use, the following are commonly used field test methods:

   - Dynamic cone penetrometer – measures to a greater depth, but is indirectly measuring the shear strength and friction of the soil.
   - Lightweight falling deflectometer – has an effective volume of material tested of about 1 percent of what a machine-integrated system would measure. As such, any non-uniformity of the materials tested would be exacerbated and made even more pronounced by the difference in volume of material tested.

Correlations between the data from measuring devices and machine-integrated measurement systems are variable, depending on which tests and how many tests are performed. When attempting to correlate machine-integrated test data with a known field test, the most satisfactory data correlations result with the use of a large plate load test or falling weight deflectometer.

The final thing to remember when utilizing machine-integrated compaction measurement technology is that what you are measuring—an indication of soil stiffness—is changing while you are measuring it.



As a result, you cannot go back and get the exact same reading you obtained with a previous pass. This can pose a problem for agencies trying to verify compaction measurement values (CMV or MDP) with some other known field test for compaction.

Post-compaction field tests with portable devices can be repeated because they are non-obtrusive and do not disturb the soil. A machine equipped with an integrated compaction measurement system alters the soil on every pass due to its weight. The plate load test is the one test that has a similar effect on the soil as the soil structure itself is changed during the measurement.

Machine-integrated compaction measurement values become more repeatable as the soil nears its final maximum compaction state. At that time, there will be very little change in compaction measurement results between passes. However, if the soil structure is somewhat fragile, the compaction values will bounce up and down because the soil structure builds up to a certain level, then breaks down on the next pass. This is called "de-compaction," and it occurs frequently in some types of granular soil.

2. **Amount of Test Data Recorded –** A narrow range or limited number of measurements can also impact the level of correlation seen with machine-integrated compaction measurement technology. It is recommended that you utilize a well-developed range of field compaction test results to compare to the integrated results and avoid single-point correlations, which do not offer enough information to interpret appropriately.

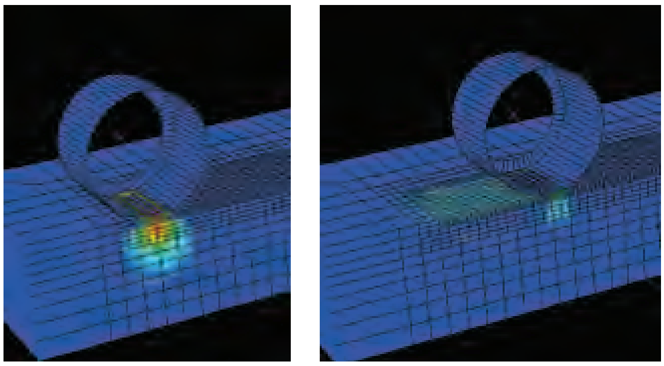
3. **Data Collection –** Uncertainty in spatial pairing of field test results to the machine-integrated compaction measurement values can cause variation and poor correlation. It is recommended to take special care to pair relative data points or to utilize a compactor with GNSS mapping/data collection capabilities in order to associate position detail on the test site to correlate appropriately with field test data.

Machine Parameters

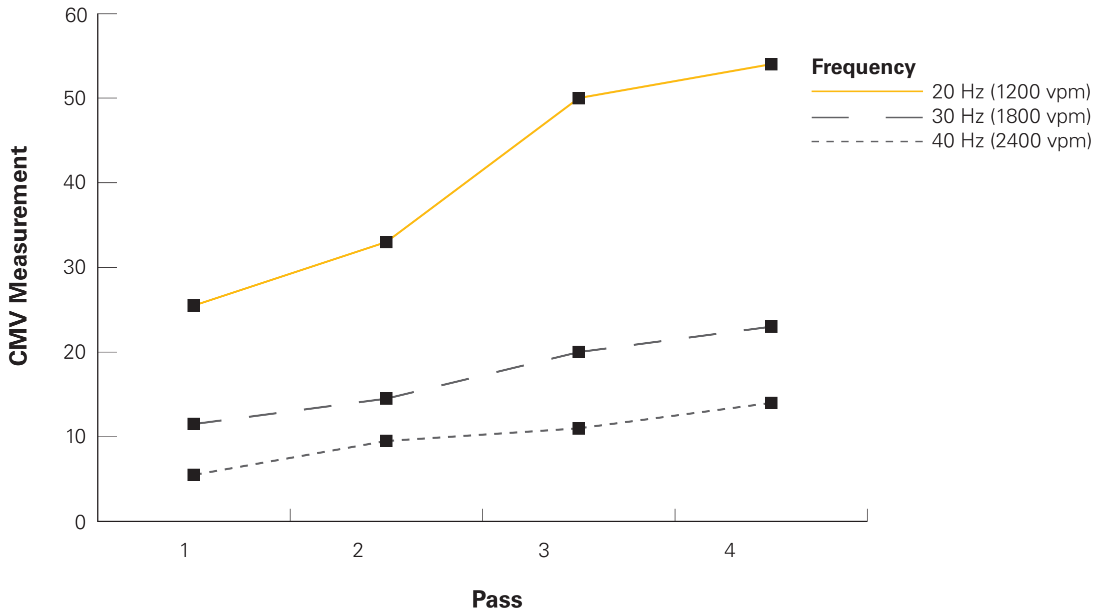
It is well known from a development standpoint—as well as from experience in the field—that machine-integrated compaction measurement technology is sensitive to certain machine operating parameters. Understanding what the system is measuring makes it easier to see how misuse of some of these factors can cause misleading data/output.

1. **Amplitude –** If the drum is at high amplitude, the effect of the drum vibration is transmitted further into the soil. This depth of vibration changes the machine-integrated compaction measurement because the amount of soil being measured is greater. Also, the likelihood increases that the soil is of a different structure and type deeper in the earth.

   If you are looking for information on the variability of soils deep into the ground, high amplitude should be used. If you are interested only in the uppermost layers, lower amplitude is recommended. Even at low amplitude, the soil measurement depth can be a meter or more for CMV results.



High amplitude is transmitted further into the soil.



2. **Frequency –** Cat Compaction Control with CMV uses a ratio of the drum vibratory frequency and a measurement of the ground frequency response back into the drum at two times drum frequency to calculate the compaction value (CMV). Changing the vibratory frequency setting of the soil compactor will subsequently change the resulting measurement, even if the soil stiffness remains the same. This is because on a soil of a given stiffness, the CMV measurement will tend to read higher if measured at low frequency, and read lower if measured at high frequency. The reasons for this are complex, and related to the ratio of the soil's natural frequency to the frequency of the vibrating drum.

   The chart illustrates how changing the frequency can affect the CMV measurement. If all other machine and soil parameters are the same (e.g. ground speed, amplitude, soil type, etc.), there is a significant difference between the measured CMVs for each frequency setting. The frequency you use will affect the CMV measurement. This is true regardless of the stiffness of the soil.

3. **Ground Speed –** Machine-integrated compaction measurement results are affected by ground speed to some extent. Generally, slower speeds allow the vibrating drum to have more contact with soil, building soil stiffness sooner and at a deeper level, resulting in fewer passes and less overall time to meet compaction requirements. Data suggests that faster ground speed generally lowers the results for CMV, but can also increase the results for MDP. It is difficult to quantify precisely how much, because variations in soil type, water content and other factors cloud the issue during testing.

   When multiple passes are required to achieve final compaction levels (indicated by soil stiffness), the most efficient method is to use a slow ground speed and let the vibrator work the soil underneath the drum. The slower speed allows the vibrating drum to have closer impact spacing and more blows per distance traveled—and it will take fewer passes—resulting in less overall time to meet compaction requirements.

   There are also fuel efficiencies: two low-speed passes will consume less fuel than six high-speed passes. General rule of thumb: go slowly to compact quickly and maximize efficiency, but not so slow that de-coupling or de-compaction occurs. With machine-integrated compaction measurement technology, it is recommended to maintain a suitable consistent speed of about 1-2.5 km/h (0.62-1.5 mph) on rock and clay, and 2-5 km/h (1.2-3.1 mph) on sand and gravel. Automatic Speed Control on Cat B-Series compactors can be utilized to help with this factor.

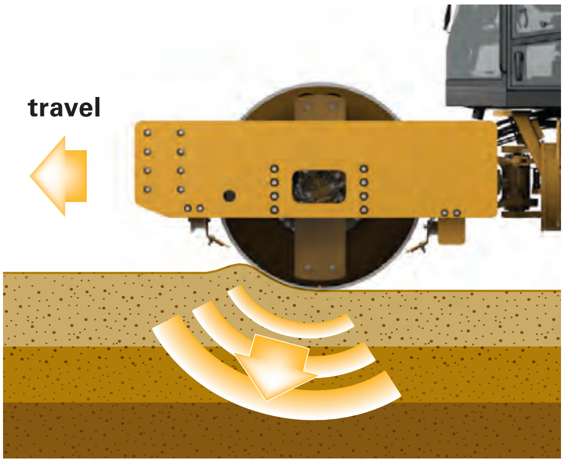
4. **Direction of Travel –** The direction of travel, forward or reverse, has an effect on the value of the machine-integrated compaction measurement data recorded for a given soil stiffness. The amount of variation between forward and reverse measurements typically ranges from 5 percent to 20 percent with higher variation on extremely soft soils.

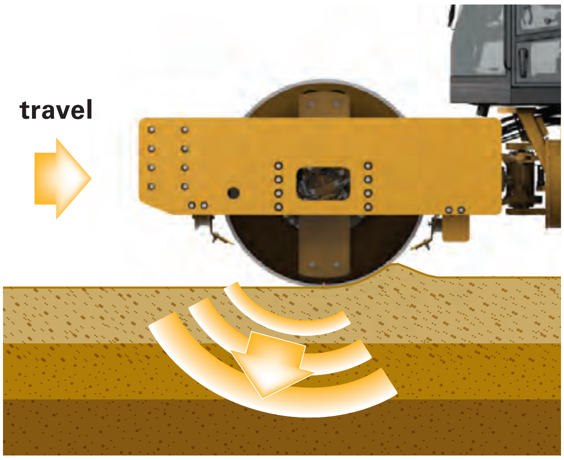
   Machine-integrated compaction measurement results differ depending on travel direction because the rotation of the eccentric weight inside the drum either adds to or subtracts from the net torque applied to the drum as it is propelling over the soil (also due to balance of weight, wheels in front/behind the drum, and other factors). This torque influences the direction of the effective vibration into the ground and will cause the drum to sense either more toward the region already compacted or toward the softer area yet to be compacted.

5. **Vibratory State –** An active vibration system can also affect machine-integrated compaction measurement values. The impact may or may not be significant depending on the material. For test data, technologies that allow you to measure with the vibratory system off produce more reliable results because there are fewer variables influencing the measurement. Energy-based technologies like MDP allow you to do this.

6. **De-coupling or Double Jump –** When the stiffness of the soil increases, its natural or resonant frequency will come closer to matching the drum vibratory frequency. When this happens, the drum begins to completely bounce off the surface of the soil at half of the drum vibratory frequency, and the measured RMV (Resonance Meter Value) will increase. RMV is simply a measure of how much the drum is de-coupling. The more the machine is de-coupling, the less reliable the CMV measurement is.

DIRECTION OF TRAVEL





When the direction of the eccentric moment matches the direction of machine travel (top illustration), the net torque applied to the drum causes the accelerometer to sense the soil from a certain angle. When the direction of the eccentric moment does not match the direction of machine travel (bottom illustration), the torque forces change, changing the angle of measurement. This will result in consistently different CMV readings for forward and reverse operation.

[MACHINE-INTEGRATED COMPACTION MEASUREMENT PROCEDURES]

Soil compactors fitted with integrated compaction measurement technology have the capability to measure factors that can give operators a real-time, in-cab indication of soil stiffness. Many variables factor into the efficacy of this method and directly influence the consistency of the measurement. For that reason, the measurements are often verified utilizing one of the methods listed previously or other portable testing equipment. As the systems become more advanced, their use is better understood, and the results more accepted.

Machine-integrated compaction measurement typically has two modes of operation: production mode and proofing mode.

Production Mode – Production mode is utilized during the initial process of compaction. The intent of this mode of operation is to get as much soil compacted to an acceptable level as quickly and efficiently as possible. During production mode, machine-integrated compaction measurement technology provides the operator with a real-time indication of soil stiffness, as well as identifies areas of poor compaction where action may be necessary to bring the density up to specification.

In production mode, the machine amplitude is typically at high setting and the ground is only compacted until a nominal target value is reached. The operator monitors the display to see what areas have been adequately compacted. The primary concern is getting the job done efficiently, compacting as much fill as possible while not over-compacting areas that are sufficiently stiff.

Because the machine is operating in high amplitude, de-coupling may occur in spots. Due to all the variables—ground speed, direction, de-coupling and soil moisture variation—the integrated compaction measurement values seen during this mode of operation normally have more variation than what is possible to achieve. This may be considered the rough-cut approach to compaction measurement and the lack of accurate or less-variable data in these areas is not so important at this time.

Proofing Mode – Once production mode compaction has been completed, the compaction measurement system can be used as a proof roller to verify the quality of the work in proofing mode. Typically, this process is more precise than production mode. Many variables are controlled and kept consistent, including speed and direction of travel. This helps to ensure that these variables are not influencing the measurement.

The proofing mode is used when the contracting authority is requesting "in-field" data showing an accurate indication of ground stiffness for a particular phase or area of construction. This procedure may be done at periodic intervals of construction when it is convenient to run the compactor over a completed phase of the project in a controlled manner.

To achieve accurate results, the operator needs to keep all variables as constant as possible. This can be considered to be the precision phase of soil compaction.

RECOMMENDED PROCESS FOR PROOFING

1. Stake out the jobsite section to be tested and plan a rolling pattern that allows the operator to propel in the forward direction throughout the compaction testing operation.

2. Determine a target ground speed between 2.5-4 km/h (1.5-2.5 mph) that you will be able to maintain. Slower is better and use of automatic speed control will optimize uniformity of speed which allows for better data and compaction.

3. Set the amplitude to low. This will lessen the chance of drum de-coupling and will result in a measurement that does not penetrate as deeply into the soil. This makes correlation with other test methods easier.

4. Start vibration (or static rolling with MDP) and propel to begin compaction measurement at constant ground speed, amplitude, and frequency while driving forward.

5. Drum passes should be just touching or barely overlapped. Overlap at the ends or turnaround areas. *Note: overlapped areas can be considered as multiple passes and can cause discrepancies in the data.*

6. Manual collection of data can be cumbersome and needs to be matched up with position on the jobsite as accurately as possible within the staked out sections. Most machine-integrated compaction measurement systems do not allow for automatic data storage without the GNSS (GPS) option. Use spreadsheet software such as Excel to sort the data by direction traveled, using only the forward data for analysis. Physically mark out any locations deemed important enough to review or test with a correlation to a known field compaction measurement method.

7. For improved quality, measure the moisture content of the soil in a grid pattern over the entire area that was measured and compacted. Grid size can be adjusted to jobsite scale and requirements of the contracting agency. This will provide additional information for analysis of the compaction values, and the grid pattern will allow development of a soil moisture content iso-bar map. Soil samples for moisture measurements should be taken as soon as possible after the compactor has finished an area.

8. Review the manually recorded data and select those areas that you wish to correlate to another form of compaction measurement device. Select areas that read high values, low values and intermediate values. Select several areas of each.

9. Conduct correlation tests for previously marked locations. Don’t approximate, as soil conditions can vary widely in just a short distance.

NOTE: *In order to fully leverage the capabilities of the machine-integrated technology, GNSS (GPS) mapping capabilities would be necessary to record all data with corresponding positioning detail on the jobsite. Refer to a later section of this guide for further details about “Intelligent Compaction.”*

Summary of Machine-Integrated Compaction Measurement – On any compaction project, quality and cost are major concerns. Achieving applicable compaction targets efficiently and effectively is of the utmost importance. There are many specifications and historically based field compaction measurement methods. With machine-integrated compaction measurement methods, operators now have better tools that will ensure the best possible compaction quality at the lowest cost.

Machine-integrated compaction measurement is a wonderful technology when properly applied, but there are limitations to what it can do. Machine-integrated compaction measurement cannot tell you what soil type you are operating on, nor can it describe a soil's moisture content or physical characteristics.

Machine-integrated compaction measurement technology measures the responsiveness of the soil to provide a snapshot of the load-bearing capabilities. When properly set up and operated, a vibratory soil compactor with integrated compaction measurement provides information that the operator could not otherwise obtain. This information allows the trained operator to deduce the state of the soil. The data is an indication of the soil's stiffness, but not a guarantee. There are simply too many variables. However, a trained operator will understand what the measurements indicate and the course of action dictated by those measurements. The processes utilized are often more important than the technology itself.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Unit 5
INTELLIGENT COMPACTION

Intelligent compaction is the latest advancement in the application of vibratory soil compactors. The ability to accurately measure compaction, correlate measurements with GNSS coordinates, display them on a site map in the operator's compartment, and record and store data for documentation, was heretofore unimaginable. Only time will tell what technological innovations will come next. Caterpillar will be at the forefront of that discussion and the resulting discoveries.

[WHAT IS INTELLIGENT COMPACTION?]

Presently and in the recent past, intelligent compaction is a term applied to compaction measurement systems incorporated with a vibratory soil compactor. Definitions of intelligent compaction vary between different governmental agencies and equipment manufacturers. Generally speaking, intelligent compaction can be defined as a compactor-integrated technology applied to the compaction process that improves worksite efficiencies by eliminating human guesswork. The technologies provide operators with real-time compaction information that helps them determine when compaction is progressing and/or complete.

With this definition in mind, it is safe to say that the previously described machine-integrated compaction measurement technology is indeed a form of intelligent compaction. The integrated systems on soil compactors provide details about the compaction effort on a jobsite in real-time, enabling operators and jobsite superintendents to access information that they did not previously have.

More sophisticated systems can also map out the data to provide a visual perspective of the work completed, as well as store data for later analysis.

One example of an early specification for a State Department of Transportation (USA) is:

> **Intelligent Compaction (IC)**
> This process involves measuring **and recording the time, location and compaction parameters** of the granular treatment during the compaction process with a vibratory roller that is equipped with an accelerometer-based measuring system and global positioning system.

They now have a separate definition or requirement for what an intelligent compactor is:

> **Intelligent Compaction (IC) Roller**
> Rollers shall be vibratory rollers with an accelerometer-based measurement system and **capable of recording the compaction parameter measurements**.

At the same time, the U.S. Federal Highway Administration (FHWA) describes intelligent compaction as the following:

> **Intelligent Compaction (IC)** refers to the compaction of road materials, such as soils, aggregate bases, or asphalt pavement materials, using modern vibratory rollers equipped with an integrated measurement system, **an onboard computer reporting system, Global Positioning System (GPS) based mapping**, and optional feedback control. IC rollers facilitate real-time compaction monitoring and timely adjustments to the compaction process by integrating measurement, **documentation**, and control systems. IC rollers also maintain a continuous record of color-coded plots, allowing the user to view plots of the precise location of the roller, the number of roller passes, and material stiffness measurements.

The European Union has also created a means to define the use of intelligent compaction. In their pamphlet "Guidelines to evaluate soil and asphalt compactors equipped with continuous compaction control (CCC)," the Committee for European Construction Equipment (CECE) has created a matrix to classify equipment with continuous compaction control technologies. (See Appendix.)

It is important to note that more recent definitions of intelligent compaction are clearly defining not only the capabilities of integrated compaction measurement and real-time display to the operator, but also the capability of recording positioning data and storing it for documentation, further analysis and records retention. As such, the definition of intelligent compaction is continually evolving.

Caterpillar believes an intelligent compactor should measure compaction, correlate measurements with GNSS coordinates, display a map of the measurements, record the data and document the results. These capabilities provide many benefits in terms of time and cost for the operators, contractors, and project owners. Therefore, the current definition used by Caterpillar for intelligent compaction is as follows:

Intelligent Compaction (IC)
A system that measures soil compaction, displays the measurements to the operator, records and maps the compaction results using a GNSS mapping system, and controls or guides the machine compaction effort in response to the measurement system.

This definition can be used for both vibratory and non-vibratory compactors and does not require an accelerometer-based measurement system. As described previously, MDP is a new technology and has many advantages over accelerometer-based compaction measurement technology depending on application.

Ongoing, this guide will only refer to intelligent compaction in cases where the compactor is equipped with integrated compaction measurement capabilities (either CMV or MDP), mapping capabilities and the ability to record and store data for documentation and later analysis off-board the machine.

Positioning of the Compactor on the Jobsite

Machine-integrated compaction measurement technology can be augmented with Global Navigation Satellite Systems (GNSS) technology, which enables accurate jobsite positioning through the use of different constellations of satellites in the sky. GNSS technology is widely available and offers different levels of accuracy, some requiring off-board infrastructure providing positioning correction data.

With this level of data and detail, the compaction measurement technology can now be matched up with physical location on a jobsite and can be configured to map these values, including pass counts, direction of machine travel and many other machine settings.

Regardless of the machine-integrated compaction measurement technology employed, the system provides real-time measurement of the soil that is being compacted at any given time. Adding mapping functionality, the ability to record and plot measurements to their precise location on a map makes the information much more useful.

Positioning Data, how does it work? Mapping systems utilize the Global Navigation Satellite System (GNSS) to provide mapping data for each measurement recorded. This includes GPS (operated by the U.S. Department of Defense) and GLONASS (operated by the Russian government), as well as other systems due to come online in the future, including Galileo in the EU and Compass in China.

Location is plotted by triangulation with the known position of satellites from these systems. The satellite systems are not accurate enough to be practical without some degree of correction. The mapping systems on soil compactors use augmentation to correct the satellite signals and provide a useful degree of accuracy. There are two predominant forms of augmentation available: SBAS and RTK.

Most systems utilize SBAS, or Satellite Based Augmentation System, to correct satellite positioning signals. SBAS triangulates to multiple ground-based sites that provide known "anchor points" from which to provide a correction measurement. SBAS systems are typically accurate up to 1 m (3 ft) and require no off-board infrastructure.

Alternatively, many manufacturers can augment the signal with RTK, or Real Time Kinematic, correction. This technology requires the use of local radio base stations to provide correction data.

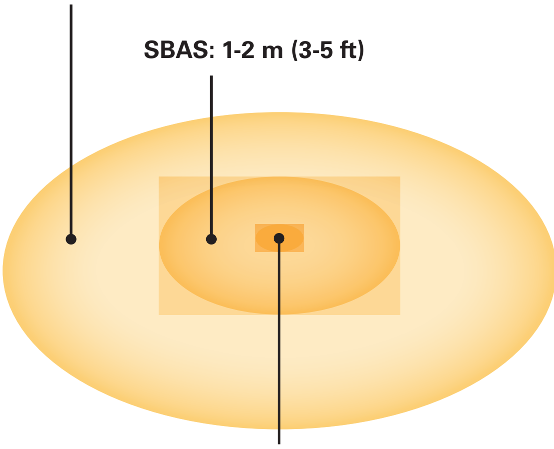
In fact, recent technology also allows for RTK accuracies via cell or modem technologies or even Virtual Reference Stations (VRS)—but this requires a more IT savvy organization and support. The base stations are expensive, and the technology requires line-of-site from the receiver on the compactor to the base station or mobile units. However, RTK provides more accuracy than SBAS, down to a few centimeters (inches). It also allows the system to record elevation data, which would enable the compactor to map grade elevations as well.

This provides a substantial benefit, as the compactor is often the last machine to operate on an earthworks jobsite and can save significant cost/time in final elevation surveying activities.

SATELLITE SYSTEM ACCURACY

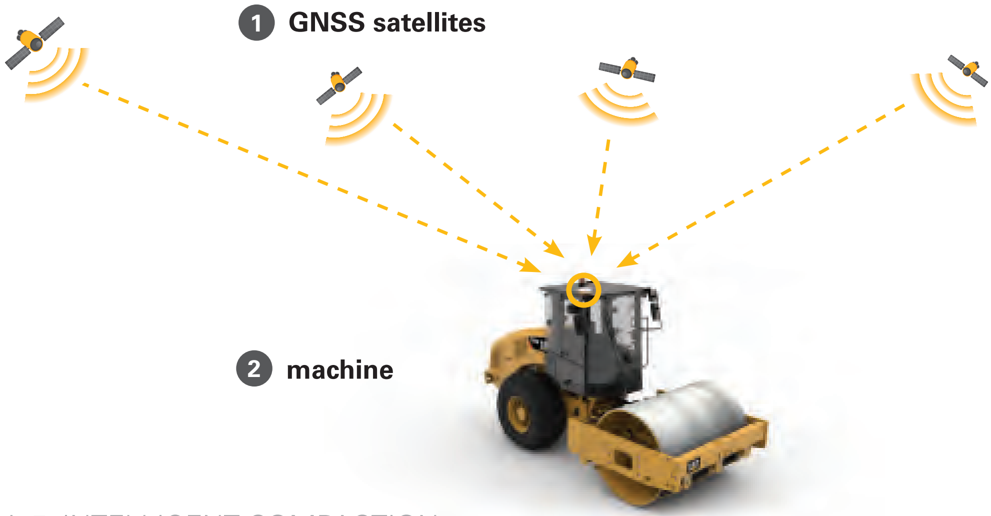
Autonomous: 10 m (30 ft)
no correction

SBAS: 1-2 m (3-5 ft)

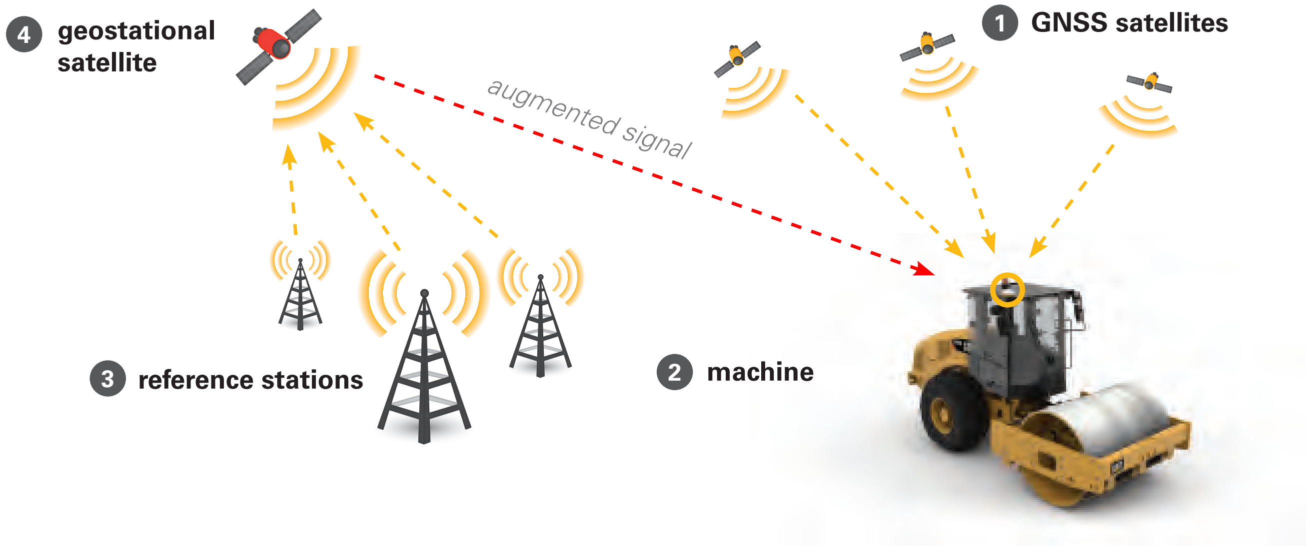


RTK: 1 cm (0.4 in) horizontal, 2 cm (0.8 in) vertical
(with local base or with VRS)

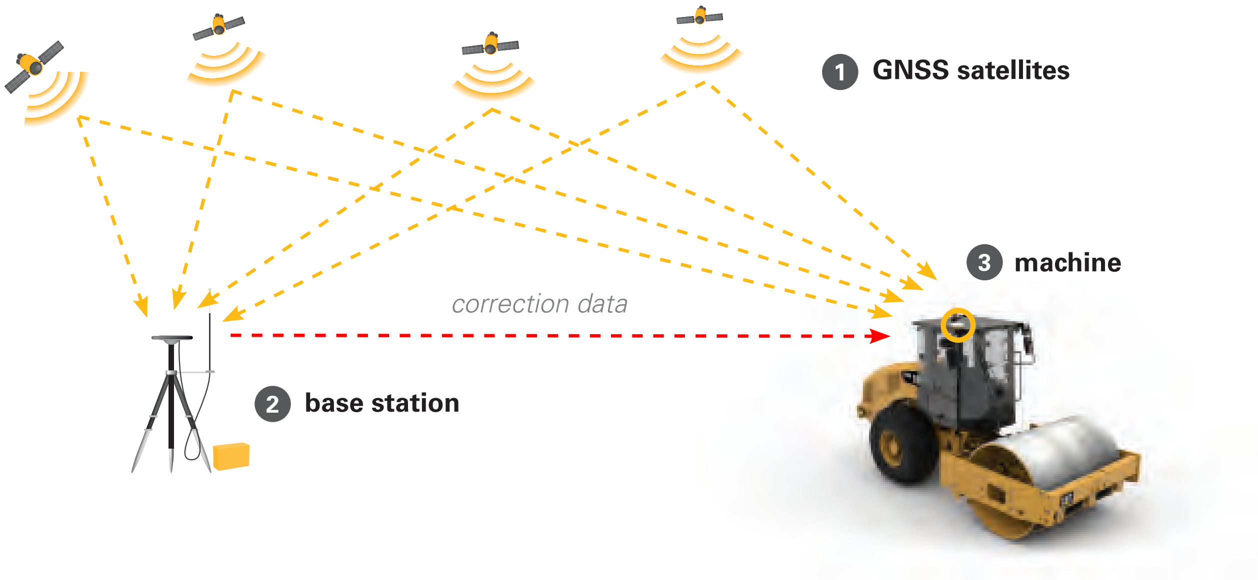
AUTONOMOUS



SBAS (SATELLITE - BASED AUGMENTATION SYSTEM)



RTK (REAL TIME KINEMATIC)



Benefits of Positioning Data

By itself, machine-integrated compaction measurement can reveal many things about the state of compaction in real-time; but this information is very specific, reflecting a momentary snapshot in time. Positioning data allows the system to provide not just a single measurement as it is taken, but ALL measurements in the context of where they were taken. This changes the view from momentary to encompassing, and opens the door for in-depth analysis. Suddenly, the operator—as well as site management—can access a picture of compaction quality for the whole site, rather than just a snapshot in time.

This capability is a big differentiator for IC systems when compared with the other testing methods. Traditionally, ground personnel conduct quality testing using portable testing procedures in a few select locations. The process is time consuming and expensive. The results from the tests are used to represent a much larger area than what is actually tested, often at a ratio of 1:1 million—not exactly statistically reassuring. IC can measure the entire site in the time that it takes to roll over it.

Additionally, some systems are capable of importing engineering or architectural 3D designs into the on-board display. This can be advantageous on a jobsite where stakeless grade control is already in use or where grade stakes and other landmarks are not available.

Using the Collected Data

It is easy to see the advantages that the additional data offers the operator, enabling a more efficient and cost effective way to achieve quality compaction on a jobsite. Many inspectors and road administrations require some real-time and basic in-field reporting, which is text data documenting basic compaction progress via an in-cab printing application. But many authorities are focusing now on more detailed off-board reports. This requires the transmission of all recorded compaction data from the jobsite machine to a PC in an office. Data can be moved manually via jump drive or wirelessly via communications hardware and software.

Once all the data has been received on the office computer, users have the challenge of filtering and sorting the data to construct reporting documentation required by inspection and road authorities. There are many such software programs available today to assist in this task, including AccuGrade Office, SiteVision Office, VisionLink, Veda and many more. These software solutions range in file format types, capabilities and prices.

VISIONLINK INTERFACE

[BENEFITS OF INTELLIGENT COMPACTION]

Quality Control & Quality Assurance Documentation – Intelligent compaction allows for documentation of work completed. It also allows in-process control with the ability to monitor progress daily or near real-time, as well as electronic storage and analysis of results that can be correlated with long-term or historical records of the jobsite data.

Increased Operator Productivity – Output is visually displayed for the operator, helping to determine if the soil has reached target stiffness. This empowers the operator with real-time data that can be acted upon. For example, the system can alert the operator to soft spots, indicate potential moisture content issues, and, with RTK accuracy, the compactor can also check final jobsite grades and elevations.

More Efficient Jobsites – Output of results delivers a map of the entire compacted area, which can reveal areas that need more compaction or areas that are already completed. This minimizes passes and fuel consumption, and can quickly reduce the number of manual compaction tests needed on the jobsite, keeping production at a constant level while reducing testing costs with fewer samples to tag and store.

Confidence in Results – Accurate positioning identifies exact locations of compaction problems early in the construction process, allowing for more cost effective corrections and reduced risk of later rework. The data provides a reliable reference of the overall quality of the job in a visual, easy-to-understand format. This allows trained operators to deduce when a job is complete, giving them the confidence to move on to the next area rather than waiting for the results of conventional testing.

MEASURING RESULTS

[CURRENT SPECIFICATIONS FOR INTELLIGENT COMPACTION]

Intelligent compaction for soil applications has generally increased in use as governmental agencies have studied and accepted the benefits of the technology and produced specifications for its use. Specifications help to ensure that the technology is applied in a manner that produces an acceptable result for the specifying agency.

The U.S. Federal Highway Administration (FHWA) has developed a set of generic specifications for the utilization of intelligent compaction on soils. These specifications are intended for state departments of transportation to use as-is or modify to meet their requirements. Here is an example of the specifications as issued:

The IC rollers shall meet the following specific requirements:

1. IC rollers shall be self-propelled single-drum vibratory rollers equipped with accelerometers mounted in or about the drum to measure the interactions between the rollers and compacted materials in order to evaluate the applied compaction effort. IC rollers may be smooth or pad footed drums.

2. The output from the roller is designated as the Intelligent Compaction Measurement Value (IC-MV), which represents the stiffness of the materials based on the vibration of the roller drums and the resulting response from the underlying materials.

3. GPS radio and receiver units shall be mounted on each IC roller to monitor the drum locations and track the number of passes of the rollers.

4. The IC rollers shall include an integrated on-board documentation system that is capable of displaying real-time, color-coded maps of IC measurement values including the stiffness response values, location of the roller, number of roller passes, roller speeds, together with the vibration frequency and amplitude of roller drums.

5. The display unit shall be capable of transferring the data by means of a USB port.

6. An on-board printer capable of printing the identity of the roller, the date of measurements, construction area being mapped, percentage of the construction area mapped, target IC-MV, and areas not meeting the IC-MV target values. (Printer option to be selected by the each state DOT.)

Governmental authorities from other countries have developed their own specifications built around the road building process in their respective countries. While they may vary from the FHWA specifications, the goal is similar in that they want to provide a standard for use of the equipment.

Spec.	Equipment	Field Size	Location Specs	Documentation
Mn/DOT (USA)	Smooth drum or padfoot vibratory roller (25,000 lbs.)	100 m x 10 m (minimum at base). Max 1.2 m thick.	One calibration/ control strip per type or source of grading material	Compaction, stiffness, moisture, QC activities, and corrective actions (weekly report)
ISSMGE (International Society of Soil Mechanics and Geotechnical Engineering) **www.issmge.org/**	Roller chosen by experience	100 m by the width of the site	Homogenous, even surface. Track overlap ≤ 10% drum width.	Rolling pattern, sequence of compaction and measuring passes; amplitude, speed, dynamic measuring values, frequency, jump operation, and corresponding locations
Earthworks (Austria)	Vibrating roller compactors with rubber wheels and smooth drums suggested	100 m long by the width of the site	No inhomogeneities close to surface (materials or water content). Track overlap ≤ 10% drum width.	Compaction run plan, sequence of compaction and measurement runs, velocity, amplitude, frequency, speed, dynamic measuring values, jump operation, and corresponding locations
Research Society for Roadand Traffic (Germany)	Self-propelled rollers with rubber tire drive are preferred; towed vibratory rollers with towing vehicle are suitable.	Each calibration area must cover at least 3 partial fields ~ 20 m. long	Level and free of puddles. Similar soil type, water content, layer thickness, and bearing capacity of support layers. Track overlap ≤ 10% machine width.	Dynamic measuring value; frequency; speed; jump operation; amplitude; distance; time of measurement; roller type; soil type; water content; layer thickness; date, time, file name, or registration number; weather conditions; position of test tracks and rolling direction; absolute height or application position; local conditions and embankments in marginal areas; machine parameters; and perceived deviations
Vägverket (Sweden)	Vibratory or oscillating single-drum roller. Min. linear load 15–30 kN.	Thickness of largest layer 0.2–0.6 m.	Layer shall be homogenous and non-frozen. Protective layers < 0.5 m may be compacted with sub-base.	—

Compaction Specs	Speed	Frequency
90% of the roller compaction measurements and average of LWD modulus measurements (based on 3 tests) must be at 90% of the target values established in the calibration strip.	Same during calibration and production compaction	
Correlation coefficient ≥ 0.7. Minimum value ≥ 95% of Ev1, and mean should be ≥ 105% (or ≥ 100% during jump mode). Dynamic measuring values should be lower than the specified minimum for ≤ 10% of the track. Measured minimum should be ≥ 80% of the specified minimum. Standard deviation (of the mean) must be ≤ 20% in one pass.	Constant 2–6 km/h (± 0.2 km/h)	Constant (± 2 Hz)
Correlation coefficient ≥ 0.7. Minimum value ≥ 95% of Ev1, and median should be ≥ 105% (or ≥ 100% during jump mode). Dynamic measuring values should be lower than the specified minimum for ≤ 10% of the track. Measured minimum should be ≥ 80% of the set minimum. Measured maximum in a run cannot exceed the set maximum (150% of the determined minimum).Standard deviation (of the median) must be ≤ 20% in one pass.	Constant 2–6 km/h (± 0.2 km/h)	Constant (± 2 Hz)
The correlation coefficient resulting from a regression analysis must be ≥ 0.7. Individual area units (the width of the roller drum) must have a dynamic measuring value within 10% of adjacent area to be suitable for calibration.	Constant	
Bearing capacity or degree of compaction requirements may be met. Mean of compaction values for two inspection points ≥ 89% for sub-base under roadbase and for protective layers over 0.5 m thick; mean should be ≥ 90% for roadbases. Required mean for two bearing capacity ratios varies depending on layer type.		Constant 2.5–4.0 km/h

[INTELLIGENT COMPACTION OPERATION PROCEDURES]

Similar to the use of only the machine-integrated compaction measurement technology discussed previously, intelligent compaction-enabled vibratory soil compactors have similar processes to follow, with slight differences due to the additional capabilities the more advanced systems provide. There are two modes of operation: production mode and proofing mode.

Production Mode – Again, the intent of this mode of operation is to compact as much soil to an acceptable level as quickly and efficiently as possible in both forward and reverse directions until a nominal target value is reached. The compaction is conducted in normal working parameters—travel speed of 1 to 2,5 km/h (0.6-1.6 mph) on rock fill and clay; 2-5 km/h (1.2-3.1 mph) on non-cohesive sands and silt soils—and the machine amplitude is typically at high setting.

In the case of an intelligent compaction equipped compactor, the operator can now receive input other than a simple dimensionless number giving an indication of soil stiffness or load bearing strength. With the additional color display and data collecting and storage capabilities, the operator has a snapshot of compaction in the exact location of the compactor and can monitor the jobsite by pass count, percent of a target compaction measurement value, or even by percent of change of the compaction target value on a pass-by-pass basis (for both areas of sufficient as well as areas of poor compaction). As necessary, the operator can also digitally mark points and areas where action may be necessary to bring the compaction up to specification. All stored data can be taken off-board to review, filter and analyze as necessary.

In this mode of operation, the mapping system provides the operator with a visualization of jobsite compaction progress and a moderate level of quality assurance. However, because of all the variables—ground speed, direction, de-coupling, soil moisture variation—the compaction data taken during this mode of operation is still of lower quality than what is possible to achieve. However, it still gives the operator data to maximize efficiency and uniformity and eliminate the reliance on guesswork during the compaction process.

When the values reach a range near the target value, the operator can move on to a new area while quality personnel conduct testing to ensure the work meets specification or the area can be made ready for a proofing mode pass.

Proofing Mode – Once production compaction has been completed, the compaction measurement system can be used as a proof compactor to verify the quality of the work in this more precise mode of operation. This approach is intended for use when the contracting authority is requesting documentation or a map showing an accurate indication of ground stiffness for a particular phase of construction.

It is of utmost importance to ensure that variables are controlled and kept consistent, thus working parameters are now constant travel speed of 3 km/h (2 mph) with machine amplitude in low setting (or off if necessary in the case of over compaction or de-coupling or other issues with an MDP equipped machine). This helps to ensure that these variables are not influencing the measurement and data being collected and stored for reporting purposes.

It should also be noted that when it comes to proof rolling, what you are measuring—the degree of compaction of the soil—is changing as you measure it. As the heavy compactor moves, its static weight is introducing pressure and other forces into the soil below. For this reason, operators need to take care to diminish the amount of force introduced as they are measuring. The ability of energy-based systems to measure with a static drum (without vibration) makes them ideal for this application.

RECOMMENDED PROCESS FOR PROOFING

1. Plan a rolling pattern that allows the operator to drive in the forward direction throughout the mapping operation.
2. Determine a target ground speed between 2.5 to 4 km/h (1.5 to 2.5 mph) that you will be able to maintain. Slower is better, and use of automatic speed control will allow uniformity of speed, which enables better data measurement and compaction.
3. Set the amplitude to low. This will lessen the chance of drum de-coupling and will result in a measurement that does not penetrate as deeply into the soil. This makes correlation with other test methods more likely.
4. Select the "proofing on" from the display menu and start vibration (or static rolling with MDP) and propel to begin compaction measurement at constant ground speed, amplitude, and frequency while driving forward.
5. Use the GNSS positioning capabilities to guide the machine so that only one pass is made over the area of interest. Drum passes should be just touching or barely overlapped. Overlap at the ends or turnaround areas. NOTE: overlapped areas can be considered as multiple passes and can cause discrepancies in the recorded data.
6. When the entire area has been covered, select "proofing off" on the display.
7. For improved quality, measure the moisture content of the soil in a grid pattern over the entire area that was measured and compacted. Grid size can be adjusted to jobsite scale and requirements of the contracting agency. This will provide additional information for analysis of the compaction values, and the grid pattern will allow development of a soil moisture content iso-bar map. Soil samples for moisture measurements should be taken as soon as possible after the compactor has finished an area.
8. Review the compaction map and data to select those areas that you wish to correlate to another form of compaction measurement device. Select areas that read high values, low values and intermediate values. Select several areas of each.
9. Conduct correlation tests using a hand held GNSS rover to locate the selected test areas as accurately as possible. Don't approximate, as soil conditions can vary widely in just a short distance. (See discussion of correlating test equipment in the next section.)

[ECHELON PATTERN WITH TWO COMPACTORS]

Several methods can be used to calibrate a target value for compaction measurement (CMV or MDP) and the required number of passes. Some of these methods will be dictated by the contracting agency, and may differ from what is printed in this guide. The industry is moving toward a practice of emphasizing that the area be uniformly compacted to an acceptable level, and is moving away from trying to obtain a specific compaction value or density for all areas of the worksite.

Site Calibration Using a Test Strip and an Independent Testing Device

This method is intended to eliminate as many variables in the measurement process as possible, and to use the same soils and methods as are going to be used during the actual construction of the road or building site. It is very time and resource consuming, but is the best way to understand the process and build a baseline understanding of the technologies involved.

1. Locate a test area that can be left intact for the duration of the project and has similar soils, grades and subsoil structure as the majority of the project.

2. Excavate/fill the test area to grade and level to create the sub-base for the test strip.

3. Bring in the vibratory soil compactor and create a base line compaction map using the intelligent compaction system in proofing mode and low amplitude, constant frequency (or with vibration off in the case of MDP), constant forward direction at 3 km/h (2 mph).

4. If the compaction map shows high variability (90 percent of the values should be within 20 percent variation of the average value), try compacting the base in high amplitude to bring the compaction level of the soft areas up to be more equal to the higher value areas. Repeat step #3.

5. If the sub-base is now uniformly compacted (meeting the test: 90 percent of the values within 20 percent variation of the average value), go on to step #6. If not, either a new test strip site needs to be selected (step #1) or remedial work needs to be done to the sub-base to obtain a more uniform map. Remedial work may involve excavating hidden objects such as rocks and clay balls or stabilizing the soil with lime or some other agent. If a stabilizing agent is used on the test strip, it must also be used throughout the jobsite for the test strip to have validity.

6. Measure the compaction of the sub-base with a portable plate load test or light falling weight deflectometer using a uniform pattern of test points across the full area of the test strip. Avoid using nuclear density or sand cone density devices, as they measure a different soil characteristic (density) than the vibratory compactor (stiffness). These test points need to be located using a precision GNSS device capable of decimeter accuracy in order to be correlated correctly to the GNSS compaction map obtained from the intelligent compactor. As an alternative to testing in a grid pattern, use the compactor GNSS map and pick several scattered locations that represent the high, medium and low compaction values. Obtain at least three tests for each range of values (9 test points minimum). Using more test points provides a more statistically accurate result.

7. Measure the moisture content at each of the test points. If the moisture content shows wide variation, the correlations will not produce uniform results.

As a cautionary note, remember that the portable test device used to calibrate the compactor-integrated compaction measurement value has its own variability of measurement. That means that it could be used to measure the same soil with the same properties several times and not provide the exact same results. For example, nuclear density measurements can vary by 15 percent on the same sample. Current practice is to take a reading, rotate the device 90 degrees and take another reading. The average of the two readings is recorded as the measured value.

8. Correlate compaction test values to those obtained from the GNSS map on the compactor and graph the results with compaction measurement values on the y-axis and portable field test results on the x-axis. This is called a scatter plot.

9. Use curve-fit methodology to determine the best calibration curve between the integrated compaction measurement values and the field test method. This is the tool that will only be used for that soil type on the jobsite and tests of the sub-base compaction.

10. Bring the first lift of fill material and place uniformly at the specified depth.

11. Compact the material until it is uniformly compacted and the integrated compaction measurement values do not change much when traveling in the forward direction.

12. Repeat steps #2 through #9 for this lift of material. This base lift will have its own calibration curve that will be used throughout the jobsite for this lift of material.

13. Repeat steps #10 through #12 for all layers of fill that are brought in, each layer having its own calibration curve.

14. If the ground conditions change due to the weather, rerun a proof run on the test strip to re-establish what constitutes an acceptance level for the integrated compaction measurement value.

Calibration of Integrated Compaction Measurement Results and Pass Count Using a Soil Compactor (No Independent Field Test Device)

This process, or a similar one, is used in some Scandinavian countries. It is more pragmatic and demands less time and resources while providing a means of having good compaction control without using some other compaction measurement as a standard. The objective is to use the compactor to establish a nominal maximum level of compaction for the worksite materials, and determine the number of passes to reach that level. The purpose is to create a uniform level of compaction across the entire jobsite. The following process uses a test strip to set compaction baselines. A test strip is optional, as a portion of the worksite or the entire worksite can be compacted as if it were a test strip.

1. Locate a test area that can be left intact for the duration of the project that has similar soils, grades and subsoil structure as the majority of the project.
2. Excavate/fill the test area to grade and level to create the sub-base for the test strip.
3. Bring in the vibratory soil compactor and create a base line compaction map (proof map) using the intelligent compaction system in proofing mode and low amplitude, constant frequency (or with vibration off in the case of MDP), constant forward direction at 3 km/h (2 mph).
4. Check moisture content of the soil at multiple locations on the test strip. If it is too high or too low, correct before doing any additional compaction.
5. If the compaction map shows high variability (90 percent of the values should be within 20 percent variation of the average value), compact the base in high amplitude until the compaction measurement values are more consistent across the test strip. Repeat step #3.
6. Upon obtaining uniform compaction, check the moisture content at several locations and record the results.
7. Bring the first lift of fill material. Select the proof map feature and compact the fill layer using a high amplitude setting and slow uniform ground speed of 3 km/h (2 mph). Complete an up and back pass in each track before moving over to run on uncompacted material. Moisture content should be uniform and at an optimum level for the soil or rock fill being used.
8. Repeat the compaction cycle over the entire area again, noting the level of compaction measurement value that is most predominant for each compaction pass.

9. Keep repeating step #8 until the compaction level between passes does not change substantially, or the compactor starts to de-couple.

10. The average value that the compaction measurement begins to level off is the target value and the number of passes it took to reach this level of compaction is your target pass count.

11. Record these results, and set the display target value and pass count accordingly for this lift.

12. Repeat steps #7 through #11 with a new proof map for each new lift. When complete, you will have a target compaction measurement value and pass count for each layer.

13. If several of the layers possess nearly identical values, use a single target compaction measurement value for all corresponding layers of fill.

14. Compact the worksite as normally done, using the compaction map as a guide to achieve uniform compaction over the entire area.

15. With time and experience in a region, skilled operators may be able to set the target compaction measurement values and pass counts without utilizing a test strip.

16. If a more precise measure of the final compaction level is desired, use the compactor in the proofing mode (low amplitude, constant speed of 3 km/h [2 mph], constant frequency and forward direction only).

Use of Intelligent Compaction Values Without Calibration on the Jobsite

This process is the most pragmatic and demands little or no additional time. It must be noted that this process is best suited for what is described previously as a production mode of compaction and requires some experience with the system, an understanding of how the technology works and the process of soil compaction in general.

The objective of this process is to use the intelligent compaction technology to compare the relative change in compaction progress on a pass-by-pass basis in order to know when the physics behind the compactive effort is adequate for the conditions at hand. As stated earlier, using intelligent compaction and integrated compaction measurement technology is not a guarantee of compaction or density; and, often times, the process employed is more important than the tools and technology used on a jobsite. A compactor of given characteristics can become ineffectual after a certain number of passes on a certain material, rendering the compaction goal unachievable and making all subsequent passes wasteful. It would be beneficial to know when this condition takes place in order to stop wasting time and consuming fuel unnecessarily.

1. Size the vibratory soil compactor with intelligent compaction capabilities as best you can considering compaction targets, soil types, moisture levels, lift thickness, etc. Details provided earlier describe some factors to take into consideration when sizing and choosing the configuration of the compactor.

2. Begin compaction on the jobsite with the intelligent compaction display set up to map compaction measurement values and comparing the percent change from one pass to the next.

3. The mapping feature can be set up and customized to assign a certain color for a certain range of percent change, one pass to the next. As an example, set the display to map the color red for areas showing 50-100 percent change pass-to-pass, yellow for areas showing 10-49 percent change pass to pass, and finally green for 0-9 percent change pass to pass. These ranges can be changed according to experience or jobsite conditions as necessary.

4. Continue rolling and compacting with the focus on turning the map green.

5. If there are areas that cannot be brought to green (little to no change from one pass to the next), this is an indication that there may be some issue with the suitability of the soil in that area, or perhaps some sub-base concerns that need to be addressed.

6. When the map is sufficiently green and no further change in compaction measurement values are noted from one pass to the next, utilize a portable plate load test or light falling weight deflectometer as described in the examples. Be sure to use a uniform pattern of test points across the full area being compacted/tested or as desired to prove that the compaction will pass or fail the compaction target specified for the project.

7. If the tests show a passing level of compaction, continue with the process on the jobsite as described.

8. If the tests show that compaction targets are not met, one of two things is happening. 1) The machine size and operating weight are not correct for the soil type and lift thickness and/or 2) the moisture content of the soil is incorrect (either too dry or too wet). Either way, the compactor on the jobsite will not be capable of further compaction progress until some conditions are changed.

[TROUBLESHOOTING INTELLIGENT COMPACTION RESULTS]

As described previously, several jobsite conditions and operational factors can affect the results of intelligent compaction systems. With experience, operators will begin to recognize certain patterns and understand the probable cause of a deviation from expected values. Following are some common problems and related causes and solutions. Understanding this information will help you solve jobsite problems in a shorter period of time.

Problem: Compaction Measurement Values Are Lower Than Expected

Cause: Granular soil is too dry to compact. Added compaction results in soil structure are breaking down and de-compacting the soil.***Solution:*** Add moisture to the soil before compacting further. Granular soils can take a lot of water without becoming too wet, as the water tends to drain away. Add a bit more than ideally required to allow for dryout and drainage.

Cause: Soil composition is clay rather than gravel or granular material. Or, the clay can be buried below surface level and still affect the measurements.
Solution: Remove clay soil if practical, or accept lower values. Alternatively, utilize an energy-based, compactor-integrated compaction measurement technology such as MDP, which is not as affected by cohesive soils.

Cause: Drum is de-coupling on the hardest areas of ground. When the drum de-couples, RMVs are high and compaction measurement values (CMV) tend to read lower than the ground conditions would suggest.
Solution: Reduce amplitude to low setting. If still de-coupling, compaction is complete. Further compaction while de-coupling can cause de-compaction.

Cause: Clay soil is too wet.
Solution: Use a disk, harrow, or rotary mixer to dig up the soil so it can dry before attempting to compact it. Alternatively, utilize an energy-based compactor-integrated compaction measurement technology such as MDP which is not as affected by cohesive soils, but note that the moisture levels may still be unsuitable to achieve proper compaction.

Cause: Material being compacted was placed over a non-compacted or non-stabilized soil base. As a result it is flexing too much during compaction and will not compact.
Solution: The upper layer of soil will need to be removed and the lower layer of soil will need to be remedied. This might involve drying it out and re-compacting, adding lime or some other soil stabilizing agent, or even excavating the poor soil and replacing it.

Cause: The drum frequency is higher than it should be (this is unlikely).
Solution: Drum frequency should be near 30 Hz (1800 VPM) for the most consistent results. Have a mechanic determine why vibration speed is not performing properly and correct it. Alternatively, an energy-based, compactor-integrated compaction measurement technology such as MDP can be utilized in static mode (vibration off) to see if there is any effect on uniformity of compaction results.

Cause: There is a buried object or objects that are not as stiff as the surrounding soil, a pit where trees or other biomass are buried, buried refuse, or a clay ball. It will show up on the map as a relatively localized area.
Solution: Excavate and replace materials with good soil if the situation is serious enough to warrant it.

Cause: Travel speed is too fast.
Solution: Slow down to obtain most efficient productivity and higher compaction values. Utilize automatic speed control if the compactor is equipped with this option.

Cause: Travel direction affects the integrated compaction measurement values.
Solution: This is normal; the values will measure differently in forward than in reverse. There is no solution other than to drive only in one direction or accept the compaction values from only one direction during analysis.

Problem: Compaction Measurement Values Are Higher Than Expected

Cause: Base or sub-base is stiffer soil type than expected.
Solution: None, test using a dynamic cone penetrometer and check sub-soil shear strength. If stronger, accept results as normal.

Cause: Hidden object is buried below the surface. This might be a rock, concrete slab, old pavement, or building foundation.
Solution: Excavate object to achieve uniform compaction.

Cause: Travel speed is occasionally too slow. (This is unlikely unless the operator is trying to compact using a given number of passes).
Solution: Keep speed consistent. Utilize automatic speed control if the compactor is equipped with this option.

Cause: Ground is frozen.
Solution: None.

Problem: Compaction Measurement Values Are Erratic

Cause: Actual soil conditions are varying either at the surface or below surface level. This is more common than people assume. Hidden objects, changes in fill materials and varying water content can all affect compactor-integrated compaction measurement values.
Solution: If serious variations exist and need to be rectified, start with the easiest solutions first. Check soil moisture content and adjust. Excavate hidden objects if necessary and replace soil if critical.

Cause: Compactor-integrated compaction measurement values measured in forward are higher/lower than those obtained in reverse.
Solution: This is normal, and varies with soil type and compaction level. Typically the differences become smaller as the soil becomes more fully compacted.

Cause: Drum is de-coupling while compacting. De-coupling can cause wide variation in the compactor-integrated compaction measurement values, as the average values tend to drop when the drum begins de-coupling on harder ground.
Solution: Change to low amplitude. If de-coupling in low amplitude, the soil has reached the maximum stiffness the compactor can provide. Alternatively, an energy-based integrated roller compaction measurement technology such as MDP can be utilized in static mode (vibration off) to see if there is any effect on uniformity of compaction results.

[THE FUTURE OF INTELLIGENT COMPACTION]

As has been explained, measuring soil stiffness is extremely complex due to all of the variables involved. However, the more IC is used, the deeper your understanding of the capabilities and shortcomings of the technology. As your experience with it grows, new technologies, like Machine Drive Power, will emerge offering further benefits and addressing application issues that the last wave of progress has provided. As time passes, hardware solutions for existing technologies become less expensive, making them more accessible to repurpose for soil compaction applications.

The compactor of the future will likely have multiple measurement technologies available, as each technology has different useful capabilities. New measurement technologies will emerge—perhaps ground penetrating radar, ultrasound or magnetic imaging. Three-dimensional images documenting the entire road structure could be built. Moisture sensing technologies could alert an operator to call for a water truck or a ripper. Every compactor operator would have access to information from all machines on the jobsite (machine-to-machine communications). This provides real-time jobsite progress with advantages most easily seen with a multiple number of compactors or measuring devices. Jobsite superintendents can monitor and use the data to make the most cost-effective decisions on a daily basis.

Looking to the future, data will become more and more important. Data from yet-to-be-developed sensors, and the ability to quickly and easily take the data off the jobsite and into other off-board applications (PC, hand-held tablets, and others) will be an area of specific development. Current technologies already provide more data than can be easily sorted in a way that is useful to today's jobsite managers and inspectors. The capability of off-board data filtering, sorting and ability to create a jobsite report that meets the needs of the end-user will be of huge importance and an area where many specifications will soon be written.

It is an exciting era in the science of compaction and time will tell what advances and technologies will come next, but one thing is certain: With the cost savings, quality and efficiencies provided by intelligent compaction, the technologies will increasingly be required and included in specifications for jobsites worldwide.

APPENDIX

[SOIL CLASSIFICATION SYSTEMS]

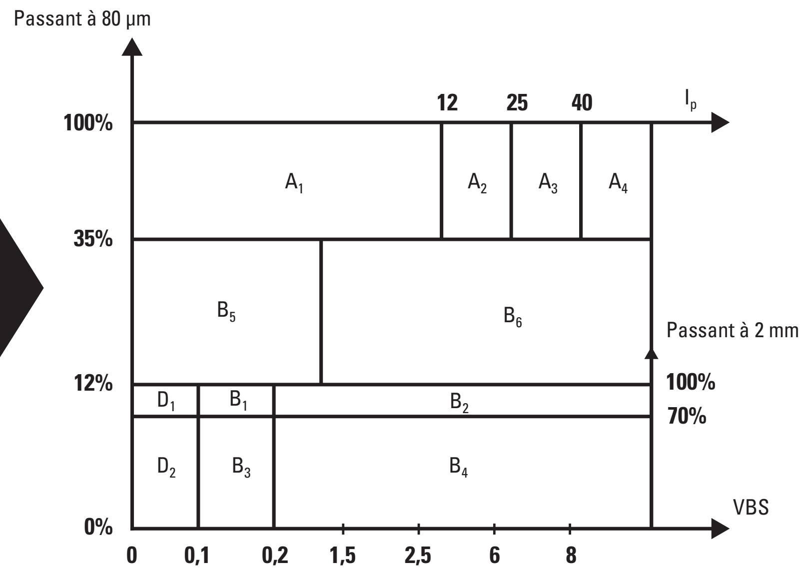
AASHTO CLASSIFICATION OF HIGHWAY SUBGRADE MATERIALS
(with suggested subgroups)

General Classification	Granular Materials (35% or less passing #200)							Silt-Clay Materials (more than 35% passing #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 Percent Passing:											
# 10	0-50										
#40	0-30	0-50	51-100								
#200	0-15	0-25	0-10	0-35	0-35	0-35	0-35	36-100	36-100	36-100	36-100
Characteristics of Fraction Passing #40:											
Liquid Limit				0-40	41+	0-40	41+	0-40	41+	0-40	41+
Plasticity Index	0-6		N.P.	0-10	0-10	11+	11+	0-10	0-10	11+	11+
Group Index	0		0	0		0-4		0-8	0-12	0-16	0-20
Usual Types of Significant Constituent Materials	Stone Fragments Gravel and Sand		Fine Sand	Silty or Clayey Gravel and Sand				Silty Soils		Clayey Soils	
General Rating as Subgrade	Excellent to Good					Fair to Poor					

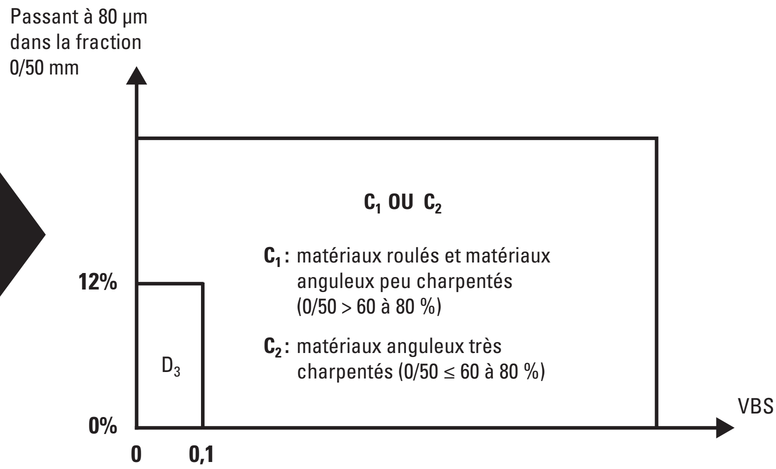
AASHTO Soil Classification System

Tableau synoptique de classification des matériaux selon leur nature

Sols Dmax ≤ 50 mm



Sols Dmax > 50 mm



Matériaux rocheux

Roches sédimentaires	Roches carbonatées	Craies	R_1
		Calcaires	R_2
	Roches argileuses	Marnes, argilites, pélites...	R_3
	Roches siliceuses	Grès, poudingues, brèches...	R_4
	Roches salines	Sel gemme, gypse	R_5
Roches magmatiques et métamorphiques	Granites, basaltes, andésites, gneiss, schistes métamorphiques et ardoisiers...		R_6

Matériaux particuliers

Sols organiques et sous-produits industriels	F

French Soil Classification System

Hauptgruppe	Korngrößenanteil ≤ 0,06 mm	Korngrößenanteil > 2,0 mm	Gruppe (allgemein)	Gruppe (detailliert)	Kurzzeichen Gruppensymbol
Grobkörniger Boden	≤ 5	< 40	Kies	Enggestufte Kiese	GE
				Weitgestufte Kies-Sand-Gemische	GW
				Intermittierend gestufte Kies-Sand-Gemische	GI
			Sand	Enggestufte Sande	SE
				Weitgestufte Sand-Kies-Gemische	SW
				Intermittierend gestufte Sand-Kies-Gemische	SI
Gemischtkörniger Boden	5 bis 40	< 40	Kies-Schluff	5 bis 15 Gew.-% ≤ 0,06 mm	GU
				15 bis 40 Gew.-% ≤ 0,06 mm	GU*
			Kies-Ton	5 bis 15 Gew.-% ≤ 0,06 mm	GT
				15 bis 40 Gew.-% ≤ 0,06 mm	GT*
		≤ 40	Sand-Schluff	5 bis 15 Gew.-% ≤ 0,06 mm	SU
				15 bis 40 Gew.-% ≤ 0,06 mm	SU*
			Sand-Ton	5 bis 15 Gew.-% ≤ 0,06 mm	ST
				15 bis 40 Gew.-% ≤ 0,06 mm	ST*
Feinkörniger Boden	< 40	–	Schluff	Leicht plastische Schluffe $W_L \leq 35$	UL
				Mittelplastische Schluffe W_L=35 bis 50	UM
			Ton	Leicht plastische Tone $W_L \leq 35$	TL
				Mittelplastische Tone W_L=35 bis 50	TM
				Ausgeprägt plastische Tone W_L=50	TA
Organogener Boden	< 40	–	Nicht brenn- und schwelbar	Organogene Schluffe W_L=35 bis 50	OU
				Organogene Tone W_L>50	OT
	≤ 40			Grob bis gemischtkörnige Böden mit humosen Beimengungen	OH
				Grob bis gemischtkörnige Böden mit kalkigen, kieseligen Bildungen	OK
Organischer Boden	–	–	Brenn- und schwelbar	Nicht bis mäßig zersetzte Torfe	HN
				Zersetzte Torfe	HZ
				Mudden (Faulschlamm)	F
Auffüllung[1]	–	–	–	Auffüllung aus Fremdstoffen	A

1 - Eine Auffüllung ist eine unter menschlicher Einwirkung entstandene Schüttung aus natürlichen Böden oder Fremdstoffen.

German Soil Classification System

USCS SOIL CLASSIFICATION SYSTEM			
SOIL FRACTION	**SYMBOL**	**SIZE RANGE**	
Boulders	**None**	Greater than 12”	
Cobbles	**None**	75 mm (3”) to 12”	
1- Course Grained Soils:			
Gravel	**G**	75 mm (3”) to #4 Sieve (4.25 mm)	
Course Gravel		75 mm to 19 mm	
Fine Gravel		#4 Sieve to 19 mm	
Sand Course Sand Medium Sand Fine Sand	**S**	#4 Sieve to #200 Sieve (0.075 mm)	
2- Fine Grained Soils:			
Fines		Less than #200 Sieve	
Silt	**M**	Use Atterberg Limits	
Clay	**C**	Use Atterberg Limits	
3- Organic Soils	**O**	**Use Atterberg Limits**	
4- Peat	**Pt**	**Visual Identification**	
Gradation Symbols		**Liquid Limit Symbols**	
Well-graded	**W**	High LL	**H**
Poorly-graded	**P**	Low LL	**L**

United Soil Classification System

SOIL GROUPS GRAVEL and SAND may be qualified sandy GRAVEL and gravely SAND where appropriate			SUB-GROUPS and in-laboratory identification: GROUP SYMBOL		SUB-GROUP SYMBOL	FINES % < 0.06 mm	LIQUID LIMIT
COARSE SOILS less than 35% of the material is finer than 0.06 mm	**GRAVELS** More than 50% of coarse material is of gravel size (coarser than 2 mm)	Slightly silty or clayey GRAVEL	G	GW GP	GW GPu CPg	0 to 5	
		Silty GRAVEL Clayey GRAVEL	G-F	G-M G-C	GWM GPM GWC GPC	5 to 15	
		Very silty GRAVEL Very clayey GRAVEL	GF	GM GC	GML, etc. GCL GCI GCH GCV GCE	15 to 35	
	SANDS More than 50% of coarse material is of sand size (finer than 2 mm)	Slightly silty or clayey SAND	S	SW SP	SW SPu SPg	0 to 5	
		Silty SAND Clayey SAND	S-F	S-M S-C	SWM SPM SWC SPC	15 to 35	
		Very silty SAND Very clayey SAND	SF	SM SC	SML, etc. SCL SCI SCH SCV SCE	15 to 35	
FINE SOILS more than 35% of the material is finer than 0.06 mm	**Gravelly or sandy SILTS and CLAYS** 35% to 65% fines	Gravelly SILT Gravelly CLAY	FG	MG CG	MLG, etc. CLG CIG CHG CVG CEG		< 35 35 to 70 50 to 70 70 to 90 > 90
		Sandy SILT Sandy CLAY	FS	MS CS	MLS, etc. CLS, etc.		
	SILTS and CLAYS 65% to 100% fines	SILT (M SOIL) CLAY	F	M C	ML, etc. CL CI CH CV CE		< 35 35 to 70 50 to 70 70 to 90 > 90
ORGANIC SOILS		Description letter 'O' suffixed to say group or sub-group symbol			Organic matter in significant amount e.g. MHO – organic silt of high LL		
PEAT		Pt – consists predominantly of plant remains (fibrous or amorphous)					

Classification v1.00 Sept 2010

Primary Letter
G = Gravel
S = Sand
M = Silt
C = Clay
O = Organic Soil
Pt = Peat

Secondary Letter
W = Well graded
P = Poorly graded
M = With non-plastic fines
C = With plastic fines
L = Of low plasticity (LL < 50)
H = Of high plasticity (LL > 50)

United Kingdom Soil Classification System

[COMPACTION REQUIREMENTS]

Compactor integrated devices performing continuous compaction control soil application

BASIC/MINIMUM REQUIREMENTS					
One of the lower 3 blocks (one value)	At least 2 blocks	3 top blocks	Top block or 4 lower blocks	2 lower blocks	At least one block
		Time stamp	Close-loop mode		
Qualitative observation (ex: double-jump...)		Mapping on board	Actual N passes	Data post-treatment facilities, & additional information	
Dimensional bearing capacity (ex: modulus...)	Number of passes (actual vs. target value)	Automatic positioning on board 2D or 3D	Actual frequency	Result by histogram and statistics	Data exchange between machines
Dimensional (ex: stiffness...)	Relative evolution (% related to target values D or ND)	Manual positioning 2D + layer (optional)	Actual amplitude A0	Result by distance or surface	Remote data exchange
Non-dimensional value	End of compaction (D or ND)	Distance 1D	Actual speed V	Identification of machine and CCC device	Data exchange from office (USB stick)
1 Behaviour of the material (dynamic response)	2 Status of compaction (Comparison)	3 Positioning, traceability during process	4 Operational information (record and display)	5 Control report, documentation	6 Communication, others

From the pamplet *CECE – Guidelines to evaluate soil and asphalt compactors equipped with continuous compaction control (CCC)*

GLOSSARY OF TERMS

- A -

Aggregate	The granular, load-bearing mineral component of a road structure, usually sand, gravel, shells, slag, crushed stone or fines.
Amplitude	The measure of one-half of the total peak-to-peak vertical movement of a vibrating drum per complete cycle.
Atterberg Limits Method	A set of standards that describe seven stages of soil characteristics moving from a solid to a liquid. The most important stages are the Plastic Limit and the Liquid Limit.

- B -

Base	Also referred to as the "base course"; a layer of specified or selected material of planned thickness constructed on the sub-base for the purpose of serving one or more functions including distributing the load, providing drainage and minimizing frost action.

- C -

Calibration	The process of adjusting the parameters of the system to maximize its capabilities for use in the site material.
Capillarity	The ability of a material to absorb water upward or laterally.
Centrifugal Force	The force that causes a rotating, unbalanced weight to accelerate away from its axis.
Clay	A fine-grained mineral material (soil) that uses electro-chemical surface charges to bond well with water.
Coarse-grained Soil	A classification for soil comprised of particles (grains) that lack cohesion. Sand and gravel are considered coarse-grained soils. Coarse-grained soils are defined as well-graded or poorly-graded, which reflect the ability of the soils to be compacted.
Cohesion	The ability of a material to maintain its strength when unconfined; i.e. cling together and maintain its form through changes in moisture content or submersion.
Compaction	The process of reducing voids in a material through the use of mechanical manipulation; increasing the density.
Compactability	The degree to which a soil material is able to overcome material-specific deformation resistance.
Compaction Meter Value (CMV)	An indication of soil stiffness calculated by measuring the G-forces at the vibratory frequency of the drum and at the first harmonic (2x the vibratory frequency of the drum).
Compaction Meter Value Method	A method of indicating soil stiffness invented by the Swiss firm Geodynamik and utilized by Caterpillar.
Compressibility	The rate at which a material reduces in volume when a force is applied to it.

- D -

De-compaction — A loss of compaction due to re-application of unnecessary compactive force.

De-coupling — Also referred to as "double-jumping"; is a phenomenon where the drum rebounds from a vibratory impact and bounces high enough to allow the next vibration to occur while the drum is still in the air.

Density — The measure of mass per unit of volume; a traditional indicator of load-bearing strength.

Double-jumping — See De-coupling.

- E -

Elasticity — The tendency of a material to return to its original (or near original) shape after a compressive load is removed.

Embankment — Any fill whose top is higher than the adjoining surface.

Energy Method — The principle behind Machine Drive Power (MDP), a Caterpillar proprietary method of determining compaction by measuring the energy required to drive over the soil (rolling resistance).

- F -

Fines — Generally, materials of very small particle size falling below a certain threshold established by sieve testing. Fines will pass through the smallest sieve. Organizations around the world have independent definitions of the precise sieve size, but they are approximately the same.

Fine-grained Soils — Soils composed predominantly of fines.

Force/Displacement Method — A method of indicating soil stiffness by using drum characteristics and drum acceleration measurements to calculate drum displacement.

Frequency — A measure of the number of complete cycles (e.g. vibrations) over a given length of time.

- G -

Global Navigation Satellite System (GNSS) — An overarching term used to describe satellite based mapping technologies, including GPS and GLONASS.

Global Positioning System (GPS) — A US controlled worldwide radio-navigation system composed of a constellation of 24 satellites and their ground stations.

GLONASS — A Russian satellite constellation similar to GPS.

Grade — The inclination of a surface.

Gradation — The size range of individual soil particles.

Gradient of Compaction — The degree of compaction throughout the depth of influence. Soil will tend to be less compact at the surface, be more compact through a large central zone, and become less compact again toward the extreme depth of influence.

Grain — A mineral particle.

Grain-size Distribution — The measure of the range and distribution of different particle sizes in a soil.

Gravel — A coarse-grained mineral material; defined by the USCS as those particles less than 75 mm (3 in) in diameter not passing through a #4 sieve.

- I -

Impact — A force of increased magnitude created by causing static pressure to become dynamic, e.g. dropping a weight. Low-frequency or irregular frequency blows (blows of 50-600 blows per minute) are considered impact forces.

Intelligent Compaction — Generally speaking, intelligent compaction can be defined as a compactor integrated technology applied to the compaction process that improves worksite efficiencies by eliminating human guesswork.

- L -

Lift — A single layer of placed soil material. It can vary in thickness.

Linear Load — The measure used by the industry to compare the compaction potential of static smooth drum compactors.

Liquid Limit — A highly significant Atterberg Limit; the point at which a soil contains so much water that it is considered a liquid.

Load-bearing Strength — The ability of a material to support a load.

- M -

Machine-integrated Compaction Measurement — Conducting compaction measurement with technologies incorporated into the machine performing the compaction.

Manipulation — A kneading process that rearranges particles into a more dense mass.

Moisture Content — The amount of liquid (water) per volume of a mass.

- N -

Natural Frequency — The frequency at which a mass vibrates due to its own characteristics.

- P -

Particle Distribution — See Grain-size Distribution.

Pass — The number of times a compactor will pass over an area of ground. Sometimes, a "pass" will be defined as a round trip forward and back, passing over a particular area twice; and other times a pass will mean a single instance that a compactor travels over an area. Caterpillar defines a pass as a single trip over an area in either a forward or reverse direction.

Permeability — A material's ability to allow the passage of a gas or liquid.

Plasticity — The property of a fine-grain soil that allows it to deform beyond the point of recovery without cracking or appreciable volume change.

Plasticity Index — The difference between the Liquid Limit and the Plastic Limit of a soil. This measure is used to determine the extent of soil stabilization required for fine-grained soils.

Plastic Limit — A highly significant Atterberg Limit; the point at which a soil retains enough moisture to become plastic.

Poorly-graded	Also referred to as uniformly-graded; the quality of coarse-grained soils to contain particles of relatively uniform size, making it difficult to compact.
Proctor Test (Standard or Modified)	A laboratory test that determines the maximum dry density of a soil material as well as the optimum water content to achieve maximum density.
Production Mode	A compactor system setting that optimizes system useability for high-production applications where accuracy is not the main goal.
Proofing Mode	A compactor system setting that optimizes system useability for high-accuracy applications where machine productivity is not the main goal.

- Q -

Quality Assurance (QA)	The testing methods and data that the project owner uses to document the quality of the compaction achieved on a project.
Quality Control (QC)	The procedure a contractor implements to ensure that the compaction work will be completed to specification.

- R -

Remediation	The process of altering the soil by chemical or mechanical means to improve its engineering properties.
Resonance	The convergence of the vibratory frequencies of two vibrating masses.
Resonance Meter Value (RMV)	An indication of the degree to which the drum is de-coupling.
Resonant Frequency	For vibratory compactors, the point at which vibrating soil material contributes to the vibration of the compactor enough to cause the compactive effort to exceed the centrifugal force generated; i.e. the output is greater than the effort.
Rolling Resistance	The amount of energy required to roll a round shape through a material.

- S -

Sand	A non-cohesive mineral particle of a defined size and shape.
Settlement	The process of decreasing surface elevation due to consolidation of fill material.
Shear Resistance	The ability of a soil's particles to resist sliding across each other when a compactive force is applied.
Silt	A non-cohesive, fine-grained mineral material (soil).
Soil	Unconsolidated material composed of mineral particles that may or may not contain organic substances.
Soil Stabilization	The process of maximizing the suitability of soil for a given construction purpose.
Static Pressure	A weight applied to the compaction effort.
Station	A non-standard area defined by engineers and marked by stakes at the jobsite for the purpose of controlling preparation by manageable sections.
Stiffness (Soil)	The ability of a material (soil) to resist deflection under load; a primary indicator of load-bearing strength.
Sub-base	A layer between the sub-grade and base.
Sub-grade	The soil prepared to support a traffic structure. Essentially, it performs as the foundation of the structure, and is sometimes referred to as "basement soil" or "foundation soil."

- T -

Texture	A quality that defines the surface friction of a soil particle.
Total Applied Force	A calculation of the maximum amount of vibratory energy that a compactor can apply to the ground.

- U -

Uniformity	The maintenance of consistency in materials and applications.
Uniformity Coefficient	A parameter to describe the particle size distribution (grading curve) of a soil.
Uniformly-graded	Also referred to as poorly-graded; the quality of coarse-grained soils to contain particles of relatively uniform size, making them difficult to compact.

- V -

Vibration	A high-frequency series of blows (1400-4000 blows per minute) that produce a rapid succession of pressure waves. Vibrations produced by a compactor can break the bonds between particles of a material that is being compacted.
Void	The space in a volume of material not occupied by solid mineral material.

- W -

Well-graded	The quality of coarse-grained soils to contain particles of many sizes, making them easier to compact.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