



TECHNICAL NOTE 2.

SOIL PARTICLE AND BULK DENSITY

2.0 BACKGROUND

Particle and bulk density are measurable soil properties. Particle density is an indicator of soil mineral composition and is needed to calculate related parameters such as porosity. Particle density is typically measured in a laboratory with special apparatus. Bulk density can be measured in the field or laboratory. Bulk density has multiple practical uses for example:

- Calculating the weight of soil per unit area and depth ($l \times w \times d$)
- Calculating total water storage capacity per volume of soil
- Calculating plant-essential nutrient content per unit area and depth of soil
- Calculating soil porosity (if particle density is known)
- Evaluating the significance of soil compaction

If an inveterate dirt hog were to go into the field and extract, carefully, a $1 \times 1 \times 1$ meter block of soil, full inspection would reveal that it is made up of four components:

- *Solid particles*, which are in contact with each other and may vary from macro (visible to the eye) to micro (visible only under a magnifying device) size.
- *Pores or voids*, the open spaces between particles containing air and water.
- *Water*, containing dissolved substances. Water may be present in sufficient quantity to completely fill the pore space between particles, or may only surround the particles in a very thin film. Differences in soil water content cause the soil to feel wet, somewhat moist, or dry.
- *Organic matter*, the decayed or partly decayed remains of once-living biomass. Organic matter accumulates in the topsoil layer where it imparts a dark brownish hue.

In this technical note, treatment of soil particle and bulk density rests on the first two components: soil particles and pore space. Soil water is not considered when measuring particle or dry bulk density. Organic matter is also ignored. However, water and organic matter content strongly influence the degree of **soil compactibility**.

The relationship between bulk density and soil compaction is a perennial topic about which much has been written. Here, we examine several properties of soil that influence compactibility, and the practical consequences, good and bad, of soil compaction.

2.1 SOIL PARTICLE DENSITY

Density is a physical property of all substances. In principle, density is defined as the mass of a substance per unit volume:

$$\rho = \frac{m}{V}$$

where ρ is the density (symbolized by the lower case Greek letter rho), m is the mass, and V is the volume. Units for density may grams per cubic centimeter (g/cm^3 : CGS metric), kilograms per cubic meter (kg/m^3 : MKS metric), or pounds per cubic feet (lb/ft^3 : English).

Physical materials have different densities depending on their chemical structure and degree of purity. To simplify comparison of density across substances and units of measurement, a dimensionless ratio “relative density” or “specific gravity” is often used instead. Here, the ratio of a substance is always compared to that of a standard substance, usually pure water at 24 degrees centigrade, which has a density of 1 g/cm^3 . The density of water varies slightly with temperature. However, for practical purposes a density of 1 g/cm^3 can be assumed.

Particle density, ρ_s , is a physical property of soil, defined as the mass per unit volume of soil solids, reported in grams per cubic centimeter (g/cm^3 : metric). Particle density depends upon the chemical composition and crystal structure of solid mineral particles and is not affected by pore space. As such, particle density is independent of the size of particles and their arrangement in the soil.

Mineral particles (sand, silt, clay) have higher densities compared to organic matter. Typical particle densities range from $2.6\text{--}2.75 \text{ g/cm}^3$, with 2.65 g/cm^3 often used as an “average” value for calculations involving mineral soils. The particle density range is narrow because quartz, feldspar, mica, and colloidal silicates make up the main portion of mineral soils and their densities are in this range.

By comparison, water, pine wood, concrete, mild steel, and lead metal have densities of 1.0, 0.7, 2.4, 7.7, and 11.3 g/cm^3 (Table 1).

Table 1. Density of various substances.

	g/cm^3	lb/ft^3	kg/m^3
Water	1.0	62.4	1,000
Pine wood	0.7	44	700
Concrete	2.4	150	2,400
Steel, mild	7.7	480	7,700
Lead metal	11.3	706	11,300

Organic matter has a lower particle density than soil minerals, ranging from 0.9 to 1.3 g/cm^3 . The topsoil layer typically has higher organic matter content and lower bulk density compared with that of the subsoil. In all cases, dry bulk density values are lower than soil particle density.

A volumetric glass flask, called a pycnometer, or specific-gravity flask, is employed for measuring soil particle density. The flask is fitted with a with ground glass stopper that is perforated lengthwise with a capillary channel (Figure 1a and 1b). Sometimes a thermometer is included in the apparatus but it isn't an integral component. A length of capillary tubing is immersed in the mineral particle-water mixture through the capillary channel. Entrapped air is removed by applying vacuum pressure through the capillary tubing. Specific gravity is calculated using a mathematical formula covered by Blake and Hartge (1986) and ASTM D854.

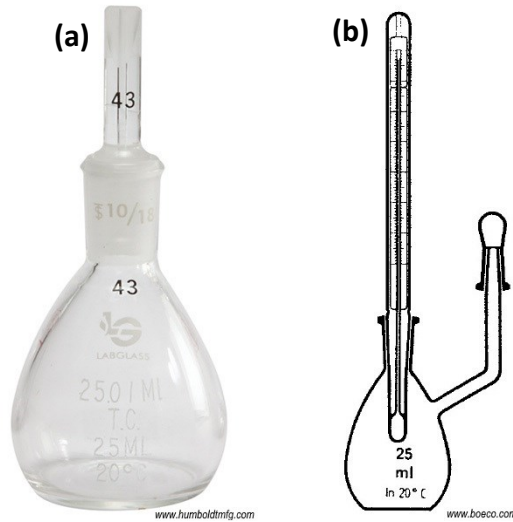


Figure 1. Pycnometer flasks for determining soil particle density (a) without and (b) with thermometer.

2.2 SOIL BULK DENSITY

Bulk density is the mass per unit volume of dry (moisture-free) soil in its natural state. The formula for bulk density is:

$$\rho_b = \frac{\text{soil mass oven-dry}}{\text{soil volume}}$$

where ρ_b is the bulk density (symbolized by the lower case Greek letter rho subscripted with the lower case letter *b*). Where bulk density is computed on a moisture-free (i.e. oven-dry) basis, the amount of water in the soil is ignored¹. Note that bulk density is obtained by dividing by the total “bulk” sample volume, including all particle solids and pore space, by the oven-dry soil mass. In contrast, density is obtained by dividing the measured mass of a substance by its volume. In civil engineering practice, the term *dry density* is often used instead of bulk density. However, in principle, the measurements are not different.

¹ Bulk density can be calculated on a dry or wet basis. When reporting bulk density, soil scientists usually mean dry bulk density although the fact is not always made explicit. Wet density is measured where information about the total mass of soil + water per unit volume is needed, for example when evaluating the bearing capacity of structural members under the weight of soil at a given water content.

Compared to particle density, bulk density takes account of the total pore space in a soil body. Bulk density can provide insight to other soil properties such as porosity, water storage, fluid permeability, and compaction. Bulk density of surface mineral soil typically falls within 1.0 to 1.6 g/cm³ range, varying primarily with:

- *Pore space.* An average, well-aggregated soil has approximately 50 percent pore space. In general, soils with less pore space are more compacted; soils with more pore space are less compacted. Soil with less than 45% by volume of pore space is not optimal for agricultural use.
- *Texture.* Fine-textured soils like silt loam, clay, and clay loam generally have lower bulk density compared to sandy soils. Bulk density levels for cultivated, fine-textured soils range from 1.0 - 1.6 g/cm³, while sandy soils have bulk densities greater than 1.4 g/cm³ (Table 2). These differences are primarily due to greater soil aggregation and structure in fine-textured soils.
- *Organic matter.* Organic matter content of the soil affects bulk density, generally decreasing the bulk density as organic matter content increases, and vice-versa. Organic soils commonly have bulk density < 1.0 g/cm³. Sandy soils tend to have lower organic matter and granular structure. As such, they often have higher bulk densities compared to fine-textured soils.
- *Soil depth.* Bulk density tends to increase with depth in the soil profile. This is due to (a) lower organic matter content in the subsoil; (b) compaction due to the weight of the overburden material; (c) less aggregation, and (d) less root, earthworm, and meso-fauna activity.

Table 2. General relationships among texture, particle and bulk density, and porosity of soils.

Soil Type	Particle density (g/cm ³)	Bulk density (g/cm ³)	Porosity (cm ³ /cm ³)
Mineral soils, plowed horizons			
fine-medium texture	2.60	1.0-1.6	0.69-0.46
coarse texture	2.60	1.4-1.8	0.46-0.35
Subsoil and parent materials	2.65	1.5-1.8	0.43-0.32
Grassland and woodland, surface horizon	2.4	0.8-1.2	0.67-0.50
Peats	1.4	0.1-0.3	0.93-0.79

Source: Rowell (1994) and McCarty et al. (2016)

Bulk density is determined by measuring the mass of soil in a container of known volume, typically a cylinder. The cylinder's inside volume is equal to the soil volume. After pushing the soil out of the cylinder, it is dried in an oven at 105° centigrade until reaching a constant weight. Bulk density is calculated by dividing the oven-dry mass by the cylinder volume. It is not necessary to extract a uniform shaped soil sample for bulk density. Any volume of soil can be extracted provided the excavation volume can be determined. Clods can be coated with liquid paraffin and dipped into water to measure water displacement (Archimedes' principle) and, in turn, to calculate volume. One piece of equipment for measuring bulk density “in situ” consists of a smooth-walled, single- or double cylinder sampler equipped with drive head and hammer assembly (Figure 2).

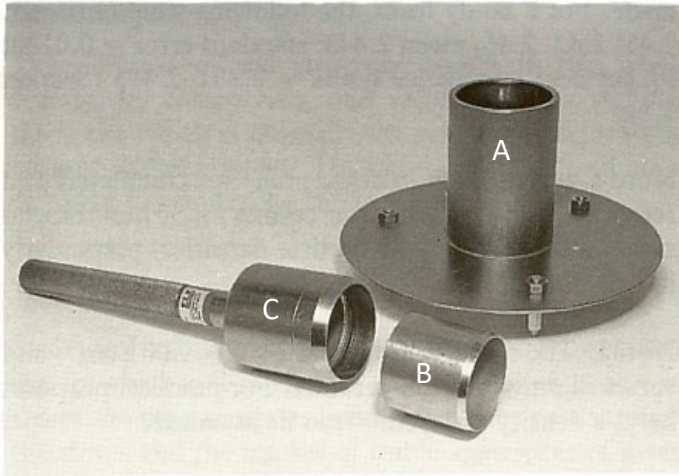


Figure 2. Equipment for measuring soil bulk density in the field. The guide plate and cylinder (A) is placed on the soil surface. The sampling cylinder, or “Shelby” drive tube (B), is machined to fit inside the drive hammer (C). The drive hammer and tube are then inserted into the guide cylinder and hammered into the soil by dropping a sliding weight attached to the stem of the drive hammer (not pictured). The drive hammer includes some headspace allowing soil to extend beyond the drive tube, avoiding sample compaction (*ELSE International/Soiltest*).

2.3 SOIL POROSITY

Soil porosity, pore space, or void space, in a soil consists of that portion of the soil volume not occupied by solid particles, either mineral or organic. An “ideal” soil for crop production would contain 25 percent water and air by volume, and 50 percent consisting of solid particles (Figure 3).

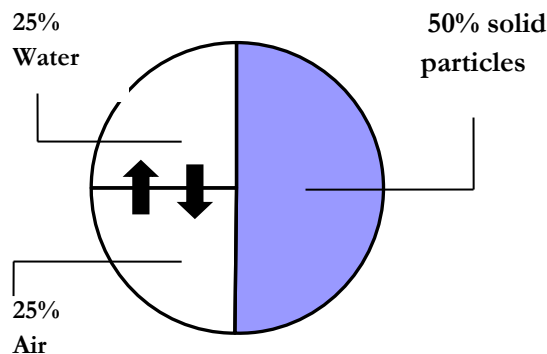


Figure 3. “Ideal” mineral soil for crop production consisting of 25% air and water by volume, and 50% solid particles (minerals and <4% fraction of organic matter). Although the percentages vary, every soil has the same four components: mineral and organic matter, air, and water.

The solid portion is made up of the minerals sand, silt, and clay, and a small fraction (usually < 4%) of organic matter. Under field conditions, air and water occupy the pore space between the mineral particles at all times. The size of individual pores depends on the shape and size of primary particles and how tightly they are packed together. When solid particles are in close contact with each other, porosity is predicted to be low, and bulk density high. When particles are arranged in porous aggregates, as so often in medium-textured soils high in organic matter, the volume of pore space is predicted to be high and bulk density low.

The formula for calculating the percentage of the total volume of soil occupied by pore space is given by:

$$f_t = \left(1 - \frac{\text{bulk density, } \rho_b}{\text{particle density, } \rho_s} \right) \times 100$$

where f_t is the fractional volume of soil occupied by pore space (air- or water-filled) expressed as a percentage of the total volume of soil² (symbolized by the lower case letter t). The formula above indicates that two density measurements, particle density (Section 2.0), and bulk density (Section 2.2), are needed to calculate porosity. Porosity values generally range between 30%–60%. Sandy soils generally vary in total pore space from 30%–50% whereas, fine textured soils vary from 40%–60%.

A worked example calculating particle and bulk density, and soil porosity follows.

Example A cylindrical soil sample was taken for determination of bulk density. The cylinder’s inside diameter was 4.12 cm, and its height 10.16 cm, both measured with a caliper. The soil in the cylinder weighed 247.60 grams (g) in its natural state and 218.90 g when oven-dried. After grinding and passing through a sieve with 2 millimeter diameter openings, a 25.00 g subsample was poured into a beaker with 100 milliliters (mL) distilled water where the soil-water volume was 109 mL. Calculate the bulk density (ρ_b), particle density (ρ_s), and percent pore space (f_t). Assume 1 mL water = 1 cm³ water, i.e. density of 1.0.

$$\begin{aligned} \text{cylinder volume (V}_s\text{)} &= \pi r^2 h \\ &= (3.14)(2.06 \text{ cm}^2)(10.16 \text{ cm}) \\ &= 135.45 \text{ cm}^3 \end{aligned}$$

$$\begin{aligned} \text{volume of water displaced by soil (V}_s\text{)} &= 109.5 \text{ mL} - 100 \text{ mL} \\ &= 9.5 \text{ mL or } 9.5 \text{ cm}^3 \end{aligned}$$

$$\begin{aligned} \text{particle density (}\rho_s\text{)} &= \frac{m_s}{V_s} \\ &= \frac{25.00 \text{ g}}{9.5 \text{ cm}^3} \\ &= 2.63 \text{ g/cm}^3 \end{aligned}$$

$$\begin{aligned} \text{bulk density (}\rho_b\text{)} &= \frac{m_s}{V_t} \\ &= \frac{218.90 \text{ g}}{135.45 \text{ cm}^3} \\ &= 1.62 \text{ g/cm}^3 \end{aligned}$$

$$\begin{aligned} \text{total porosity (f}_t\text{)} &= \left(1 - \frac{\text{bulk density, } \rho_b}{\text{particle density, } \rho_s} \right) \times 100 \\ &= \left(1 - \frac{1.62}{2.63} \right) \times 100 \\ &= 38.4\% \end{aligned}$$

² Void ratio is parallel index of porosity employed by civil engineers. Void ratio is calculated by dividing the volume of voids (pore space), by the volume of solids (soil particles). Void ratio relates the volume of pores to the volume of solids. As such void ratio is independent of total volume.

In the example above, particle density was calculated using the displacement method. The “average” particle density 2.65 g/cm³, is often employed for all but the most exacting work.

With a bit more finagling, we can calculate the percentage of the total pore space occupied by water and air. To calculate water-filled porosity, the volumetric water content, or percentage water by volume, must be determined. Volumetric water content is determined by finding the percentage water content by weight in the sample, then multiplying the water content of the sample by its bulk density. Soil water content is determined as follows:

$$\begin{aligned}\text{water content } (\theta_g) &= \frac{\text{wet soil mass} - \text{dry soil mass}}{\text{dry soil mass}} \\ &= \frac{247.60 \text{ g} - 218.90 \text{ g}}{218.90 \text{ g}} \\ &= \frac{28.7 \text{ g}}{218.9 \text{ g}} \\ &= 0.13 \text{ g H}_2\text{O/g soil} \text{ (13\% by mass)}\end{aligned}$$

Soil water content, θ_g (symbolized by the lower case Greek letter theta subscripted by the lower case letter g) is the mass of water per unit mass of solid particles. For the sample above, each gram of soil contains 0.13 grams water. The subscript “g” stands for “gravimetric”, which means that the water content in the sample was determined by mass difference (in this case, loss of water mass during oven-drying).

Volumetric water content, θ_v , is determined as follows:

$$\begin{aligned}\theta_v &= \text{water content, } \theta_g \times \frac{\text{bulk density, } \rho_b}{\text{water density}} \\ &= \frac{0.13 \text{ g water}}{\text{g soil}} \times \frac{1.62 \text{ g/cm}^3}{1 \text{ g/cm}^3} \\ &= 0.21 \text{ cm}^3 \text{ water/cm}^3 \text{ dry soil (21\% by volume)}\end{aligned}$$

The water-filled porosity is determined by:

$$\begin{aligned}\text{water-filled porosity } (f_w) &= \frac{\% \text{ water by volume, } \theta_v}{\text{total porosity, } f_t} \times 100 \\ &= \frac{21\%}{38.4\%} \times 100 \\ &= 55\%\end{aligned}$$

The following table summarizes the soil properties determined for our sample:

Property	Value
Particle density	2.63 g/cm ³
Bulk density	1.62 g/cm ³
Total porosity	38.4%
Water-filled porosity	55%
Gravimetric water content	0.13 g/g
Volumetric water content	0.21 cm ³ /cm ³

What does this information reveal about the soil?

Particle density of 2.63 g/cm³ indicates that the sample is a mineral soil with relatively low organic matter content (Table 1). The percentage sand, silt, and clay is unknown; however, particle density suggests the sample is higher in coarse-texture sand particles compared with fine-texture silt and clay.

From Table 1, a soil with bulk density 1.62 g/cm³ and 38.4% total porosity also suggests that, along with particle density, the soil is coarse textured. Total porosity includes large and small pores. As such, it tells us nothing about the distribution of pore sizes in the soil. Water is held in small pores less than about 50 microns (μm) in diameter by adhesive and cohesive (surface tension) forces collectively called *capillary forces*. Capillary pores are the main reservoir of plant available water and determine the soil's water holding capacity. In contrast, water drains by gravitational force from pores larger than about 50 microns (μm) in diameter, called *noncapillary or macropores*.

If we assume the soil was at **field capacity** when the sample was taken, i.e. all gravitational water having drained away from the sample zone, the volume of water-filled pore space should roughly equal to the volume of capillary pore space. The calculated volume of water-filled pore space in our sample was 55%. In turn, the percentage by volume of air-filled pore space can be found by subtraction, i.e. 100-55 = 45%. These figures come pretty close to the “ideal” agricultural soil with air-filled (non-capillary) and water-filled (capillary) pore space occupying about equal volume of the total pore space. However, the reader should bear in mind that the relative amounts of water- and air-filled pore space fluctuates constantly. Rainfall infiltrating the soil drives air out of the pores. As the soil dries, air re-enters and pores, gradually reaching field capacity over a period of 1-3 days depending on soil texture and internal drainage. For growing plants, the *distribution* of pore sizes is more important than total porosity.

The depth of water in the soil can also be calculated from the volumetric water content since 1 cm³ of water also occupies a cube 1 cm x 1 cm x 1 cm (l x w x h) if no soil particles are present. Thus, soil with a volumetric moisture content of 0.21 cm³ would occupy a layer 1 cm long x 1 cm wide x 0.21 cm high. A volumetric water content of 21% is therefore equivalent to a depth of 0.21 centimeters water *per centimeter depth of soil*. Our core sample measured 10.16 cm deep so the total depth of water in the core is 10.16 x .21 = 2.13 cm (0.84 inches). This is more water than predicted by coarse texture alone so our assumption about the soil reaching field capacity may not be true³.

The exact weight of soil per hectare can be calculated from bulk density using the following equation:

$$\begin{aligned}\frac{\text{kilograms soil}}{\text{hectare}} &= \\ \text{cm depth} \times \frac{10,000 \text{ m}^2}{\text{hectare}} \times \frac{1 \text{ m}}{100 \text{ cm}} \times \frac{1.62 \text{ g}}{\text{cm}^3} \times \frac{\text{cm}^3}{1 \text{ g H}_2\text{O}} \times \frac{1,000 \text{ kg H}_2\text{O}}{1 \text{ m}^3}\end{aligned}$$

³The soil was a Rains sandy loam 15-25 cm deep sampled in November from a field that had been tilled six months prior with a subsoiling chisel, tandem disk and field conditioner.

This equation tells us that in calculating the weight of one hectare (=2.47 acres) of soil, the weight of soil is compared to water in weight. Soil with a measured bulk density of 1.62 g/cm³ weighs 1.62 times (62%) more than the equivalent amount of water (the density of pure water at 25° C is given as 1 g/cm³).

A cubic meter of water weighs 1,000 kilograms (symbol: kg). If soil is 1.62 times heavier, then its weight is 1,000 x 1.62 = 1,620 kg per cubic meter, and 1,620 kg x 10,000 cubic meters per hectare = 16,200,000 kg soil (16,200 metric tons). Since our core measures 10.16 cm deep, the adjusted weight of soil is 16,200,000 x 0.1016 = 1,645,920 kg (~ 1,468,160 lb/acre, 4 inches deep).

Soil testing laboratories typically assume a sampling depth between 6–7 inches. The exact weight of soil per acre is usually calculated on the basis of pounds per acre-furrow slice (lb/AFS). By definition, an acre-furrow slice of soil is 6.7 inches deep. It is the assumed depth that a 16-inch moldboard plow bottom reaches. A *furrow slice* of soil is the layer of soil sliced away and inverted by a moldboard plow. Acre-furrow slice is the assumed mass of one acre of soil 6 inches deep, 1,000 tons (2,000 pounds per ton). *Hectare-furrow slice* is the assumed mass of one hectare (2.47 acres) of soil 15 cm deep, 2,200 metric tons (1,000 kilograms per ton).

In practice, plowing may be deeper or shallower than 6.67 inches. A such, acre-furrow slice is not an exact, scientific unit of measure. However, *acre-furrow slice* is firmly entrenched in the agronomy and soil sciences lexicon. The term is used in practical situations where an approximation is needed.

A soil with bulk density of 1.48 g/cm³ weighs 2,011,427 lb/AFS (~2,255,520 kg/ha) or approximately 2 million pounds. Therefore, we can convert quantitative parts per million (symbol: ppm) of a nutrient to pounds per acre furrow slice (6 inches deep) by multiplying ppm by 2. For example, a potassium concentration of 150 ppm in a soil with bulk density of 1.48 would have an exact potassium content of 150 x 2 = 300 lb/acre (336 kg/ha) six inches (15 cm) deep. Generally, the supply of plant essential nutrients in pounds per acre can be approximated by multiplying ppm by 2 if the sample depth is 6 inches⁴. Note that the calculated supply is valid only through the depth of sampling. Plant roots often extend deeper than six inches. Estimating the total supply of plant essential nutrients is impossible without sampling beneath the surface rooting zone.

2.4 BULK DENSITY AND COMPACTION

Bulk density is also a measure used to quantify the density of soil at different levels of compaction. The evaluation of soil compaction from bulk density relies, to some extent, on knowledge of particle size distribution, i.e. the percentage sand, silt, and clay. For example, a clay soil with a bulk density of 1.4 g/cm³ may feel hard and compact, especially

⁴In comparing results from different labs, always verify the analytical methods and rationale. North Carolina Department of Agriculture (NCDA) soil tests are made on a mass per unit volume basis, reported as sufficiency index values for easy interpretation. Conversion to an area equivalent is based on a depth of 20 cm (7.9 inches) and a bulk density of 1 g/cm³. See end note "Conversion" for full rationale.

when dry. But a loose coarse sandy soil may have a bulk density of 1.7 g/cm³. The reason is that clay soils have many small pores giving high porosity. Sandy soils have few large pores with overall lower porosity. The density of clay particles is also lower than sandy particles due to alteration of the mineral structure from weathering. Table 3 provides rough guidelines for the minimum dry bulk density at which root growth is affected for various soil textures.

Table 3. Bulk density and root growth relationships based on soil texture.

Soil Texture	Ideal bulk density (g/cm ³)	Marginal bulk density (g/cm ³)	Root restricting bulk density (g/cm ³)
Sands, loamy sands	<1.60	1.69	>1.80
Sandy loams, loams	<1.40	1.63	>1.80
Sandy clay loams, clay loams	<1.40	1.60	>1.75
Silts, silt loams	<1.40	1.60	>1.75
Silt loams, silty clay loams	<1.40	1.55	>1.65
Sandy clays, silty clays, clay loams	<1.10	1.49	>1.58
Clays (>45% clay)	<1.10	1.39	>1.47

Source: USDA-NRCS

Compaction occurs when soil particles and aggregates are pressed together into a smaller volume. For example, if we filled a bucket with soil and packed it down such that it occupied one-half the volume, the mass of soil per unit volume must increase. This is the procedure of compaction (Figure 4).

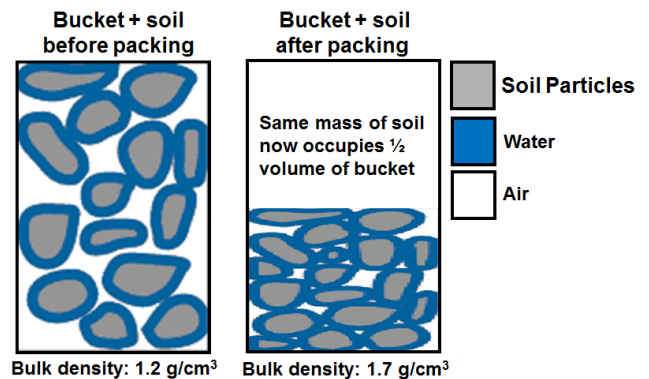


Figure 4. General relationship between packing density and volume for two levels of bulk density.

Soil compaction is conditioned on two principal factors:

- *Natural*: soil particle size distribution properties; pressure from root penetration; kinetic energy of rainfall and infiltrated water; overburden pressure; extent of water-logging and freeze-thaw cycles.
- *Artificial*: field machinery pressure, number of passes, drive slippage; actions related to tillage and crop residue management; mistakes in crop rotation such as continuous cropping.

As the level of compaction increases, the volume of air-filled porosity in the soil decreases, and its *density*, or mass per unit of volume, increases.

Harking back to our bucket of soil, it is evident that the packed soil occupies a smaller volume but the mass of soil in the bucket has not changed. The soil is simply denser than before; the reaction of soil to packing was the expulsion of air and the rearrangement of solid particles so that they are in closer contact. In practical terms, compaction is a rearrangement of soil particles under *loading* that decreases the fractional volume of air-filled pores.

Soil compaction can be either good or bad. From an agricultural point of view, excessive compaction is bad because it reduces seedling emergence and vigor, root growth, infiltration and internal drainage, decreases aeration and increases the energy costs of tillage (Figure 5, see note 2.41).



Figure 5. Root deflection caused by soil compaction. Shallow rooting limits nutrient and water access by plants, so reducing yield. Escaped nutrients go to waste or worse, may become pollutants. The plants pictured here are “tillage” radish (*Raphanus sativus*), a strain of daikon radish employed to break up hard pans in soil. These specimens were evidently having trouble penetrating a 15-cm deep traffic pan with a measured bulk density of 1.82 g/cm³. Tillage radish is not invincible! Source: R. Walters, N.C. State Univ.

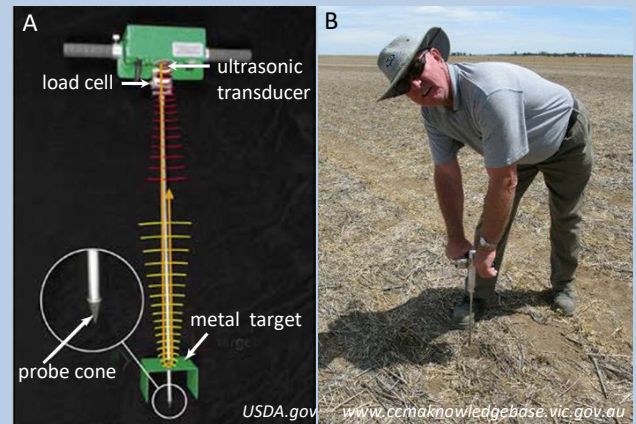
On the plus side, some compaction is needed for proper seed-soil contact when planting. Modern row crop planters are equipped with trailing press wheels for this purpose (Figure 6). Down pressure from the press wheels closes the planter disk opening, providing contact between the seed and surrounding soil particles. Compaction also increases the mechanical strength of soil, which provides anchorage for a plant throughout its life cycle.



Figure 6. Planter press wheel ensures favorable seed-soil contact by firming the soil 360 degrees around the seed after it is placed in the slit opening. Target soil density of ~1.3 g/cm³ surrounding the seed provides optimal movement of nutrients, water, and air through the soil. Source: CaseIH.com

NOTE 2.41

Bulk density is measured to evaluate the level of soil compaction. However, plant roots do not respond directly to bulk density. The rate of root extension, and increase in root diameter, is governed by soil *mechanical impedance* which is conditioned on particle size, pore space geometry and water content. Generally, as bulk density increases and soil water decreases, mechanical impedance increases. Water in the soil acts as a lubricant, allowing plant roots to extend even through very small pore spaces. The exact change in mechanical impedance per unit change in bulk density and water content is soil dependent. Mechanical impedance is measured in the field with a *cone penetrometer* (Insets A and B)



Inset (A) shows the principle operating components of a typical hand-held penetrometer, and (B) field operation. The metal target kicks a signal back to the transducer, allowing the penetrometer to calculate the probe's depth. Cone penetrometer readings may be expressed in kilograms-force per square centimeter (kg-f/cm²: aka “cone index”) or converted to pressure units, kilopascal (symbol: kPa).

Properly calibrated, cone penetrometers are useful for detecting zones of compaction or loosening in the subsoil.

Soil compaction in traffic lanes increases machine traction and reduces the horsepower needed for tillage. Compaction ensures the stability of earthworks formed from transported fill material placed beneath buildings, roads, bridges, power plants, etc. Unforeseen changes in soil volume beneath a structure can result in cracking, shifting, sagging, or in extreme cases, failure.

As the weight of modern farm machinery increases, problems related to soil compaction have become more urgent. The shift toward labor- and energy-saving conservation tillage farming means there is less soil disturbance through tillage manipulation. Less soil disturbance is generally viewed as beneficial for conservation purposes, but unless machinery traffic is controlled the benefits may be erased by compaction.

2.5 PARTICLE SIZE DISTRIBUTION

The compactibility of soil is strongly influenced by the three primary mineral components: sand, silt, and clay. The percentage of sand, silt, and clay in a soil sample is called *particle size distribution* and the way it feels is called *texture*. Obviously, there is a relationship between particle size

distribution and texture. A soil that feels gritty has a high percentage of sand; a silky soil is high in silt; a soil that is plastic and can be molded into a ribbon is high in clay. Particle size distribution may vary with depth and location in a field, an important point to remember when evaluating soil compaction.

Figure 7 shows seven soil textures and their particle size distribution profiles. While these figures are considered 'typical', the sand fraction in a sandy loam soil may vary from ~50-80%. Conversely, soils with more than 20% clay are loamy in texture, and soils with more than 45% clay are called clays. Even small amounts of clay influence soil physical and chemical properties disproportionately relative to same amount of sand and silt.

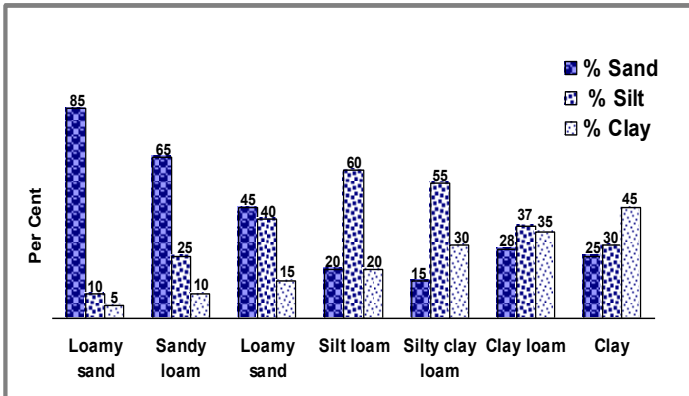


Figure 7. Percentage sand, silt, and clay for seven soil textural classes. Source: redrawn and slightly modified from Siemens et al. *John Deere Publ.* (1993).

The packing density of soil particles depends largely on the shape of the soil particles and the proportion of different sizes present in the soil. The shape of sand particles can be described approximately as 'spherical' while the shape of clay particles is plate-like. Silt particles are intermediate, but considered as approximately spherical in shape because silt is nothing more than very highly weathered sand particles. An equal mixture of sand, silt, and clay can be packed together in a very dense configuration (Figure 8a) because the smaller silt and clay particles occupy the pore space between the larger sand particles. The extent of contact surfaces between individual particles is maximized, resulting in a very dense, mechanically stable mass with minimum pore space. On the other hand, a sandy soil consisting of many grains of uniform size would be more difficult to compact because the geometry of the sand particles does not lend itself to tight packing. The arrangement of uniform sand particles in soil does not affect packing density. There are still many large pores between the sand grains (Figures 8b and 8c). Increasing the force of compaction will not produce tighter packing.

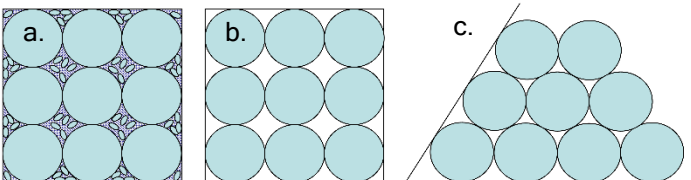


Figure 8. Packing density of soil particles: (a) mixture of sand, silt, and clay particles with capillary micropores; (b) uniform sand particles with non-capillary macropores; (c) the density of uniform sand is independent of packing arrangement.

Several important agricultural soils in the southern U.S. Coastal Plain have shallow, subsurface "pan" layers consisting of naturally compact, sandy loam and loamy sand "E" horizons (Figure 9). These light-colored, moderately well to well-drained soils are typically low in clay and organic matter, with diversified particle sizes in the sand fraction. What is reason for such "genetic" hard pans?



Figure 9. Two related southern U.S. Coastal Plain soil series with E horizons. The E horizon begins at the base of the darker colored topsoil layer and extends through several inches of lighter colored sandy soil beneath. Zones of compaction in the subsoil cannot be diagnosed by evaluating surface texture alone. Image source: J. Kelly SoilScience.info

Again, we must reach back to particle size distribution for understanding. Diversified particles in the sand fraction promotes tight packing, creating an interlocking mass with very little pore space, high bulk density and internal strength. Annual subsoiling is often needed to maintain profitable row crop production on these soils.

To sum up: The total volume of soil is made up of the volume of solid particles and the volume of pores (air- and water-filled) between the solid particles. The ratio of the volume of voids to total volume of soil is the porosity while the ratio of the volume of voids to the volume of solids is the void ratio. The mass of oven-dried solids contained in a unit volume of soil is the bulk density. All three parameters are measures of soil compaction. Particle size distribution is the primary factor governing soil susceptibility to compaction. An equal mixture of different size particles will pack together in the tightest configuration, with minimum pore space, high bulk density and internal strength. This is true for loamy soils, as well as sandy soils that are diversified with respect to the sand fraction. Clayey soils also have a high degree of compactibility because of the plate-like structure of clay minerals.

2.6 SOIL WATER-DENSITY RELATIONSHIPS

Water in soil has a lubricating effect, making it easier to press soil particles and aggregates together (compaction), or to pull them apart (tillage). It is easier to compact a moist soil compared with a dry soil. It is also easier to plow a moist soil than a dry soil. The optimum moisture content for compaction varies with soil. Particle size distribution being equal, the pressure required to compact soil is inversely related to moisture content but only up to a point. Figure 9

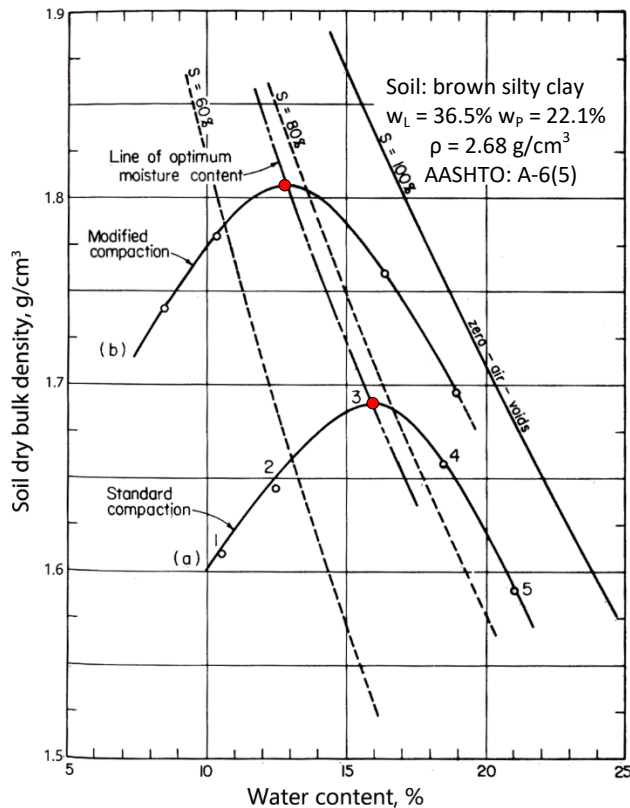


Figure 9. Relationship between soil dry bulk density and water content at two compaction levels. Red dots point the maximum dry density. The figures w_L and w_P are the upper and lower plasticity limits ("Atterberg" limits), i.e. moisture content where the soil behaves as a moldable plastic. S =degree of saturation; ρ =particle density defined in Section 2.0. Source: adapted from Bowles, 1984.

portrays the relationship between soil dry bulk density and water content.

The two compaction curves in Figure 9 are five-point *Proctor density* curves, named after R.R. Proctor who first developed them for control specifications of dam construction earthworks for the Los Angeles Water District during the late 1920s. The point of maximum density is reached at a critical optimum moisture content depending on compaction pressure. As moisture content increases above the optimum for maximum density, water occupies greater volumetric pore space. Because the density of water is 1 g/cc, and water itself is non-compressible, dry density decreases. Higher pressure ("Modified compaction") produces maximum density at lower moisture content compared with lower pressure ("Standard compaction"). In practical terms this means it takes more effort to compact dry soil and, at all pressures, greatest compaction occurs at a soil moisture content near the optimum. As such, soil is most susceptible to compaction from machinery traffic when the moisture content is near field capacity. Less compaction is predicted when soil is above field capacity because water-filled pore space can't be compacted. This is borne out visually by 'rutting' caused by machinery trafficking fields that are too wet. As a result, soil is displaced laterally (Figure 10). Dry soil is also susceptible to compaction under loading, but it takes considerably more pressure than at higher moisture content.



Figure 10. Field rutting from machinery traffic. As soil is saturated above field capacity it becomes less compressible. Red arrows point up "side walls" i.e. soil that has been displaced away from the center footprint. Annual tillage can smooth out field ruts. Rutting is more problematic under minimum and conservation tillage planting systems.

CORE INTELLIGENCE

Conversion: As footnoted in the Section 2.3, North Carolina Department of Agriculture (NCDA) soil tests are made on a mass per unit volume basis. Conversion to an area equivalent is based on a depth of 20 cm (7.9 inches) and a bulk density ("weight per unit volume") of 1 g/cm³. Since the area of one hectare is 10,000 m² or 1 million dm², the volume of one hectare to a depth of 20 cm or 2 dm equals 2 million dm³. Under this rationale, 1 mg/dm³ = 1 ppm. To convert nutrients to kilograms per hectare (kg/ha, area basis), mg/dm³ is multiplied by 2. To convert to pounds per acre (lb/acre) multiply kg/ha by a factor of 0.892.

Field capacity: This is the amount of water remaining in the soil after free drainage. Water entering the soil from irrigation or natural precipitation initially moves downward due to the pull of gravity. The point at which drainage ceases (or becomes very small) is determined by soil particle shape and the packing density of the particles. Water remaining in the soil after free drainage is held by capillary forces (adhesion and the surface tension of water molecules), and represents its water content at 'field capacity'. A sandy loam soil reaches field capacity when capillary suction, i.e. "negative pressure", is near -10 kPa. Medium to fine-textured soils may reach field capacity near -33 kPa pressure. Field capacity is mainly used to infer soil physical attributes like workability or available water capacity as related to water content. Most agricultural soils reach field capacity within 24 to 72 hours after wetting provided the soil is deep enough.

Soil compactibility: Soil compaction, soil compressibility, and soil compactibility are terms that are often used indistinctly in the literature. Here, soil compaction is defined as a procedure that decreases the volume of air-filled pore space through the application of an external load. Soil compactibility is the sensitivity of a soil to change in air-filled porosity per unit change in loading stress. Soil compressibility describes the sensitivity of a soil to changes in pore space per unit change in loading stress, irrespective if water or air is expelled from the pore space. Soil

consolidation is a procedure wherein change in pore volume, or void ratio, is coupled with expulsion of excess pore water from the soil body. We do not consider the effect of soil consolidation in this technical note.

FURTHER READING

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