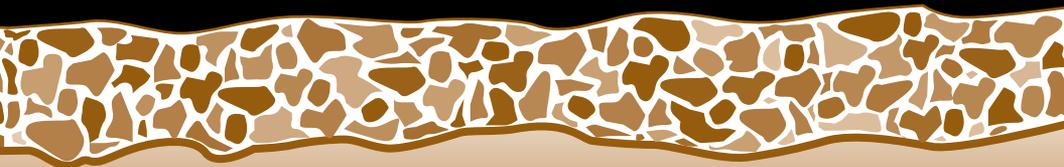


SOIL

FUNDAMENTALS



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Part 1

Soil Mechanics

WHAT IS SOIL?

Soils are deposits of disintegrated rocks, broken down into small particles by natural physical and chemical weathering processes. These weathering processes include freezing and thawing, rolling and grinding, or blowing, as dust in the air. The resulting granular particles (called gravels, sands, or silts) are essentially miniature boulders. Clay is formed by chemical processes, created by the long term action of warm and cold climates, with rainfall. Clay consists of tiny, flat particles possessing a distinct plate-like structure. Clay particles can be derived from a wide variety of parent rocks. Plant growth also contributes to the formation of soils. When plants die, their residue becomes part of the soil. This organic matter is generally too spongy and weak to be used for structural purposes, however.

SOIL GROUPS

Soils vary widely in physical and chemical properties. Five distinct soil groups are recognized based on individual particle size and/or shape.

1. *Gravel* Individual particles vary from 3 inches (76.2 millimeters) maximum size to the number 10 sieve (2.0 millimeters) in diameter. Gravel particles often have a rounded appearance or can appear sub-angular in shape.
2. *Sand* Smaller rock or mineral fragments, from the number 10 sieve (2.0 millimeters) to the number 200 sieve (0.074 millimeters) in diameter. Sand particles normally have a sub-angular or semi-sharp appearance.

3. *Silt* Fine grained particles which have a soft and floury texture when dry. When moist and pressed between the thumb and fore finger, silt will have a broken surface appearance.
4. *Clay* Very fine textured soil particles which form hard lumps or clods when dried. When moist, clay is very sticky and can be rolled into a ribbon between the thumb and forefinger.
5. *Organic* Consists of either partially decomposed vegetation (peat) or finely divided vegetable matter (organic silt and clay).

GRAIN SIZE LIMITS

Most soils consist of mixtures of the five basic soil types and are identified according to the classifications and amounts of each soil type included, such as sandy clay, clayey sand, silty gravel or gravelly silt. The physical mineral particles of soils are divided into five types, each with a specific physical grain size range, as shown in the chart below.

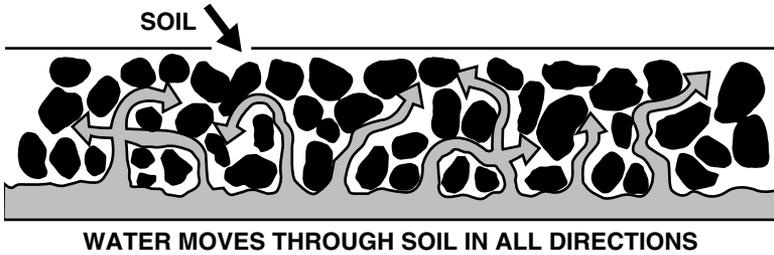
GRAIN SIZE LIMITS FOR SOILS			
NAME	SIZE IN INCHES	SIZE IN MILLIMETERS	SIEVE NO.
Gravel	3.0 to 0.08	76.2 to 2.0	3 in. to No. 10
Sand	0.08 to 0.003	2.0 to 0.074	No. 10 to No. 200
Silt	0.003 to 0.0002	0.074 to 0.005	
Clay	Less than 0.0002	Less than 0.005	
Colloids	Less than 0.00004	Less than 0.001	

SOIL PROPERTIES AND CHARACTERISTICS

Soils engineers and technicians use a variety of terminology to express the properties and characteristics of various materials. A basic knowledge of these terms and their application to soils and the compaction of soils will provide a more thorough understanding of important soil properties and characteristics. It will also provide additional background information for the selection of the proper compaction equipment for a particular job.

Capillarity is a fine-grained soil's capacity to absorb water and transmit it in all directions. Capillary action can damage embankments sealed by pavement since the water cannot escape. The trapped water softens and expands the subgrade, resulting in an inadequately supported surface and pavement. The following illustration depicts water movement through a soil by capillarity.

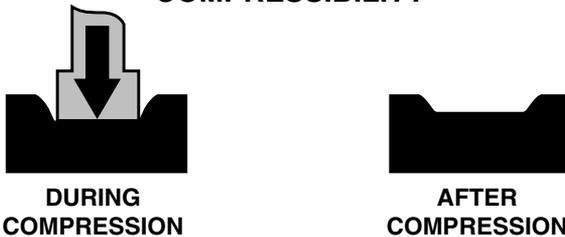
CAPILLARITY



By placing an insulating layer of sand, gravel or rock between the soil and water source, capillary action can be prevented. The proper placement of an insulating layer of rock between a wet embankment and pavement structure will protect the pavement from water damage.

Compressibility refers to the reduction in soil volume which occurs when force is applied to it. Air between the particles is compressed or escapes and any water that may be present has been squeezed out. As a result, the soil particles are spaced closer together and occupy less volume. The effects of compression on a soil are depicted in the illustration below.

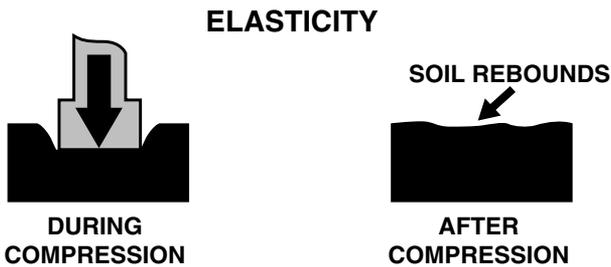
COMPRESSIBILITY



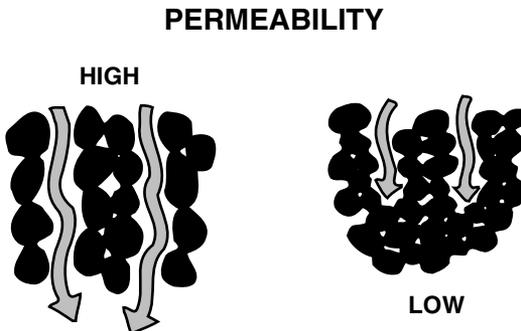
Consolidation refers to the increase in density of fill material under actual service conditions. Consolidation results from presence of permanent loads

or because of the passage of traffic. Relatively long periods of time usually transpire before consolidation takes effect. This is considered a natural process, as compared to compaction which is an artificial process.

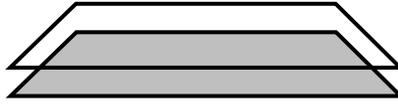
Elasticity is the property of any material to recover its size and shape after deformation. Elasticity is the measure of the ability of a soil to return, fully or partially, to its original form after a compressive load is removed. Pavement surfaces underlain by elastic soils will deteriorate because of their constant flexing under loads. Elastic soil rebound is illustrated below.



Permeability is that property of a material which allows fluid to pass through it; in the case of aggregates or soils, specifically, water is able to permeate. Coarse-grained soils like sands and gravels are very permeable. Fine-grained soils like silts or clays, are least permeable. Permeability of most soils, as illustrated below, is dependent upon particle size, gradation and relative density (particle spacing and orientation).



SETTLEMENT

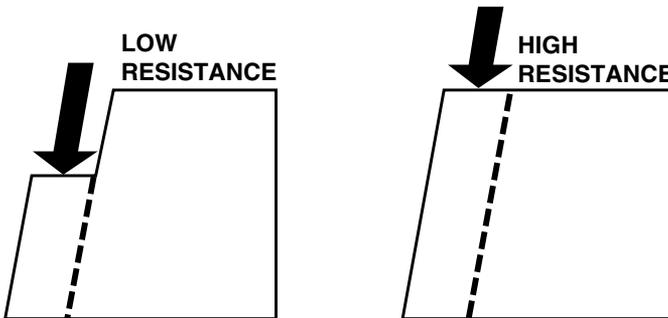


Settlement is the action which occurs in an embankment to decrease its surface elevation. This is accomplished through consolidation of the fill materials within the embankment. When settlement occurs unevenly in the structure, failure of the structure or support mechanism can result. The illustration above depicts the effect of settlement on an embankment.

Shearing resistance is the ability of soil particles to resist sliding past one another whenever force is applied (see below).

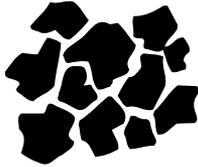
There are two mechanical properties of soil which determine its shearing resistance. The property of granular or coarse-grained soils which provides shearing resistance is termed *internal friction*. Internal friction results from the soil particles' resistance to sliding over each other. This force is high in gravel and sand and much lower in silt or clay. The property of fine-grained soils to resist movement is termed *cohesion*. Cohesion is the result of attraction between the water-coated surfaces of fine-grained soils. Cohesion is low in coarse-grained materials like gravel or sand and high in fine-grained silt and clay. Soils which possess high bearing capacity may contain gravel and sand in sufficient quantity to contribute high friction, plus sufficient fine-grain material to provide adequate cohesion. Friction and cohesion between particle shapes is illustrated on page 6.

SHEARING RESISTANCE

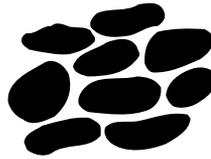


SHEARING RESISTANCE DEPENDS ON . . .

1. INTERNAL FRICTION

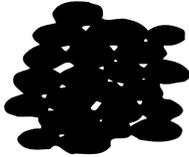


HIGH FRICTION



LOW FRICTION

2. COHESION



HIGH COHESION



LOW COHESION

Shrinkage occurs in fine-grain soils as water within the soil is lost through evaporation. Sand and gravel shrinkage is very slight; clays shrink a great deal. Soil which shrinks when dried, and expands when wet, provides a poor foundation. The resulting movement can cause structural failures in pavements or buildings dependent on their support. The illustration below shows the effect of shrinkage of a fine-grained soil.

SHRINKAGE



SOIL ANALYSIS

Soils have infinitely diverse characteristics. It may be necessary to consult records of similar soils to predict the behavior of any given sample. However, several systems for identifying and classifying soils with similar properties have been developed and are in widespread use today. Some standard must be employed to properly evaluate any soil, and to predict its suitability for construction purposes. These standards for soil analysis, and their relative merits, will be discussed later in this section. However, all of these systems are based on two factors: the relative percentages of coarse-grained and fine-grained material present; the plastic qualities of the fine-grained material.

Sieving or the separation of a soil sample into its various size grains, and the measurement of the percentages of each within a sample, is performed by sifting a dry sample through progressively smaller sieves and weighing the amount caught on each.

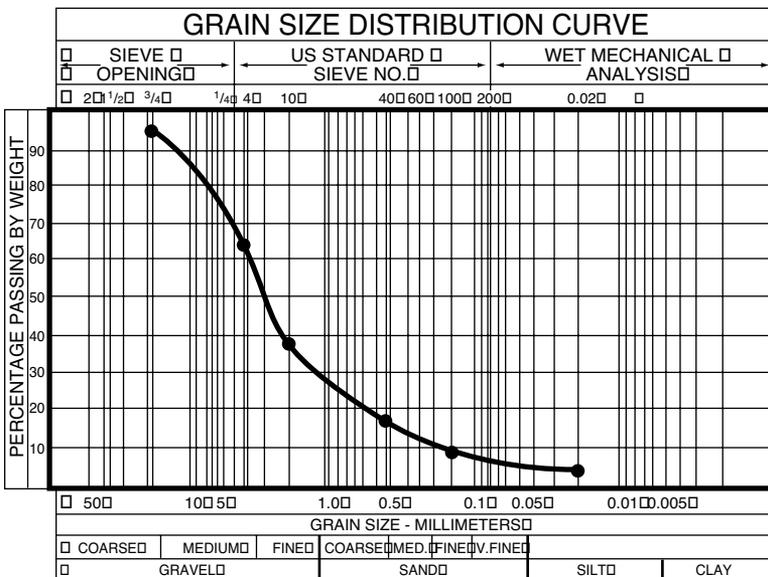


The distinction is, therefore, strictly based on the sizes of individual grains. A sieve analysis is conducted by separating the soil grains on sieves having physical openings between 3 inches (76.2 millimeters) in dimension down to the number 200 sieve (0.074 millimeters). In the United States and Canada, sieve sizes of 1/4 inch (6.35 millimeters) and larger are expressed in inches. Smaller sieves are denoted by the number of openings per inch of wire mesh screen. For the 1/4 inch sieve, each opening is 1/4 inch square. For the number 200 sieve, each opening measures 0.003 inches.

To determine material gradation, the amount of material retained on each size sieve is weighed and compared to the weight of the original sample. The percentage, by weight, of each grain size is then calculated. The chart on page 8 shows a typical sieve analysis for a coarse-grained soil material.

TYPICAL SIEVE ANALYSIS				
SIEVE OR SCREEN SIZED	SIEVE OPENING (MILLIMETERS)	WT RETAINED ON SIEVE (GRAMS)	WT PASSING SIEVE (GRAMS)	%
2"	50.8			
1-1/2"	38.1			
1"	25.4	0	431	100.0
3/4"	19.1	20	411	95.4
1/4"	6.35			
No. 4	4.75	126	285	66.1
No. 10	2.00	121	164	38.1
No. 40	0.42	86	78	18.1
No. 60	0.25			
No. 100	0.149	37	41	9.5
No. 200	0.074	15	26	6.0

Particles smaller than 0.003 inches (0.074 millimeters) which pass through the number 200 sieve are separated by a wet analysis hydrometer test, Their percentage by weight also recorded. Upon completion of the dry analysis sieve test and wet analysis hydrometer test, the results from both tests are represented on a grain size distribution curve, as illustrated below.



On this *Grain-Size Distribution Curve*, the vertical scale represents the percent-by-weight of the total sample passing or retained on each sieve. The horizontal scale identifies the sieve opening size and wet mechanical analysis grain sizes. The steeper the slope of the curve, the more uniform the entire range of grain sizes. Therefore, a vertical line would represent a material sample containing only one, uniform particle size. To the soils engineer, this represents poorly-graded material.

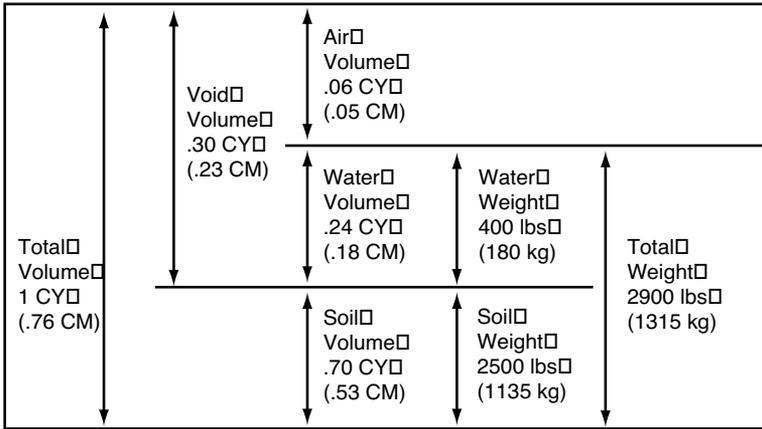
If the slope of the plot line of grain size distribution is at 45 degrees, this indicates representation of the entire range of particle sizes possible. This is considered to be well-graded material by the soils engineer. Recording the grain-size distribution of soil samples by this means, therefore, enables simple, accurate classification of soils.

MOISTURE CONTENT

Classification by particle size alone is satisfactory for all granular soils, and for most fine-grained soils. However, some fine-grained soils can exhibit dramatically different behaviors, even when they have equal particle sizes. This is due to the influence of moisture content on the physical properties of many soils, especially predominantly fine-grained ones. Some physical relationships between properties and moisture content can be determined by laboratory tests. Knowing the results of these tests and the percentage moisture of a soil enables the the engineer to group soils according to their physical characteristics.

The moisture content of a soil is the ratio of the weight of water within the soil to the total weight of the dry soil sample. It is measured by weighing the soil wet, then drying and weighing it again; the difference between the wet and dry weights represents the weight of the water. Moisture content is usually expressed as a percentage, calculated by dividing the weight of the water by the weight of the dry sample.

The relationships between air, water and soil can be expressed on both a volume and a weight basis. This relationship is depicted on page 10, for a loose cubic yard of damp soil. Imagine that the air, water and soil particles are neatly sorted out by weight and volume.



Generally, there are three types of water or moisture recognized by soils engineers. The type and amount of water occurring in a soil can have a great influence on its performance.

Gravitational water is water that can drain naturally through or from a soil, freely, due to the force of gravity.

Capillary water is moisture which is held in a soil by small pores or voids. Capillary water is considered free water which can be removed only by lowering the water table or through evaporation.

Hygroscopic water is moisture still present in a soil after gravitational and capillary water are removed. This water is retained by individual soil grains in the form of a very thin film which has physical and chemical affinity for the soil grains. It is also referred to as “air-dry” moisture content.

ATTERBERG LIMITS

Certain measures of soil consistency, the Liquid Limit, Plastic Limit, Shrinkage Limit and Plasticity Index, were developed by A. Atterberg, a Swedish soil scientist. These moisture content evaluations, named the Atterberg Limits in honor of their discoverer, are discussed below. It should be noted that the Atterberg Limits are the basis for differentiating between highly plastic, slightly plastic and non-plastic materials.

Liquid Limit (LL) The liquid limit is the moisture content at which a soil passes from a plastic to a liquid state. To illustrate this, select a wet sample of a plastic soil and knead it gently between the fingers; then place the soil in the shallow bowl of the testing apparatus, flattening it out. Next, make a deep groove in the wet soil. Then mechanically tap the bowl against the base of the apparatus ten to twenty times, watching the groove. If the faces of the groove remain the same distance apart, remove the sample from the bowl and add more water to the soil. Repeat the test process. When the two sides of the sample come in contact at the bottom of the groove along a distance of about one-half inch (13 millimeters) after approximately 25 test blows, the sample has become liquid and it is said to have reached its Liquid Limit.



The procedure described above is a somewhat simplified explanation of the official AASHTO test method T 89, Determining the Liquid Limit of Soils. It does, however, illustrate the means by which a soil's LL is found. The value of the liquid limit test is that it indicates the moisture content at which a soil overcomes internal friction and cohesion by lubrication. High LL values, as determined by this laboratory test, are associated with soils of high compressibility. Liquid limit of soil is directly proportional to its compressibility.

Plastic Limit (PL) The plastic limit of a soil is the moisture content at which the soil changes from a semi-solid to a plastic state. It is considered to prevail when the soil contains just enough moisture that a small sample of it can be rolled into a one-eighth inch (3 millimeters) diameter thread without separating.



The plastic limit of a soil is considered to have several significant values. It represents the moisture content at which particles slide over each other yet still possess appreciable cohesion. The strength of a soil has been proved to decrease rapidly as moisture content increases beyond the PL. The plastic limit is the moisture content at which soil sticks most readily to metallic surfaces and also where best compaction is achieved with pure clay soils.

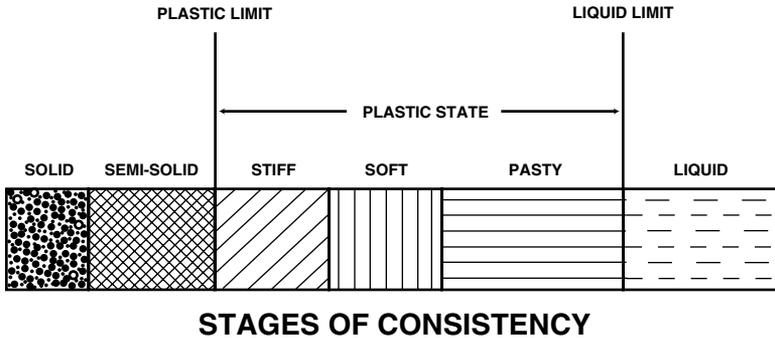
Plasticity Index (PI) The plasticity index of a soil is the numerical difference between the soil's liquid limit and plastic limit. Soils having high PI values are quite compressible and have a high degree of cohesion. A soil with a PI of zero is cohesionless or non-plastic.

Soil has little or no cohesion when moisture content is at the liquid limit, but it still has considerable cohesion remaining when the moisture content is at the plastic limit. Therefore, the PI provides a means of measuring the compressibility and cohesion of a soil. PI also indicates soil permeability. The higher the PI, the lower the permeability, and vice versa. On many jobs, the specifications will call for material with a certain gradation, a maximum liquid limit and a maximum Plasticity Index.

Shrinkage Limit (SL) As soil is dried below the plastic limit it shrinks and gets brittle until finally all the particles are in contact and the soil can shrink no further. This point is called the shrinkage limit. The soil still has moisture within it but if any of this moisture is lost by further drying, air

has to enter the soil to replace it. The SL is the best moisture at which to compact many non-plastic soils. Soils containing enough clay to give them a low plasticity index are best compacted somewhere between SL and PL.

The relationships among the liquid limit, plastic limit and shrinkage limit for soil consistency are shown in the illustration below.



Soil Color As soil moisture content varies, so does its color. Determinations on color are always done with soil in a moist condition; moisture content is always recorded.

Color indicates certain soil characteristics as well as the presence of certain compounds. Dark brown to black colors usually indicate organic matter. Reddish colored soils indicate unhydrated iron oxides (hematite) which are usually well drained. Yellow to yellowish-brown soils indicate the presence of iron or hydrated iron, but are poorly drained. Grey to greyish-blue and yellow mottled colors also usually indicate poor drainage. White indicates the presence of measurable silica or lime, or aluminum compounds, in some instances.

SOIL CLASSIFICATION

Although there are five different agency soil classification systems in use today, only the three most commonly used will be covered. They all use the same terminology of gravel, sand, silt and clay. However, each has slightly different numbering or lettering.

AASHTO CLASSIFICATION SYSTEM

The American Association of State Highway and Transportation Officials system for soil classification is the most widely known and used. This classification system is based on field performance of materials used for construction of highways. This system was formerly called the Bureau of Public Roads Soil Classification.

AASHTO SOIL GROUP DESCRIPTIONS

Granular Materials:

group A-1 -- Well-graded mixtures of stone fragments or gravel ranging from coarse to fine with a non-plastic or slightly plastic soil binder; also includes coarse materials without soil binder.

subgroup A-1-a -- Materials consisting predominantly of stone fragments or gravel, either with or without a well-graded soil binder.

subgroup A-1-b -- Materials consisting predominantly of coarse sand either with or without a well-graded soil binder.

group A-2 -- A wide variety of granular materials that are classify borderline between group A-1 and group A-3 and the silt-clay materials of group A-4, group A-6 and group A-7; group A-2 includes all materials with 35 percent or less passing the number 200 sieve (0.074 millimeters) which cannot be classified as either group A-1 or group A-3.

subgroups A-2-4 and A-2-5 -- Include various granular materials containing 35 percent or less passing the 200 sieve (0.074 millimeters), with that portion passing the 40 sieve (0.425 millimeters) having characteristics of the A-4 and A-5 groups; include such materials as gravel and coarse sand with silt contents in excess of limitations of group A-1, and fine sand with non-plastic silt content in excess of limitations of group A-3.

subgroup A-2-6 and A-2-7 -- Include materials similar to subgroup A-2-4 and A-2-5 except that the fine portion contains plastic clay having the characteristics of groups A-6 or A-7 ; approximate combined effects of plasticity indexes in excess of 10 and in excess of 15 percent passing the 200 sieve (0.075 millimeters) is reflected by group index values of 0 to 4.

group A-3 -- Material consisting of sands deficient in coarse material and soil binder; typical is fine beach sand or desert blow sand without silt or clay fines and with very small amount of non-plastic silt.

Silt-clay Materials:

group A-4 -- Typical material is non-plastic or moderately plastic silty soil having 75 percent or more passing the 200 sieve (0.074 millimeters); group includes mixtures of fine silty soil with up to 64 percent of sand and gravel retained on the number 200 sieve (0.074 millimeters). Group index ranges from 1 to 13; increasing percentages of coarse material is reflected by decreasing group index value. Predominantly silty soils with texture varying from sandy loams to silty and clayey loams.

group A-5 -- Typical material is similar to group A-4, except it is usually diatomaceous or micaceous and may be highly elastic as indicated by high liquid limit. Group index values range from 1 to more than 50, with increasing values indicating combined effect of increasing liquid limits and decreasing percentages of coarse material. Normally elastic or resilient in both damp and semi-dry conditions.

group A-6 -- Typical material is plastic clay soil usually having 75 percent or more passing 200 sieve (0.074 millimeters); includes mixtures of fine clayey soils and up to 64 percent sand and gravel retained on 200 sieve (0.074 millimeters). Materials usually have high volume change between wet and dry states. Group indexes range from 1 to 40; increasing values indicating combined effect of increasing plasticity indexes and decreasing percentages of coarse material.

group A-7 -- Typical materials are similar to group A-6 except they have high liquid limit characteristic of A-5 and may be elastic as well as subject to high volume change. Range of group index is from 1 upward, with increasing values indicating combined effect of increasing liquid limits and plasticity indexes and decreasing percentages of coarse material.

subgroup A-7-5 -- Includes materials with moderate plasticity indexes relative to liquid limit which may be highly elastic as well as subject to considerable volume change.

subgroup A-7-6 -- Includes materials with high plasticity indexes in relation to liquid limit which are subject to extremely high volume change.

UNIFIED SOIL CLASSIFICATION SYSTEM

Professor Arthur Casagrande proposed the Airfield Classification System, now called the Unified Soil Classification System, as a means of classifying soils in accordance with their values as subgrades for roads and airfields. The Unified system was used by the U.S. Army Corps of Engineers as early as 1942 and was adopted by the U.S. Bureau of Reclamation in 1952. This soil classification system uses *texture* as the defining characteristic. It is based on plasticity-compressibility for soils where fines affect behavior. Symbols are used to identify textural groups, as shown in the chart below. Group symbols and modifiers are described on pages 17 and 18.

MAJOR DIVISIONS		GROUP SYMBOL	TYPICAL NAMES	
Coarse-grained soils (More than half of material is larger than No. 200 sieve size)	Gravels (More than half of coarse fraction is larger than No. 4 sieve size)	GW	Well-graded gravel, gravel-sand mixtures, little or no fines	
		GP	Poorly graded gravels, gravel-sand mixtures, little or no fines	
		GM ^U GM ^L	Silty gravels, gravel-sand-silt mixtures	
		GC	Clayey gravels, gravel-sand-clay mixtures	
		SW	Well-graded sands, gravelly sands, little or no fines	
	Sands (More than half of coarse fraction is smaller than No. 4 sieve size)	Clean sands (Little or no fines)	SP	Poorly graded sands, gravelly sands, little or no fines
			SM ^U SM ^L	Silty sands, sand-silt mixtures
		Sands with fines (Appreciable amount of fines)	SC	Clayey sands, sand-clay mixtures
			ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
Fine-grained soils (More than half of material is smaller than No. 200 sieve)	Silt and clays (Liquid limit less than 50)	OL	Organic silts and organic silty clays of low plasticity	
		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soil, elastic silts	
		CH	Inorganic clays of high plasticity, fat clays	
	Silt and clays (Liquid limit greater than 50)	OH	Organic clays of medium to high plasticity, organic silts	
		Pt	Peat and other highly organic soils	
	Highly organic soils			

SYMBOLS

Coarse-Grained Soils:

The coarse-grained soils have 50 percent or less material passing the 200 sieve (0.074 millimeters).

G signifies *Gravel*, with individual particles smaller in size than 3 inches (75 millimeters) but larger than 1/4 inch (6 millimeters).

S identifies *Sand*, particles are smaller than 1/4 inch (6 millimeters) but larger than the 200 sieve (0.074 millimeters) which is large enough to see without magnification.

Fine-Grained Soils:

The fine-grained soils have 50 percent or more material passing the 200 sieve (0.074 millimeters).

M represents *Silt*, particles smaller than the 200 sieve (0.074 millimeters) which plot below the "A" line on the plasticity chart. Silts are fine-grained soils with individual grains too small to be seen without magnification.

C signifies *Clay*, particles smaller than the 200 sieve (0.074 millimeters) which plot above the "A" line on the plasticity chart. Clay particles are also too small to be seen with the naked eye.

MODIFIERS

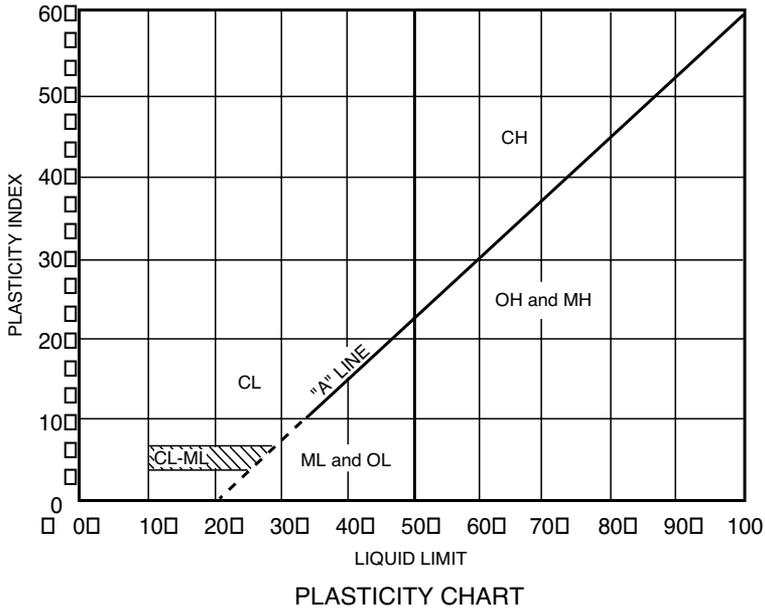
Gravel and Sand:

W symbolizes *Well-Graded* gravelly and sandy soils with little or no non-plastic fines. Well-graded soils contain large, medium, and small sized grains; the presence of fines must not noticeable change the strength of the coarse-grained fraction nor interfere with free-draining characteristics.

P indicates *Poorly Graded* gravels and sands with little or no non-plastic fines. These materials have uniformly-sized grains and may be classed as uniform or gap-graded.

M represents the Swedish term *Mjåla* (flour) which describes silt. Silty gravels or silty sands having more than 12 percent fines but having low or no plasticity. Their liquid limit and plasticity index will plot below the "A" line on the plasticity chart. Normally these soils have little to no dry strength.

C describes *Clayey* gravels or clayey sands with no or little plasticity, with more than 12 percent fines passing the 200 sieve (0.074 millimeters). The liquid limits and plasticity indexes of these soils should plot above the “A” line on the plasticity chart. This Plasticity Chart is depicted below.



Silt and Clay:

L indicates a *Low* Liquid Limit. The arbitrary value between low and high liquid limits is set at 50. Any plastic soil with a Liquid Limit value lower than 50 is said to have a low Liquid Limit.

H indicates a *High* Liquid Limit. Any silt or clay soil having a Liquid Limit value higher than 50 is described to have a high Liquid Limit.

Modifiers can be combined to describe soils more completely. Sandy silt or inorganic silt with relatively low plasticity is classed as group ML. A CH group describes inorganic clays of medium to high plasticity, for example, bentonite, fat clays, gumbo clays and certain volcanic clays.

FAA CLASSIFICATION SYSTEM

The Federal Aviation Agency Classification System is based on a gradation analysis and the plasticity characteristics of soils. The textural classification is based on the material that will pass the No. 10 sieve and the use of a chart defining sand, silt, and clay.

SOIL GROUP DESCRIPTIONS:

E-1 -- Well graded coarse granular soils with over 40 percent coarse sand, less than 60 percent fine sand and less than 15% fines.

E-2 -- Coarse granular soils with over 15 percent coarse sand, less than 85 percent fine sand and less than 25 percent fines.

E-3 -- Poorly graded sandy soils with less than 25 percent fines and PI less than 6.

E-4 -- Poorly graded sandy soils with less than 35 percent fines and PI lower than 10.

E-5 -- Mixed soils with less than 45 percent fines with PI lower than 15 and a Liquid Limit under 40.

E-6 -- Silts with over 45 percent fines of Plasticity Index lower than 10.

E-7 -- Silts with over 45 percent fines, Plasticity Index between 10 to 30 and Liquid Limit under 50.

E-8 -- Silts with over 45 percent fines, Plasticity Index between 15 to 40 and Liquid Limit under 60.

E-9 -- Silts with over 45 percent fines, plasticity Index under 30 and Liquid Limit over 40, often containing mica or other elastic particles.

E-10 -- Silts or clays with over 45 percent fines, Liquid Limit under 70 and PI between 20 to 50.

E-11 -- Silts or clays with over 45 percent fines, Liquid Limit less than 80 and Plasticity Index higher than 30.

E-12 -- Silts and clays with over 45 percent fines and LL above 80.

E-13 -- Muck and peat; organic materials.

There are some simple field tests which may be used to classify various soils when complete laboratory facilities are not available. These tests will give reasonable indication of the important properties of a soil to determine construction suitability.

GRADATION

If a soil is already dry, spread a sample out on in the palm of one hand or onto a flat surface. A piece of stiff paper or cardboard can be used as a rake to sort the larger soil grains to one side. Estimate the percentage of total volume of particles larger than 1/4 inch (6 millimeters) in diameter and the percentage of particles in the sample which are too small for the individual grains to be easily distinguished without magnification. Estimate volume rather than weight. For those soil grains large enough to be seen, estimate whether they are uniform in size or have large, medium and small sizes. A soil having uniformly-sized grains is considered poorly-graded; and a soil having many grain sizes is termed well-graded.

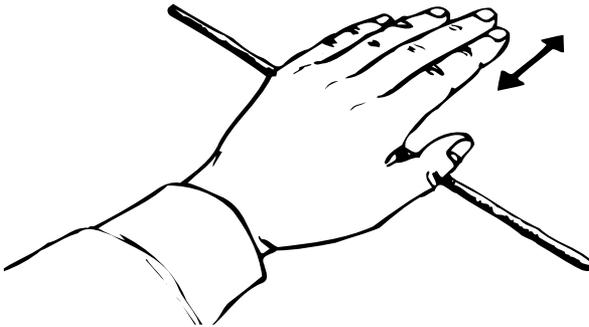
If the soil is damp or wet, break a clump apart with a pencil to estimate particle size(s) as previously described. To find the percentage of grains too small to be seen with the unaided eye, a baby food jar can be used. Put 1/8 inch (3 millimeters) of water in the jar, then add enough soil to fill the jar 1/4 inch (6 millimeters) full. Add more water until the soil is covered. Mark this level with a rubber band. Fill the jar to 75 percent full with water and either shake or stir it vigorously. Let it settle about one and one-half minutes and mark the height of soil that has settled out. The difference between these two levels represents the volume percentage of fines in this sample. This volume percentage is close enough to the weight percentage for purposes of estimating material type.

PLASTICITY OF FINE-GRAINED SOILS

Shaking Test -- Pick out a lump of fine-grained soil about the size of a golf ball. Knead it together and work out as many of the larger sized grains as possible. Add water a few drops at a time, mixing it in by kneading until the soil starts to get cohesive (sticky). Roll the ball of soil around in the palm of one hand and tap the back of this hand with the fingers of the other hand (as illustrated in the sketch on page 21). Observe whether or not the ball of soil gets shiny and wet on the surface. Then squeeze the soil ball and note whether or not the wetness disappears, leaving the surface dull. Alternately shake and squeeze the soil ball to decide whether surface water appears and disappears rapidly, slowly, or exhibits no change at all. Fine sands and silts have a rapid reaction to this test; clays show little or no reaction and simply become messy.



Toughness Test -- Set aside about half of the ball of soil from the shaking test test, and knead the remainder into a ball. Begin to roll it between the thumb and fingers into a thread or “worm”. The soil will be sticky at first; continue kneading it to gradually dry it out. The object of this test is to gauge the “toughness” of the soil when it gets close to its Plastic Limit, that is, when it is rolled into a worm 1/8 inch (3 millimeters) diameter, as shown below. If a worm cannot be formed, the soil is silt or fine sand. Plastic silts and lean clays feel soft as they begin crumbling. Highly plastic soils take a long time to dry out. They become so hard that considerable pressure is required to form a worm which crumbles at the diameter of 1/8 inch (3 millimeters).



Dry Strength Test -- Select the soil set aside at the beginning of the Toughness Test and knead it into a ball. Then set it aside to air dry. When thoroughly dry, crush it and select an angular, jagged fragment. Try to

crush this small piece between the thumb and forefinger. A silt will turn to powder with little effort; a clay will be rock hard and nearly impossible to crush with the fingers.

Hand Washing -- After handling silty soils, the fingers will feel dusty and gritty. Rubbing the fingers together will almost clean them. Water flowing gently from a faucet will rinse off all remaining soil. Clays, when handled, will form a crust on the fingers which cannot be rubbed off when dry. Running water alone will not rinse clay from the hands; they must be rubbed together under the water to completely cleanse them.

SUMMARY OF CLUES FOR IDENTIFYING GRADATION AND PLASTICITY:

Clay -- Clay exhibits no reaction to the shaking test. Clay forms a tough worm that dries out slowly, leaving a crusty residue on the hands which is hard to remove. This group of soils includes sand and gravel containing enough clay fines to enable performance of the toughness test.

Silt -- Silt has a rapid reaction to the shaking test. Silt forms a weak or crumbly worm, leaving a powdery residue on the hands that is easily rubbed or washed off. Lime treated clay also falls into this category.

Silt and Clay mixtures -- Fine-grained soil mixtures show intermediate or conflicting reactions to hand tests. Thus they are difficult to identify.

Sand or Gravel with clay fines -- These materials contain enough clay to dirty the hands if a wet sample is kneaded, but not enough to allow a ball of clay to be easily formed.

Sand or Gravel with silt fines -- These soil mixtures possess dusty or faintly gritty fines.

Clean Sand and Gravel -- Water added to clean sand or gravel permeates through immediately without creating any muddy residue.

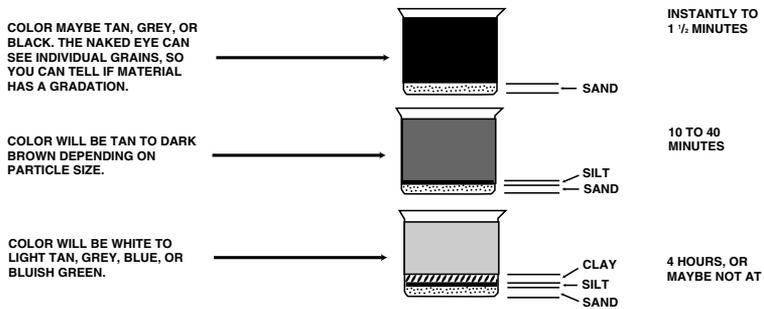
Shot or Ripped Rock -- Material thus classified appears jagged in shape; large particles are present without sufficient smaller particles to fill the voids.

DISPERSION

In addition to the hand tests described on page 22, the dispersion test can be used to indicate relative percentages of soil grain sizes. It can also give an indication of how difficult a soil will be to compact. This is a relatively simple test requiring a representative sample(s) of the fill material, a tall and straight-sided clear container, a rubber band and some water.

Fill the container with the soil sample about 1/4 to 1/3 full. Be sure the material is well broken up. Add enough water to cover the material. Then position the rubber band around the container so it indicates the top of the material. Fill the container with water to within 1/2 inch (12 millimeters) of the top. Stir well and observe how the material settles out (see below).

STIR WELL AFTER ADDING WATER



The difference between the level of the material settled from solution and the initial soil sample level marked by the rubber band will indicate the percentage of clay in solution.

The material will settle out in distinct layers. Because of its larger particle size and weight, sand will fall first and appear on the bottom. Silt will fall from solution next, followed by clay.

In addition to indicating the different particle sizes, this test will show whether material is well-graded (a variety of sizes) or is of uniform size. Although silt and clay particles are smaller than the eye can distinguish, their gradation change can be noted by color differences. In addition, the longer time required for the material to settle is an indication of smaller particle size.

There are several things which can be learned from the water glass test. It will indicate the basic materials present in a soil sample and the gradation of each. The settling time will give an indication of the particles' size. In most cases, poor gradation and small particle size will mean more difficult compaction than with a soil mixture where there is a good gradation of the range of all particle sizes.

Sometimes only one or two material classifications are present in a sample. In these instances, some other indicator must be used for classification. One indicator is to observe the settling material. Silt will show a distinct color line descending from the top down, leaving clear water only above the material solution line. Clay, will settle out evenly through the full depth of the water. The water will be clear through its complete depth.

Knowledge of material differences and gradation is useful when selecting compaction equipment. It helps determine how critical moisture control must be. It is also an indication of how difficult any material will be to compact. Use of the hand tests and the water glass test will give a fairly clear idea about material and its important characteristics.

Part 2

Embankment Compaction

CONTROLLING FACTORS

Several factors influence the amount of compaction which can be achieved in an embankment.

1. Material Gradation and Physical Properties
2. Moisture Content
3. Compactive Effort

MATERIAL GRADATION AND PHYSICAL PROPERTIES

Material gradation and physical properties refer to amounts and physical characteristics of all different-sized particles within a certain soil material. Well-graded soils exhibit fairly even distribution of particle sizes; these soils will compact more easily than poorly-graded soils, distinguished by having predominantly one size particle. The shape of particles, whether rounded or angular, will also be of influence during compaction. Angular or semi-angular particles will compact into a more stable structure than rounded particles of similar size.

MOISTURE CONTENT

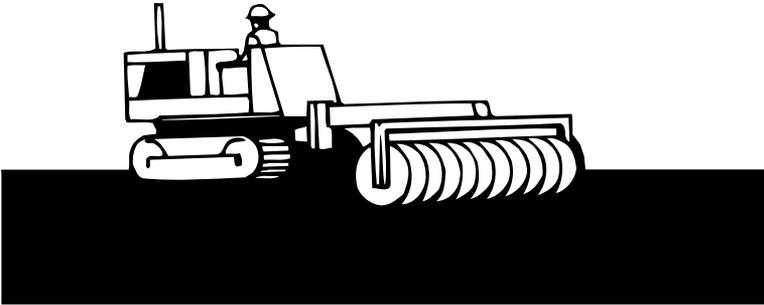
Moisture content is the amount of water present in a soil. The moisture-density relationship is a basic to soil compaction. It determines, through laboratory testing of fine-grained or mixed soil, the maximum dry density of soil based on moisture content and compactive effort. The calculations following testing will determine moisture content as a percentage of oven dry unit mass (weight) of the compacted samples in pounds per cubic foot or kilograms per cubic meter.

Optimum moisture content is the amount of water contained in a soil at which maximum dry density is achieved and is expressed as a percentage of the dry weight of that soil. Theoretically, optimum moisture is reached whenever the amount of water present within the soil being compacted is sufficient to coat the individual soil particles, without excess. Additional water only separates the soil particles, which actually decreases particle bonding strength. In dry soil, or soil having insufficient moisture, air voids separate the soil particles. With either excessive or insufficient moisture content, compactive effort available cannot compress or manipulate the soil particles into their densest mass and therefore cannot achieve that soil's maximum unit weight per volume, termed density. Theoretical maximum density (expressed in pounds per cubic foot or kilograms per cubic meter) can only be achieved at optimum moisture content. Understand, however, that optimum moisture changes with soil type and compactive effort applied. Also understand that it is possible to compact material in the field to more than 100 percent of theoretical maximum dry density (whether T 99 or T 180) if sufficient compactive effort is applied.

Moisture control of a fine-grained soil material becomes more critical as particle size decreases. Fine-grained materials have a greater affinity for water and react more noticeably to moisture changes. Rock, gravel and sand size particles can be compacted either saturated or dry, with little change in resulting density. Often, however, even small amounts of fine-grained soils in a material sample will dramatically increase the degree of moisture control needed. On the job, the level of moisture control can be interpreted from the compaction test curves for the material (refer to the section entitled Soil Moisture-Density Testing beginning on page 31). Normally, granular soils have a more-or-less flat moisture control curve; fine-grained soils will have a peaked curve which permits less moisture variance to achieve 90 to 95 percent relative density of that soil.

Control of moisture can be performed at the borrow pit, using sprinkling systems, or on the fill, using water trucks. When water is added to soil it is essential that it is evenly distributed through the lift. Granular soils take water freely and require little mixing to assure uniform moisture content. Fine-grained soils are less permeable and require considerable mixing, since water will usually not penetrate these soils more than a few inches. The most economical tool for mixing is a disc, as depicted on page 27.

SOIL MIXING



In this application, soil spreading, leveling, and mixing are accomplished in one operation. Other mixing equipment commonly utilized includes harrows, graders and mechanical soil stabilizers.

Soil which is too wet can often pose a more difficult problem than soil which is too dry. It is easier and faster to add water to dry material than to dry out wet material. In practice, many of the same tools are common to both aspects of moisture control.

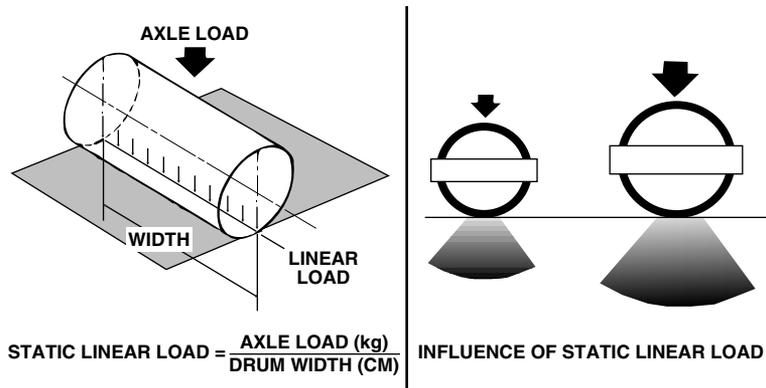
There are two commonly used methods of removing excess water from a soil. The easier, but often slower, method is aeration. By turning and manipulating the soil, aerobic and solar effects will cause evaporation of excess moisture. Discs, harrows and sheepsfoot rollers are often used to expose the soil to the air and sun. However, the disc towed during the spreading and leveling process has proved to be a more efficient and low cost aeration tool.

Another method of reducing excessive moisture is to mix dry soil with the wet soil. In this procedure alternate loads of wet and dry soil are spread and thoroughly mixed. This mixing process requires about the same amount of manipulation as the aeration method previously described; it can result in time savings, especially when climate precludes rapid evaporation. The biggest drawbacks to this method of reducing soil moisture content are locating adequate supplies of dry soil and the cost of hauling the dry soil to the job site.

COMPACTIVE EFFORT

Compactive Effort is that energy transferred into a soil by a compactor to achieve compaction. It may consist of one or more of the following: Pressure, Manipulation, Impact, or Vibration.

Pressure is the directly applied downward force exerted by a roller. The soil under the force is compressed and its density thereby increased. During application of this downward force, soil has a tendency to move away from the force and is displaced. The less displacement, the more efficient the compactive force being applied. Some compactors are more efficient than others at limiting displacement of the soil, as shown below.

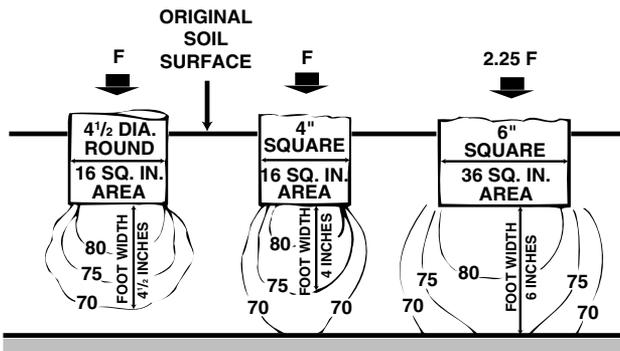


As a compactor applies force to soil, it shears the soil along the contact line where the compacting member enters the soil. Displacement and shearing action continue during compaction until the soil has been densified to the point where its bearing capacity is equal to the compactive force.

The performance of a compactor is essentially determined by its weight, as transmitted through the drum or roll onto the soil. The actual pressure on the area of contact with the ground changes as compaction progresses. With increasing compaction, the area of contact decreases in size and the pressure increases proportionately.

Manipulation of soil is also a factor in rearranging soil particles into a more dense mass. For example, the alternate high and low pressure points of sheepfoot rollers and tamping compactors cause a kneading action which is essential to rearrange heavy clay soil particles into a tighter, more dense mass.

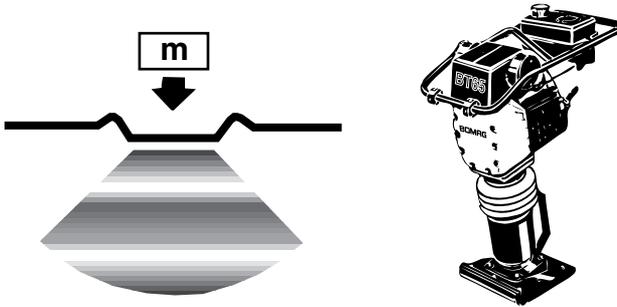
The compaction force applied to soil by a sheepfoot or tamping roller is distributed through the soil in the form of a pressure bulb. Under the feet, stresses are set-up in the soil in the form of pressure bulbs. The size of the bulbs and the depth to which compaction is achieved depends on the weight and dimensions of the load. The sketch below depicts this.



This illustration also demonstrates the importance of controlling thickness of a lift. It is necessary to impart sufficient intensity of stress into soil to obtain the desired compaction throughout the entire lift.

Impact and vibration achieve compaction through a series of blows against the surface of the material being compacted. *Impact* blows are generally considered to be within the lower frequency range from 50 to 600 blows per minute, produced by compaction tools such as impact hammers and mechanical hand tampers, which can be air or engine powered. These devices actually compact by material displacement. Impact effect is the greatest at the material surface and diminished with increasing depth.

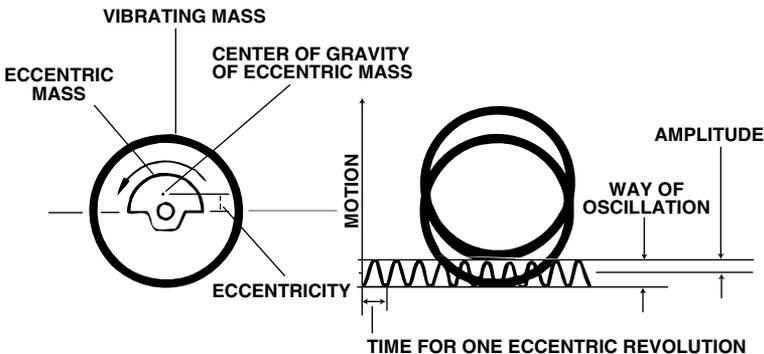
Dynamic compaction by impact is based on moving soil particles into a more closely packed configuration. Impact action uses the energy of the compaction equipment as it returns to the ground, with effect depending primarily on impact speed and vibrating mass.



Vibration results from higher frequency blows ranging from under 1000 impacts to over 4000 impacts per minute. This high frequency of vibration helps move material particles more rapidly into a dense orientation. Vibratory compaction equipment is designed to impart force efficiently and effectively.

Vibratory compaction is based on imparting forces in rapid succession into soil, causing the material particles to go into an excited state of motion, in such a way that the friction between particles is temporarily reduced or eliminated; this allows them to reposition into a more close orientation.

These vibrations are produced by a rotating eccentric mass, the turning speed of which determines the frequency of vibrations. Vertical movement of the vibrating mass is termed amplitude. Machine weight, vibrating mass, vibration frequency and amplitude must be matched for successful compaction to be accomplished.

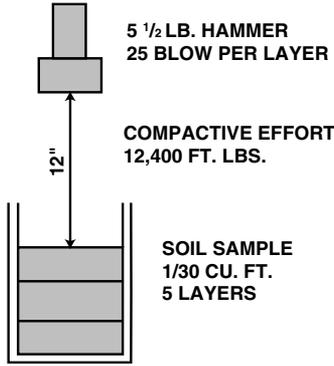


SOIL MOISTURE - DENSITY TESTS

LABORATORY TESTS

Before a job begins and after a site has been selected as a source for borrow material, laboratory tests must be performed on representative samples from the borrow source to determine the moisture-density relationships for that material. The information learned from these tests helps the soils engineer to establish guidelines for desired compaction densities. Testing of soil moisture-density relationships is usually done by one of two common laboratory procedures known as the Proctor Tests. These tests are also known as Standard AASHTO and Modified AASHTO.

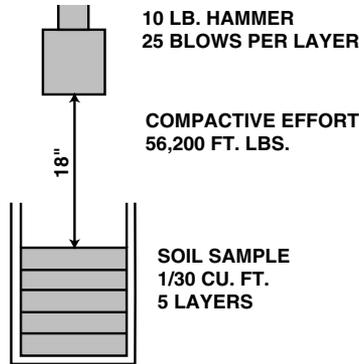
These two tests represent a considerable difference in total compactive effort; Standard AASHTO, T 99 (ASTM D 698) develops 12,400 foot-pounds per cubic foot compaction force. In the Standard AASHTO test, a 5 1/2 pound hammer is dropped 12 inches for 25 blows on each of 3 equal layers of soil in a 1/30th cubic foot mold (see figure below).



STANDARD AASHTO OR PROCTOR

Modified AASHTO, T 180 (ASTM D 1557) develops 56,200 foot-pounds per cubic foot compaction force. The Modified test is usually employed when designing projects like airports or power generating plants where the foundations require high bearing strength to support extremely heavy loads and when foundation settlement must be limited. With

Modified AASHTO, (T 180), a 10 pound hammer is dropped 18 inches for 25 blows on each of 5 equal layers of soil in a 1/30th cubic foot mold.



MODIFIED AASHTO OR PROCTOR

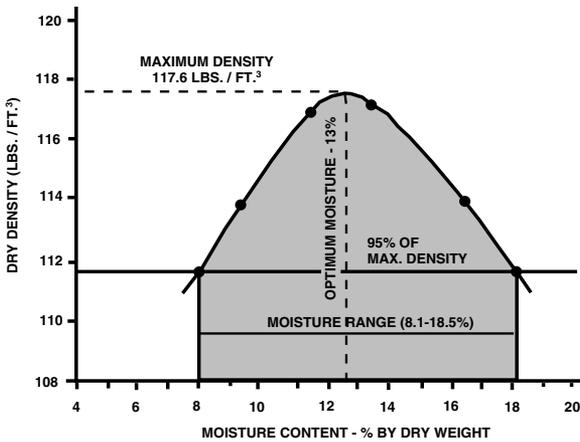
Another test used in the design of base, sub-base and sub-grade structures for asphaltic concrete pavement is the California Bearing Ratio (CBR) Method. The CBR method (including numerous variations) is the most widely used method of designing asphalt pavement structures. Developed by the California Division of Highways around 1930, it has since been adopted and modified by many other states. The U.S. Corps of Engineers adopted this method during the 1940s. Their procedure was generally used until 1961 when the American Society for Testing and Materials (ASTM) adopted it as ASTM Designation D 1883. The American Association of State Highway and Transportation Officials (AASHTO) adopted this test method in 1972 as AASHTO Designation T 193.

The CBR is a comparative measure of the shearing resistance of a soil. This test consists of measuring the load required to force a standard size plunger to penetrate a soil specimen at a specified rate. The CBR is the load in pounds per square inch (megapascals) required to force a piston into the soil a certain depth, expressed as a percentage of the load in pounds per square inch (megapascals) required to force the piston the same depth into a standard sample of crushed stone. Penetration loads for the crushed stone have been standardized. The resulting bearing value is known as the California Bearing Ratio, which is generally abbreviated to CBR. It applies to the base, sub-base and sub-grade for asphalt pavement structures.

RUNNING THE TESTS

Optimum moisture and maximum dry density, for any soil or compactive effort, are determined by compacting a series of samples, usually five, sourced from the original sample. The same compaction procedure is used for each sample, but the moisture content of each is varied and a curve is plotted which compares dry density for the soil at each moisture content. A smooth line is drawn between points to form the moisture-density curve. A typical moisture density curve is shown in the illustration below.

STANDARD AASHTO MOISTURE - DENSITY CURVE



Maximum dry density (MDD) is found by drawing a horizontal line from the peak of the curve to the left scale (Y axis) of the graph. (OM) optimum moisture content is found by drawing a vertical line through the peak of the curve to the bottom scale (X axis) of the graph.

This series of density-moisture content tests is begun with the complete soil sample in a damp condition, somewhat below its probable optimum moisture content. After the first individual sample of soil is compacted, its wet unit weight is measured and a small portion of the specimen is removed for determination of moisture content. This small portion is weighed and then placed in a drying oven to be thoroughly dried. When dry, the weight of the small portion is measured to determine the weight loss by evaporation; moisture content is then calculated as a percentage of the dry weight. A second sample, with slightly increased moisture content, is then compacted and the moisture content determination repeated.

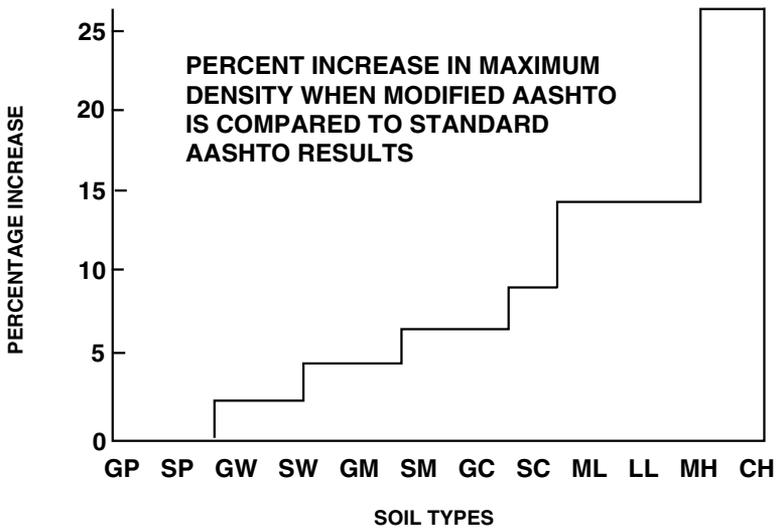
Additional samples are processed in the same manner until the actual wet unit weight of the compacted specimen decreases or when it is obvious that the soil is too wet by visual inspection. The amount of moisture added for each successive test depends somewhat on the tester's experience. The ideal test would produce "moisture content" points evenly spaced on a moisture-density graph.

After weighing each of the small samples placed in the drying oven, the dry unit weights corresponding to each sample's moisture content are plotted on a curve as shown in the graph on page 33.

The highest point on the curve represents this soil's maximum density of 117.6 pounds per cubic foot at the soil's optimum moisture content of 13%. For this particular soil, this is the relative maximum dry density which can be achieved for the amount of compactive effort applied.

Field engineers recognize that these tests determine the moisture content at which maximum density can be attained, but understand that density is not always able to be achieved in the field through use of conventional compaction equipment. Therefore, required field densities are usually specified as a certain percentage of the maximum laboratory dry density. Generally, field density requirements will fall within the range between 90% to 95% Standard AASHTO. For example, the soil represented by the moisture-density graph previously illustrated may be specified for field compaction at 95% of Standard AASHTO. So, when the soil is tested in the compacted embankment it must weight at least 111.7 pounds per cubic foot dry density. [117.6 pounds per cubic foot multiplied times 95% equals 111.7 pounds per cubic foot.] The embankment soil sample tested for moisture content must also be fall within a specified moisture content range of the laboratory determined optimum moisture content. This range is dependent on the material type.

The Modified AASHTO test applies over four and one-half times as much compactive effort to the soil as the Standard test. This higher force causes an increase in dry density, but the density increase depends on material. The chart on page 35 gives an indication of increase in maximum density of various soils in response to increased compactive effort.



This increase in soil maximum dry density practically always occurs at a lower moisture content than with the Standard AASHTO compactive effort. Each compactive effort has its own optimum moisture content. The optimum moisture content of a given soil, therefore, is not a fixed value, but is the moisture content at which the highest density can be produced with that given amount of compactive effort.

FIELD DENSITY TESTS

Periodic field testing is done in order to assure that desired compaction densities are being achieved throughout an embankment construction job. These tests can also indicate the effectiveness of the compaction equipment and construction methods being utilized.

The most common field embankment density testing methods used are the Density of Soil in Place by the Sand-Cone Method, - AASHTO T 191 (ASTM D 1556); Density of Soil in Place by the Rubber-Balloon Method, AASHTO T 205; and Density of Soil in Place by Nuclear Method, - AASHTO T 238 (ASTM D 2922).

SAND-CONE METHOD

The testing apparatus used with this method is shown in the photograph below. The actual test consists of five basic steps:



1. Select and level a test site on the compacted fill. This location must be at least 30 feet (9 meters) away from any operating equipment which might create vibrations, thus disturbing the calibrated sand used.
2. Place the base plate on the embankment and dig a test hole 6 inches (150 millimeters) deep, more or less depending on lift thickness, slightly smaller in diameter than the hole in the plate. Carefully collect all soil material removed from the hole in an adequate container; seal it to prevent moisture evaporation. Note that the sides of the hole should be vertical and relatively smooth.
3. Measure the volume of the hole by inverting the sand-filled jar and cone over the hole, filling the hole and cone with the sand from the jar. Weigh the apparatus with remaining sand and determine the mass of sand used in the test. Since the density of the sand and the volume of the cone and base plate hole are known (being previously calibrated), the volume of the dug hole can be calculated.
4. Weigh the material dug from the hole to determine its wet weight. Oven dry the material to determine its dry weight.
5. Calculate density and moisture content. Calculate in place dry density by dividing the weight of the oven dried material dug from the hole by the

calculated volume of the hole. In place moisture content is determined by subtracting the dry weight from the wet weight of the material removed from the hole and dividing this weight of water by the dry weight of the sample.

The accuracy of determining in-place density using the Sand-Cone Method is limited by the variations possible in the unit weight of sand and inability to completely fill the test hole with sand. The weight of the sand deposited in the test hole can be affected by the height from which the sand is poured, vibration present during testing, moisture content of sand, ambient conditions and amount of extraneous soil mixed with the sand. The sand's angle of repose can limit its ability to completely fill the hole.

RUBBER-BALLOON METHOD

The Washington Densometer test is one of the most common versions of the rubber-balloon method. This test's first two steps are very similar to the first test steps of the Sand-Cone Method. However, in place of the sand-filled jar and cone apparatus (step 3) to measure the hole volume, the Washington Densometer is used. It is placed over the hole, with balloon in the hole and fastened to the plate. The valve on the side of the Densometer is opened and a fluid is forced into the balloon, filling it to the shape of the hole. The Densometer is calibrated so that the test technician can read the volume of fluid that has filled the balloon and thereby determine volume the hole. (NOTE: A base line test is also done, prior to digging the hole, to establish the volume of the plate or spacer and allow for ground surface irregularities.)

Steps four and five of this test method are the same as for the Sand-Cone Method. The embankment's in place density is calculated by dividing the oven-dried weight of the material dug from the hole by the volume of the hole; the calculation of moisture content is performed as in step five above. The accuracy of density with this test method depends on the conformity of the balloon to the hole.

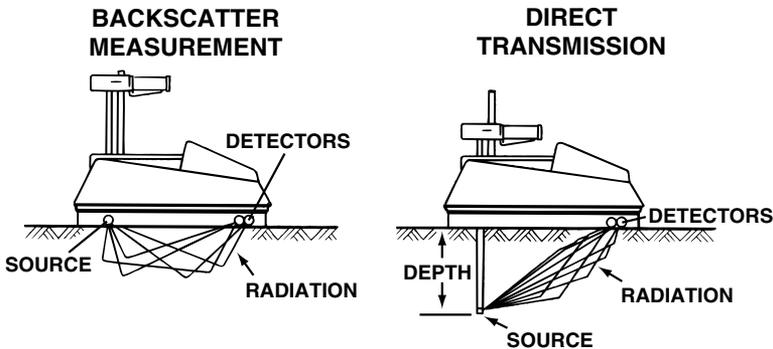
NUCLEAR METHOD

Modern technology has provided today's contractors, consulting engineers and governmental agencies with nuclear moisture-density testing devices for fast, accurate measurements of in place density and moisture content.

These devices utilize transmitted radiation to determine both moisture content and density. The entire test usually requires less than 10 minutes and can be even be performed on undisturbed samples. As evidence of their reliability and speed, many contractors and government agencies use nuclear testing devices for compaction control.

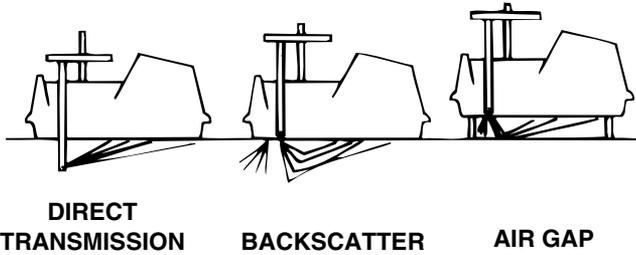
There are two methods of measuring material density, direct transmission and backscatter.

The direct transmission method offers higher accuracy, less composition error and lower test surface roughness error. It can be used for testing over the range of depths from approximately two to twelve inches (50 to 300 millimeters). The most important aspect of the direct transmission method is that the operator has direct control over the depth of measurement. The illustration below shows the physical relationship of the testing device probe to the test material.



The backscatter method eliminates the need for a probe access hole by allowing the whole unit to remain on the test surface. Due to inefficient scattering and the wide scattering angle of the gamma photons (radiation), less accuracy and larger composition errors are likely, however. Also, in shallow depth measurements below two or three inches, error is possible because of lack of measurement sensitivity to minor density variations. The ease of making backscatter measurements often offsets the possibility for errors for many users. The backscatter method is often more desirable where uniform material composition and densities are involved, such as when measuring density of asphaltic concrete pavements.

Another method offers a reduction in possible composition error and can be used with either direct transmission or backscatter test modes. This is known as the air-gap method. The testing device is raised above the test surface a measured amount. The testing measurement may vary between test units but is consistent for any one unit. Utilizing the air-gap method reduces the composition error, particularly for the backscatter method. Its accuracy will still not match direct transmission, however.



The only practical limitations for nuclear density-moisture equipment are the requirements for licensing, training of technicians using the equipment and being attentive to those specific precautions which must be observed when handling radioactive material. It should be noted that false readings are sometimes obtained in organic soils or materials with high salt content.

SPECIFICATIONS

Before a contractor bids or selects compaction equipment for any job, he determines the project's limits regarding material placement, preparation and compaction from the plans and specifications. There are four general types of specifications used by sponsoring agencies to establish minimum standards for compaction of embankments, bases or surfaces.

The first is the Method Only Specification in which the sponsoring agency describes, in detail, how compaction should be accomplished, but states nothing about results. Typical of this method is a specification calling for X passes at Y speed with Z rollers on a specified lift thickness of soil at a specific moisture content. Results from using this are least satisfactory to both the sponsoring agency and contractor. It forces the contractor to use equipment for some soils where other equipment may actually be more

efficient. This specification also requires him to use his equipment in ways which limit his imagination and economy of operation. From the agency's viewpoint, method only specifications do not assure that desired (or even satisfactory) results will be obtained. Not only is this approach costly, it can also result in shortened structure life.

The second variation is the Method and End Result Specification. This is the most restrictive of all specifications; it limits the contractor from using his experience and recent developments in compaction technology. Typical of this specification is when the contractor is required to obtain 95% AASHTO in place density by making X passes on Y lift with Z roller. In some instances, it can require a contractor to achieve an end result with a specific type or size of roller which may be incapable of achieving specified result on the particular soil being placed and compacted. This wastes both time and money since no specification change can be enacted until it has been proved that the original requirements are unreasonable or impossible to achieve.

A better arrangement is the Suggested Method and End Result Specification. This specification is gaining popularity due to the flexibility it offers the contractor while assuring the sponsoring agency of desired results. It permits the more experienced contractor the latitude to make use of his experience and initiative; it offers a guide or starting point for the less experienced or knowledgeable contractor. In addition it permits the development of compaction technology and methods of expediting and reducing the cost of the compaction process.

The fourth type is the End Result Specification, in which only the desired end result is actually specified. This specification gives a contractor full choice in selecting equipment to do his job and enhances productivity of all equipment. From the perspective of the sponsoring agency, the end result specification requires more strict testing procedures; however, it offers assurance that specified compaction requirements will be met.

One provision becoming more common permits the project engineer to authorize the contractor to use compaction equipment and methods other than those sizes or types specified. If the contractor demonstrates that a machine not meeting specifications can accomplish desired compaction, it

is approved. Sponsoring bodies permitting this procedure include the Bureau of Reclamation, U.S. Army Corps of Engineers and many state agencies. Nearly 80% of the states and agencies in the U.S. still spell out in some detail the type of compaction equipment to be used; the balance specify end result.

Requirements for embankment compactors frequently include physical specifications like operating weight, length of foot and ground contact pressure. Because of variations in machine designs and the probability that no manufacturer's unit meets all specifications, sponsoring agencies rely on the judgment of project engineers to permit use of acceptable alternates. Base course compaction requirements are also subject to project engineer's judgment in many cases, although some sponsoring agencies specify roller types. Tamping, grid, vibratory, pneumatic and static steel wheel rollers may be specified for rolling various granular base and surface courses.

JOB LAYOUT

Every contractor must consider job size, areas to be constructed, rate of placement, and project specifications before he can select his compaction equipment. When placing embankment materials, there are two types of job layouts which are considered, the Project Method and the Progressive Method.

Project Method In this project method, material is moved into a fill in lifts varying in thickness from 6 inches (150 millimeters) to 12 inches (300 millimeters) or more, depending upon compaction equipment capabilities. Compaction proceeds until the density achieved meets specifications. When density has been achieved in the first lift, another lift is spread and compacted. This construction method is generally used on smaller jobs where space restrictions preclude progressive spreading and compaction.

On this type project, the compactor used must feature maneuverability and productivity, as it is necessary for hauling and spreading equipment to sit idle during the compaction process. Often adjacent fills lend themselves to this method as the haul units can be routed to one site or the other to optimize production capabilities.

Progressive Method Continuous operation of the compaction equipment on the fill, as material is hauled and spread, is known as the progressive method. This process is generally used in highway construction where a lift of material is spread (for some distance), levelled and compacted before a second lift is placed. In the progressive construction method all equipment is teamed for continuous production. It is imperative that the compactor be capable of productivity complementary to the hauling and spreading equipment on the fill. Maneuverability is often not an important factor since the compactor is frequently shuttle operated (forward and reverse) to reduce turn around time and increase productivity. If turning around is necessary, maneuverability of the compactor is more critical. With a matched spread of equipment, the progressive method will normally reduce haul times, due to the compacted haul surface and higher transport speeds achievable. Another important feature to look for in all equipment, especially when using the progressive method, is ease of operation. Normally the operator must be more efficient for longer periods of time. Machine reliability, with reduced down time, is essential since one machine's failure could shut down the entire operation.

Embankments, bases, and surface courses are prepared using either of these two construction techniques depending upon job size. Often deep fills, bridge approaches, or other secondary structures on a major job will require both project and progressive methods to be used simultaneously. A high degree of flexibility in selecting compaction equipment is dictated; a great deal of planning is needed to maximize the production capabilities of all equipment. It is important, however, to remember that a certain haul fleet capability is available and the compactor(s) must be carefully selected to match the productivity of this fleet, whether the job is being done by project or progressive method.

COMPACTION EQUIPMENT SELECTION

There are many factors that may influence the choice of the proper piece of compaction equipment for a particular job. The first consideration, which we have already discussed, should be the material to be compacted and the specifications.

In some cases in the past, compaction had been considered a “necessary evil”. Some contractors tried to get by using their hauling units to compact or using no compaction equipment at all. A few mistakenly believed that they were financially ahead if they could get by without using compactors. It was sometimes true, if only 90% of Standard AASHTO density was specified, almost any compaction equipment or even haul units might achieve this specified density.

Today’s projects require higher material density to support the heavier loads being imposed. Any contractor trying to construct a job without dedicated compaction equipment will be wasting production time trying to negotiate the loose fill, incur increased maintenance and repairs for hauling equipment and seriously curtail production, resulting in higher actual construction costs.

Compaction equipment is necessary and aids production. The contractor should select the type of compactor most applicable to the material being placed. Based on product selection, consideration should be given to the variables of number of passes, lift thickness, rolling speed, and material gradation.



There are a number of different types of embankment compactors in use today: sheepsfoot, tamping foot, pneumatic and vibratory. No single type can perform the complete compaction task from embankment to surface

course. Each has a class of material and operating conditions under which it proves most economical.

Sheepsfoot Roller: The sheepsfoot roller is one of the most recognizable compaction devices and is used all over the world in various configurations and sizes. It works on a wide range of materials but is most effective for compaction of plastic soils like clay or silt. When used on more granular materials, sheepsfoot rollers tend to shove instead of compacting it.

The sheepsfoot compacts from the bottom of each lift toward the top, described as “walking out” of the embankment. High contact pressures cause the feet to penetrate through the loose material and actually compact the material directly beneath the foot tip. This creates a layer of relatively loose soil, up to 6 inches (150 millimeters) deep, which can slow haul unit travel speed and increase haul cycle time. This loose material can also act as a sponge when it rains, creating delays while drying out the soil before continuing the compaction process. Lift thickness for this type of roller should not exceed the length of the foot and are generally restricted to 8 inches (200 millimeters) loose, 6 inches (150 millimeters) compacted.

The towed sheepsfoot roller can only work at speeds from 4 to 6 miles per hour (6 to 10 kilometers per hour) which prevents any benefit being received from the forces of impact or vibration. Therefore, only the forces of static pressure and manipulation are exerted on the soil. A high number of coverage passes are required with sheepsfoot rollers because of the small contact area compacted by each foot.

Self-propelled sheepsfoot rollers equipped with fill spreading blades are also manufactured. These units are capable of higher productivity than towed sheepsfoot rollers because of their ability to work equally well in both forward and reverse directions. These self-propelled units may also reduce fill congestion due to their more compact configuration, shuttling operation and greater maneuverability. They are more expensive to own and operate than towed sheepsfoot rollers, however.

Tamping Foot Roller: The tamping foot roller incorporates the advantages of the sheepsfoot and steel wheel into a high speed compaction tool. Like the sheepfoot roller, it compacts from the bottom to the top of the lift for uniform density. Like the steel wheel or pneumatic it compacts from the top of the lift. The tamping foot roller is capable of high rolling speeds

without throwing material, due to the design profile of the tamping foot. Since it leaves a relatively smooth, sealed surface, haul units are able to maintain good speed when traveling over the fill. In some cases, the added productivity from this advantage can offset the cost of compaction.



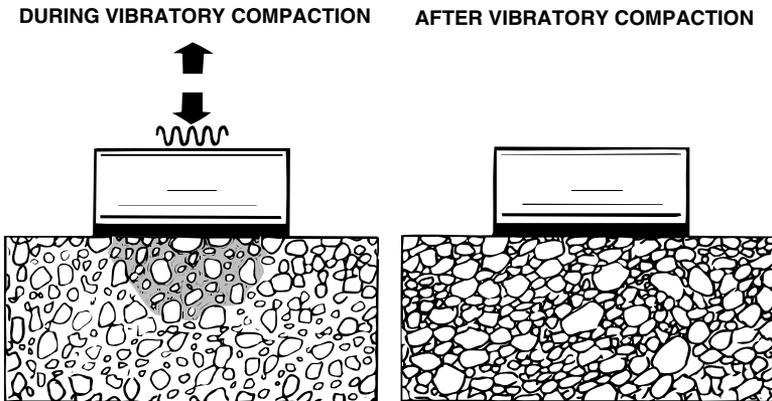
Pneumatic: Large 50-200 ton (45-180 tonne) towed pneumatic tired rollers are still considered in some areas as “good” proof rollers, despite research findings and recent experience showing otherwise. These large units are difficult to move over the embankment and are less effective in achieving compaction than high speed tamping compactors. Their high ground contact pressures too often exceed the bearing capacity of the soil and cause irreparable damage to the fill. In addition, these units are large and cumbersome, prone to tipping and must be towed at slow speeds.

Pneumatic rollers generally compact from the top of the lift down to achieve density. The relationship between tire contact area and ground contact pressure causes a kneading action which is beneficial in achieving desired compaction. This kneading action helps seek out soft spots which may exist in the fill and is why some agencies utilize heavy pneumatics as proof rollers.

The pneumatic compactors most common today are light to medium-weight self-propelled units, used primarily for granular base and flexible pavement surface compaction, as shown in the photograph on page 46.



Vibratory Roller: These compactors work on the principle of particle rearrangement to decrease the voids between particles, thereby causing an increase in density. This rearrangement results from dynamic forces which are generated by the vibrating drum(s) hitting the ground. Compaction results are a function of the frequency of these blows, the time period over which they are applied and the energy per blow. This frequency to time relationship accounts for the slower travel speed inherent with vibratory rollers and the thicker lifts on which a vibratory compactor can achieve density. It is believed that density is built from the bottom to the top of the lift by the vibratory forces and from the top down by the forces of gravity and impact working simultaneously. The illustration below depicts the principle of vibratory compaction.



Travel speed of the vibratory roller is important; it determines the duration of time a section of the fill will be receive vibration and be compacted. Generally, a speed of 2 to 3 miles per hour (3.2 to 4.8 kilometers per hour), moderate walking speed for an adult male, will provide the best results. It should be remembered that, with each successive pass, a larger mass of material must be excited into motion.



The vibratory compactor's effectiveness is related, in part, to the size of material particles being compacted. In general, larger grain size soils are compacted with greater efficiency. The best vibratory application is the compaction of granular and mixed soil materials. The addition of tamping feet to the drum, as depicted in the photograph above, has extended the vibratory application to subgranular soils with a greater percentage of fine-grained particles. It is often recommended that a smooth drum unit be used on materials having up to 10% cohesive content. Pad foot, tamping drum units can compact soils having as much as 50 percent fine-grained fraction.

There are different vibratory compactor configurations including plates, walk-behind rollers, towed rollers and self-propelled single and double drum rollers. Vibratory compactors are generally separated into classes, depending upon machine weight, coverage width, or dynamic force. The

chart below shows approximate size classes for comparison of single drum, self-propelled vibratory rollers.

VIBRATORY ROLLER CLASSES			
OPERATING WEIGHT	ROLLING WIDTH	CENTRIFUGAL FORCE	COMPACTION DEPTH
under 5 tonnes	47 to 56 inches (1200 to 1420 mm)	7000 to 16,000 pounds (31 to 71 kN)	3 to 12 inches (75 to 300 mm)
5 to 7.9 tonnes	49 to 60 inches (1250 to 1520 mm)	13,000 to 30,000 pounds (58 to 133 kN)	6 to 20 inches (150 to 500 mm)
8 to 11.2 tonnes	66 to 84 inches (1680 to 2130 mm)	45,000 to 56,000 pounds (200 to 250 kN)	8 to 30 inches (200 to 750 mm)
over 11.3 tonnes	82 to 100 inches (2080 to 2540 mm)	50,000 to 81,000 pounds (222 to 360 kN)	12 to 60 inches (300 to 1500 mm)

Self-propelled vibratory rollers offer many advantages. The very nature of the self-propelled unit, by providing its own propulsion power, makes it more compact. It is more maneuverable, able to turn around in a smaller area and move among workers and other equipment easier and safer; it is designed to operate in a shuttle mode for optimum efficiency. These advantages add up to a more productive roller.

Towed units are popular with small contractors whose production cannot justify the expense of a self-propelled vibratory roller or where utilization is low. Towed vibratory rollers are capable of doing a satisfactory job compacting granular materials; they cannot be applied to asphaltic concrete bases or materials where the towing vehicle will mark the finished surface.



Lift thickness able to be compacted with vibration will depend on the power and size of unit being used, the number of coverage passes and rolling speed. With a small to medium sized vibratory roller weighing under 8 tonnes, lift thickness on granular materials should not exceed 20 inches (500 millimeters); density should be achieved in 3 or 4 passes at a rolling speed not to exceed 3 miles (4.8 kilometers) per hour. Heavier vibratory rollers, weighing up to 25 tonnes are able to consolidate rock fills in lifts up to 5 feet (1.5 meters) thick if enough smaller material is present to fill the voids. Whenever large rock is used in a fill, the lift thickness should be about 1 foot (300 mm) greater than the maximum rock size to allow lift consolidation without the edges of the largest rocks projecting above the fill surface, causing damage to hauling, placement or compaction equipment.

There are a few terms associated with vibratory compaction which require definition, for understanding.

Amplitude is the vertical movement of a vibrating drum. Amplitude is expressed in thousandths of an inch (millimeters). Actual amplitude is the movement of a drum under operating conditions; it may change with the conditions of the material being densified and the vibration frequency. Nominal amplitude is the calculated median to peak vertical movement of the drum; this is the value advertised by equipment manufacturers in their sales literature. Double amplitude is total peak to peak vertical movement of the drum each complete vibrating cycle, in a freely suspended condition. This term is not recommended for advertising literature or specifications.

Centrifugal (sometimes termed Dynamic) *force* is the force generated by the vibration-inducing mechanism at a stated frequency. Centrifugal force is calculated based on eccentric moment and vibration frequency. Centrifugal force is measured in pounds force (Newtons).

Frequency is the number of complete cycles of the vibrating mechanism per time interval, expressed as vibrations per minute (vpm) or cycles per second (Hertz). Vibration frequency may range from under 1100 vpm (18.3 Hz) to over 4000 vpm (66.7 Hz) depending on the compactor.

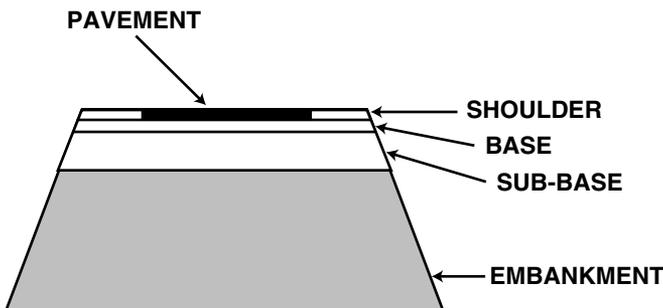
Vibrating mass (also termed *unsprung weight*) is the weight (mass) in pounds (kilograms) of all of the intentionally vibrated parts of each drum.

Part 3

Base and Sub-base Compaction

Modern highway systems have been developed to meet the expanding needs of overland transportation. However, when the first automobiles were built and sold, the roads over which they traveled were usually horse and buggy paths. As these dirt “roads” became impassable, due to increased traffic and poor weather conditions, various surfacing methods were used to improve the roads’ service life. Among the surfacing materials utilized were cobbles, bricks, rocks and wooden planks.

As the quantity and weight of vehicles increased, heavier demands were placed on road surfaces. The need for all-weather streets and highways, capable of supporting increased wheel loads, soon became apparent. During this time, the concept of constructing pavements with all-weather surfaces, supported by multiple layers of base materials, was developed. Referred to as sub-bases and bases, these material layers are constructed on top of an embankment or natural ground surface. The layers typically increase in strength (load carrying capacity) with proximity to the finish pavement. The illustration below depicts this design.



The selection of materials for construction of sub-base, base and surface course layers depends, to a great degree, on the frequency and type of loads the road or pavement structure must support. For example, a private road carrying only light automobile traffic may require gravel as a combination base and surface treatment. In contrast, a modern airport runway may require the construction of 18 inches (455 millimeters) of lime-treated clay soil sub-base, followed by 36 inches (915 millimeters) of minus 1-1/2 inch (40 millimeters) cement treated plant mixed base, topped with 24 inches (610 millimeters) of reinforced concrete pavement.

The suitability for construction and quantity of available base materials affects the economy of pavement construction, since base materials are generally less costly than surface mixes like hot-mix asphalt or Portland cement concrete. For these reasons, a wide variety of base materials and combinations of materials are utilized for construction.

SUB-BASE SOILS

Indigenous Soils: Indigenous soils are those which occur naturally within a region. From an economic point, it is preferable to use locally available materials, soils have not been treated or imported from another site, for road construction. Effective construction control and proper compaction of these soils will substantially increase their load bearing capacity, while controlling factors like permeability, capillarity, swelling and shrinkage.

Treated Soils: Mixing of certain chemicals with indigenous soils can improve their strength and load carrying characteristics. This process is known as stabilization. Fly ash, lime, liquid asphalt, salt, or Portland cement can be mixed into a soil for stabilizing purposes; the soil should always be compacted with a sheepsfoot, tamping or vibratory compactor to maximize material strength. Generally, the type of compactor used will depend upon the characteristics of the original, untreated soil. When large volumes of treated soils must be compacted, self propelled tamping or vibratory rollers will be most economical. Smaller volumes may be done with towed pneumatic, sheepsfoot or vibratory rollers.

AGGREGATE BASES

Pit-Run Base refers to natural deposits of gravel, lava, rock and similar aggregates. Pit-run material, suitable for base course construction, is found almost everywhere in the world. This material is usually excavated from its source, hauled to the construction site, spread and compacted in place. Pit-run bases are commonly used in private road construction where traffic is light, or where heavy haul trucks (construction, mining or logging) are the principal users of the road.

Prior to placing pit-run material, sub-grade should be densely compacted, with as smooth a surface as possible. This reduces the possibility for future settlement. Rock lifts should be spread to a thickness of at least 1.2 times the largest aggregate particle size; lifts should be a maximum of 6 inches (150 millimeters) thickness. Thicker base courses should be crushed and compacted in two lifts, since an excessive amount of material cannot be handled effectively. Thinner lifts of pit-run material also permit higher blading and rolling speeds.

By blading the pit-run material occasionally as it is being rolled, larger pieces from lower in the lift are brought to the surface and exposed to roller compaction and size reduction. Blading also distributes coarse and fine aggregates better, for a smoother surface. Rolling spread material from the shoulders toward the center will maintain sufficient crown for drainage, without requiring extensive reshaping. Watering pit-run material during the last crushing/rolling operations will help compact the base into a tight, dense layer with minimum surface dust. Finish rolling the shaped surface is desirable to compact any loose areas. A pneumatic-tire roller is ideal for sealing the surface and rolling out any irregularities in the finished grade.

Base courses are being constructed in this economical manner throughout the world. The actual cost of construction is largely dependent on the availability of high quality materials and on the utilization of efficient and productive equipment. Many construction projects which employ “in-place” crushing and compaction of pit-run rock have reported substantial savings in base material costs. This is due to the degree of compaction achieved. Increased wear life and higher load bearing capacity can also be realized compared to conventional, well-graded base courses.

Crushed Rock Bases: In many areas, crushed rock for base construction is readily available. Job specifications may require well-graded crushed rock to be used for base and sub-base construction. When sub-base is specified beneath the base course, it will usually consist of crushed rock from the primary crushing operation, 3 inches (75 millimeters) or 2-1/2 inches (65 millimeters) minus. Using crushed materials, gradation can be controlled during crushing to match job specifications or other requirements. These fractured aggregate materials are easier to load, spread and compact, and are somewhat more predictable for layer strength. These advantages can, at times, be offset by the significant expenses of crushing and transportation.

Project engineers sometimes specify prepared bases. *Prepared bases* consist of a specific gradation of crushed rock to which specified amounts of water, Portland cement or liquid asphalt are added. Crushed base with Portland cement added is commonly referred to as cement treated base (CTB). Base material with liquid asphalt added is commonly referred to as ATB, asphalt treated base. The rolling of ATB is discussed in another publication, our “Hot-Mix Asphalt Fundamentals” handbook.

Base material is usually transported to the job site in bottom dump trailers or end dump trucks and dumped in front of a motor grader or spreading machine. End dumps often discharge material directly into a laydown machine. The material is spread in lifts from 6 inches (150 millimeters) to 10 inches (250 millimeters) thick, depending on job specifications. After spreading, the base is compacted to required density by pneumatic tire, steel wheel or vibratory rollers. In some instances, method regulations may specify the type of roller to be used and the number of roller passes required on a specific lift thickness. Other agencies may specify an end result or final density requirement.

SOIL STABILIZATION

The objective of soil stabilization is to maintain or improve construction performance of a soil. This can be achieved in one of two ways, either mechanically or through the addition of chemicals.

Mechanical stabilization involves the mixing of locally available materials

with the indigenous soil. This is done to improve its the in-situ material's gradation and its mechanical strength following compaction. Chemical stabilization is less dependent on mechanical interlocking of soil particles. This is achieved by adding certain chemical agents like fly ash, lime, liquid asphalt, Portland cement, salt or other appropriate additive. Stabilization techniques used for various materials are illustrated in the chart below.

BROAD COMPARISON OF STABILIZATION TECHNIQUES

INDIGENOUS MATERIAL	PAVEMENT THICKNESS	MECHANICAL	CEMENT	LIME	BITUMEN
Nature Gravel □ □□ □□□□ □□□□ □□□□	Minimum 4 in. (10 cm.)	Fines may be □ needed to prevent raveling□□	Probably not□ necessary□	Not necessary□	Not necessary unless lacking fines. 3%□ residual bitumen.□ Use medium or slow□ curing cut-back or□ emulsion.□
Clean sand □ □□ □□□□ □□□□ □□□□	Minimum 4 in. (10 cm.)	Coarse material for□ strength and fines□ to prevent raveling□□	Unsuitable, produces□ brittle material□	Unsuitable,□ no reaction□	Most suitable. 3%□ residual bitumen.□ Rapid curing cut-□ backs may be used.□ Add 2% lime for wet□ sand.□
Clayey sand, □ loam□ □□	6-10 inches□ (15-25 cm.)□	Coarse material for□ strength and seal□□ adhesion□□	4-8%□	May be suitable□ depending on □ clay content*□	May be suitable 3-4%□ □ □
Sandy clay□ □ □	6-14 inches□ (15-35 cm.)□□	Not usually suitable□□	4-12%□	4-8% depending□ on clay content□	May be suitable for□ light traffic. 3-4%□
Heavy clay□ □ □□□ □□□ □□□	10 inches□ (25 cm.)□□	Unsuitable□	Difficult mixing□ maybe assisted by□ pretreatment with 2%□ lime then 8-15%□ cement.	Most suitable□ 4-8% depending□ on clay content□	Not usually suitable□ □

*Lime may render the material non-plastic if clay content is low. Usually less than 4% lime.

As soil stabilization techniques have improved, the ability to upgrade the strength and wearing characteristics of poor materials has also improved. As a direct consequence of the growing technology of soil stabilization, many regions now have the ability to produce higher quality road bases at lower construction cost.

Stabilization with cement: When using cement for stabilization, cohesion is increased by adhesion of the fine soil grains. A higher resistance of the soil against traffic loads and climactic stress is thereby achieved. The soil becomes permanently stable. Portland cements are commonly used for soil stabilization. Mixing of cement with the soil is an important process. Uniform distribution is needed to ensure stabilization. Best mixing results are experienced with upward cutting rotors.

Stabilization with lime: Lime causes immediate and long-term reactions in

soils. These can be influenced by the type and quantity of lime, depending upon the type of soil and its moisture content. Creation of fines, reduction of moisture content, improvement of plastic properties, compactability and load-bearing capacity are important characteristics of the initial lime and soil reaction.

The compaction method employed on stabilized soils depends on the soil, mixing method and stabilizing agent. When an additive has been partially mixed, a tamping compactor (with its manipulation action) will greatly improve the mixing process. If a smooth finish on stabilized materials is required a pneumatic-tire, static steel wheel or vibratory compactor should be used.

Mechanical stabilization improves the load-bearing capacity of poorly-graded soils by mixing the soil with the necessary granular materials. Binding agents are not used in this application. Sands of uniform grain size cannot be compacted. Grain composition and compactability can be improved by mixing in coarse and fine grains. Soft and cohesive materials can be improved by blending in non-cohesive materials.

Regardless of application, soil stabilization can be an effective solution to the shortage of high-quality natural construction material resources. It can reduce construction costs, material transportation costs and shorten road construction process time through soil rehabilitation or soil improvement.



GLOSSARY

AASHTO: American Association of State Highway and Transportation Officials.

AASHTO T 96: Los Angeles Abrasion Test. A method used to determine the hardness of rock.

AASHTO T 99: A laboratory test used to determine optimum moisture content necessary to achieve maximum dry density using 12,400 foot pounds per cubic foot compaction force; also termed standard Proctor.

AASHTO T 180: A laboratory test used to determine optimum moisture content necessary to achieve maximum density using 56,200 foot pounds per cubic foot compaction force; also termed modified Proctor.

Abrasion: Wear by rubbing of coarse, hard or sharp materials.

Adhesion: The quality of a soil which makes it stick to buckets, blades and other parts of compactors, dozers and other construction equipment.

Aggregate: Crushed gravel or rock screened to size for use in road surfaces, Portland cement concrete or bituminous concrete mixes.

Air-On-The-Go: A mechanical system on pneumatic tire rollers to change or maintain identical air pressures in all tires, while in operation.

Amplitude, Double: Total peak to peak vertical movement, per complete vibrating cycle, of a drum in a freely suspended condition. Note that this term is not recommended for specifications.

Amplitude, Nominal Single: One half of the total peak to peak vertical movement of a vibrating drum, calculated by formula.

Amplitude, Variable: A feature of vibratory rollers that permits amplitude change without changing frequency, normally accomplished by varying the eccentric moment of the vibrating mechanism.

Basalt: A dense, fine-grained dark gray to black igneous rock.

Base: A foundation course consisting of mineral aggregates.

Base Course: The layer of material immediately beneath the surface or intermediate course. It may be composed of crushed stone, crushed slag, crushed or uncrushed gravel and sand, or combinations of these materials. It may also be bound with asphalt.

Bearing Capacity: That unit pressure on a surface, greater than which will result in progressive settlement, which then leads to structural failure.

Bearing Resistance: That property of a material which controls its ability to withstand imposed loads.

Bearing Value: The unit load for a specified amount of settlement and a specific loaded area.

Bedrock: Solid rock, as distinguished from boulders.

Berm: An artificial ridge of earth.

Binder: Finest particles which hold gravel or other aggregate particles together.

Blanket: Soil or broken rock placed over a blast to contain or control throw of material.

Blue Tops: Grade stakes whose tops indicate finished grade level.

Borrow Pit: An excavation from which material is taken for use as fill in another location.

Boulders: Aggregates of round, sub-angular or angular fragments of rock with a particle size of more than 8 inches (200 millimeters) diameter.

Burden: The volume of soil or rock which must be removed to expose a desired surface or formation.

Caliche: A layer of soil in which the soil grains are cemented together by carbonates such as lime.

California Bearing Ratio (CBR): A measure of the shearing resistance of soil under carefully controlled density and moisture condition; expressed as a percentage of the unit load required to force a piston of specific diameter into the soil, divided by the unit load required to force a piston of the same diameter into a standard sample of crushed aggregate.

Capillarity: That property of a soil which permits water to be drawn into it either upward or laterally.

Centrifugal (Dynamic) Force: The force generated by the compactor's vibration inducing mechanism at a stated frequency. Centrifugal force is calculated by formula.

Clay: Any material of microscopic or sub-microscopic particles derived from the chemical decomposition of rock.

Cleavage Plane: Any uniform joint, crack or change in quality of formation along which rock will break easily when blasted or dug.

Coarse Aggregate: Any material of particle size greater than or equal to the number 10 sieve (2 millimeters) size.

Cohesion: The quality of soil particles to stick together, which determines the capacity of the soil to resist shearing stresses.

Compacted Yards: The measurement of material area or volume after it has been placed and compacted.

Compaction: The act of compressing a given volume of material into a smaller volume. Insufficient compaction of an asphalt pavement may result in channeling on the pavement surface. Compaction is accomplished by rolling with pneumatic, tamping, sheepsfoot, steel wheel, vibratory, or combination rollers.

Compactor: A self-propelled or towed vehicle used specifically to densify materials through the application of static pressure, or through dynamic force combined with static pressure.

Compressibility: That property of a soil which permits it to deform under the action of a compressive load.

Dense-Graded Aggregate: Material which is uniformly graded, from the maximum size to the minimum size, so that the compacted specimen is without voids.

Density: The weight of a unit volume of material, usually expressed in the terms pounds per cubic foot.

Densification: The act of increasing the density of a mixture during the compaction process.

Diatomaceous Earth: A deposit of fine, generally white, siliceous powder composed chiefly of the remains of diatoms.

Dolomite: A calcium magnesium carbonate of varying proportions, such as white marble.

Drum: A rotating cylindrical member used to transmit compaction forces to material surfaces.

Dynamic Force: The force generated by the vibration inducing mechanism of a vibratory compactor at the stated frequency of the vibrating drum(s).

Eccentric Moment: The product of the unbalanced weight (mass) times the distance from the center of gravity of the unbalanced weight (mass) to the bearing center.

Elasticity: That property of soil which permits it to return to its original dimensions following removal of an applied load.

Embankment: A fill whose top is higher than the adjoining surface.

Erosion: Wear caused by moving water or wind.

Excavation: Specific material, whether soil or rock, removed from a source and paid for at a fixed price per material volume, generally cubic yards or cubic meters.

Expansion: The increase in material volume resulting from an increase in moisture content.

Fine Aggregate: Aggregate of a particle size which passes the No. 10 sieve (2 millimeters) diameter.

Frequency: The number of complete cycles of the vibrating mechanism per minute.

Gradation: The distribution or percentage of sizes of an aggregate.

Grade: Usually the elevation of a real or planned surface or structure. The surface slope expressed as rise or fall in elevation per unit length.

Grade Stake: A stake indicating the amount of cut or fill required to bring the surface to a specified level.

Gradient: Slope along a specified route, of a road surface, channel or pipe.

Grading: The distribution or percentages of sizes in an aggregate sample.

Granite: A very hard, natural, igneous rock of visible crystalline structure, composed essentially of quartz and feldspar.

Gravel: A material of rounded, sub-angular or angular fragments with a particle size ranging from 3 inches (75 millimeters) to the number 10 sieve (2 millimeters).

Haul Distance: The distance measured along the center line or most direct route between the center of the excavation and the center of the fill as placed.

Igneous Rock: The classification of rock formed from the molten elements within the earth's core known as magma:

Intrusive Rock: Igneous rock that is formed as magma forces its way into other rock.

Extrusive Rock: Igneous rock that is formed as magma forces its way to the earth's surface.

Impervious: Resistant to movement of water.

Limestone: A rock consisting chiefly of calcium carbonate, usually formed from an accumulation of organic remains, such as shells.

Liquid Limit: The minimum moisture content at which a soil will flow upon the application of a very small shearing force; expressed as a percent of water content to the dry soil weight.

Loam: A soft, easily-worked soil containing sand, silt and clay.

Metamorphic Rock: The class of rock formed as a result of drastic natural changes in igneous or sedimentary rock. Forces such as heat, pressure and chemical action are necessary for formation.

Mineral: A substance having a definite chemical composition; as a rule, a crystalline structure.

Mineral Dust: A finely divided mineral product, all of which will pass the number 200 sieve (0.074 millimeters).

Mineral Filler: A finely divided mineral product, 65 percent of which will pass the number 200 sieve (0.074 millimeters).

Open-Graded Aggregate: An aggregate containing little or no mineral filler, resulting in a relatively large void content.

Operating Weight: A machine's gross vehicle weight, with full mechanical operating systems, plus a full tank of fuel, one-half tank of water (if so equipped,) plus a 175 pound (80 kilograms) weight operator. If this weight includes ballast, the location, type(s), and weight of the ballast should be so designated.

Optimum Moisture Content: The exact amount of water necessary to coat each particle of soil in a manner that the maximum weight per volume can be attained for any given material with a given compactive effort.

Pass: A working one way trip of a roller over a surface. A round trip is two passes.

Permeability: That property of a material which permits water to flow through it.

Plastic: A soil is described as plastic if, at some moisture content, it can be rolled out into thin threads .

Plastic Limit: The lowest moisture content at which a soil specimen can be rolled into a thread of one-eighth inch (3 millimeters) diameter without the thread breaking into small pieces.

Plasticity Index: The numerical difference between the Liquid Limit and Plastic Limit of a soil; PI indicates the range of moisture content over which the soil is in a plastic consistency.

Pneumatic Tire Roller: A roller which has (smooth) rubber tires to achieve compaction through manipulation of the material surface.

Proctor Test(s): The more common name for the laboratory tests AASHTO T 99 and T 180.

Profile: A charted line indicating grades and distances (and usually depths of cuts and heights of fills) for excavation and grading work, commonly taken along the centerline of the project.

Sand: A cohesionless aggregate consisting of rounded, sub-angular and angular fragments of rock, with particle size between the number 10 sieve (2 millimeters) and the number 200 sieve (0.074 millimeters).

Sedimentary Rock: Fragments and particles of igneous rock that have been broken down, transported and resolidified by natural forces.

Sieve Analysis: A mechanical separation process for determining fractional amounts of various grain size materials contained in a material sample.

Slag: Refuse from steel-making.

Specific Gravity: A number which represents the relationship of volume of a substance compared to an equal volume of water.

Static Force: The force exerted on the ground by the static weight at the drum.

Static Weight: That portion of the operating weight exerted on the ground at the drum(s), roll(s) or tires.

Sub-base: A thoroughly compacted portion of the embankment or special material directly under the base.

Tamping Feet: Specifically designed and evenly arranged projections on a compactor drum used to achieve compaction and prevent layering within a fine-grained soil fill.

Total Applied Force: The sum of the dynamic force plus the force exerted on the ground by the static weight. This term is not recommended for advertising.

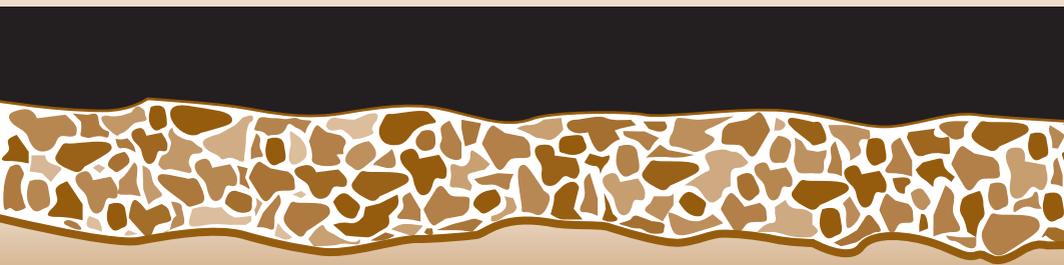
Unsprung Weight: The mass of all the intentionally vibrated parts at each drum. Term is used synonymously with vibrating weight.

Vibrating Weight (Mass): The weight (mass) of all intentionally vibrating parts at each drum.

Vibratory Roller: A compactor designed with mechanical systems which cause one or more of its drums to be intentionally vibrated.

Windrow: A ridge of loose soil or rock.

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