

SOIL COMPACTION

Compaction is the application of mechanical energy to a soil to rearrange the particles and reduce the void ratio.

3.1 Purpose of Compaction

- The principal reason for compacting soil is to reduce subsequent settlement under working loads.
- Compaction increases the shear strength of the soil.
- Compaction reduces the voids ratio making it more difficult for water to flow through soil. This is important if the soil is being used to retain water such as would be required for an earth dam.
- Compaction can prevent the build up of large water pressures that cause soil to liquefy during earthquakes.

3.2 Factors affecting Compaction

- Water content of the soil
- The type of soil being compacted
- The amount of compactive energy used

3.3 Laboratory Compaction tests

There are several types of test which can be used to study the compactive properties of soils. Because of the importance of compaction in most earth works standard procedures have been developed. These generally involve compacting soil into a mould at various moisture contents.

- Standard Compaction Test AS 1289-E1.1

Soil is compacted into a mould in 3-5 equal layers, each layer receiving 25 blows of a hammer of standard weight. The apparatus is shown in Figure 1 below. The energy (compactive effort) supplied in this test is 595 kJ/m^3 . The important dimensions are

Volume of mould	Hammer mass	Drop of hammer
1000 cm^3	2.5 kg	300 mm

Because of the benefits from compaction, contractors have built larger and heavier machines to increase the amount of compaction of the soil. It was found that the Standard Compaction test could not reproduce the densities measured in the field and this led to the development of the Modified Compaction test.

- Modified Compaction Test AS 1289-E2.1

The procedure and equipment is essentially the same as that used for the Standard test except that 5 layers of soil must be used. To provide the increased compactive effort (energy supplied = 2072 kJ/m³) a heavier hammer and a greater drop height for the hammer are used. The key dimensions for the Modified test are

Volume of mould	Hammer mass	Drop of hammer
1000 cm ³	4.9 kg	450 mm

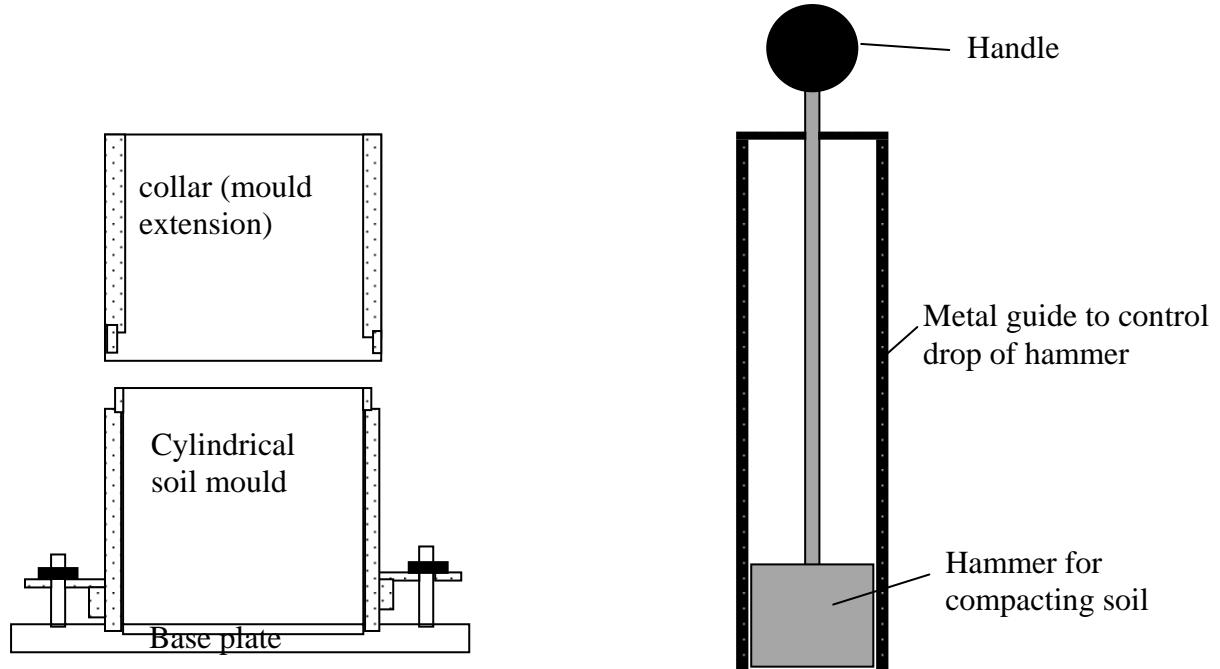


Figure 1 Apparatus for laboratory compaction tests

3.4 Presentation of Results

To assess the degree of compaction it is important to use the dry unit weight, γ_{dry} , because we are interested in the weight of solid soil particles in a given volume, not the amount of solid, air and water in a given volume (which is the bulk unit weight). From the relationships derived previously we have

$$\gamma_{dry} = \frac{G_s \gamma_w}{1 + e}$$

which can be rearranged to give

$$e = \frac{G_s \gamma_w}{\gamma_{dry}} - 1$$

Because G_s and γ_w are constants it can be seen that increasing dry density means decreasing voids ratio and a more compact soil.

In the test the dry density cannot be measured directly, what are measured are the bulk density and the moisture content. From the definitions we have

$$\gamma_{dry} = \frac{Wt\ of\ Solids}{Total\ Volume} = \frac{W_s}{V} \quad m = \frac{Wt\ of\ Water}{Wt\ of\ Solids} = \frac{W_w}{W_s}$$

$$\begin{aligned}\gamma_{bulk} &= \frac{W}{V} = \frac{Wt\ of\ Solids + Wt\ of\ Water}{Total\ Volume} = \frac{W_s + W_w}{V} \\ &= \frac{(1+m) W_s}{V} \\ &= (1+m) \gamma_{dry}\end{aligned}$$

This allows us to plot the variation of dry unit weight with moisture content, giving the typical response shown in Figure 2 below. From this graph we can determine the optimum moisture content, m_{opt} , for the maximum dry unit weight, $(\gamma_{dry})_{max}$.

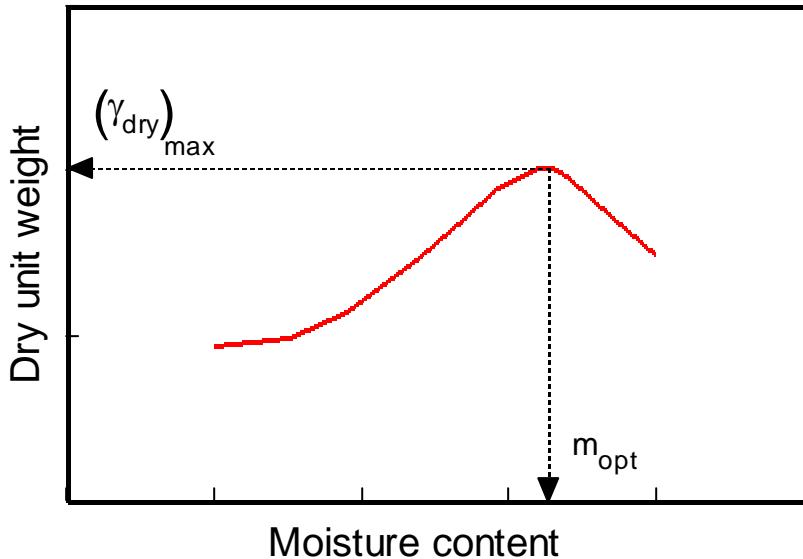


Figure 2 A typical compaction test result

If the soil were to contain a constant percentage, A , of voids containing air where

$$A (\%) = \frac{V_a}{V} \times 100$$

writing V_a as $V - V_w - V_s$ we obtain

$$1 - \frac{A}{100} = \frac{V_w + V_s}{V}$$

then a theoretical relationship between γ_{dry} and m for a given value of A can be derived as follows

$$\gamma_{dry} = \frac{\gamma_{bulk}}{1+m} = \frac{W_s + W_w}{V(1+m)} = \frac{(W_s + W_w)(1 - \frac{A}{100})}{(V_s + V_w)(1+m)}$$

$$\text{Now } V_s = \frac{W_s}{G_s \gamma_w} \quad V_w = \frac{W_w}{\gamma_w} = \frac{mW_s}{\gamma_w}$$

$$\text{Hence } \gamma_{dry} = (1 - \frac{A}{100}) \left[\frac{G_s \gamma_w}{G_s m + 1} \right]$$

If the percentage of air voids is zero, that is, the soil is totally saturated, then this equation becomes

$$\gamma_{dry} = \left[\frac{G_s \gamma_w}{G_s m + 1} \right]$$

From this equation we see that there is a limiting dry unit weight for any moisture content and this occurs when the voids are full of water. Increasing the water content for a saturated soil results in a reduction in dry unit weight. The relation between the moisture content and dry unit weight for saturated soil is shown on the graph in Figure 3. This line is known as the zero air voids line.

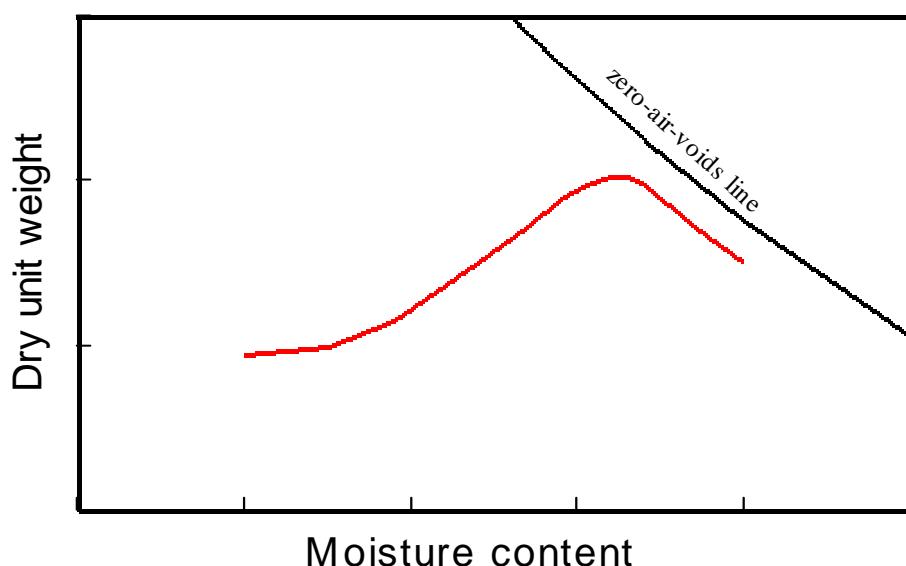


Figure 3 Typical compaction curve showing no-air-voids line

3.5 Effects of water content during compaction

As water is added to a soil (at low moisture content) it becomes easier for the particles to move past one another during the application of the compacting forces. As the soil compacts the voids are reduced and this causes the dry unit weight (or dry density) to increase. Initially then, as the moisture content increases so does the dry unit weight. However, the increase cannot occur indefinitely because the soil state approaches the zero air voids line which gives the maximum dry unit weight for a given moisture content. Thus as the state approaches the no air voids line further moisture content increases must result in a reduction in dry unit weight. As the state approaches the no air voids line a maximum dry unit weight is reached and the moisture content at this maximum is called the optimum moisture content.

3.6 Effects of increasing compactive effort

Increased compactive effort enables greater dry unit weights to be achieved which because of the shape of the no air voids line must occur at lower optimum moisture contents. The effect of increasing compactive energy can be seen in Figure 4. It should be noted that for moisture contents greater than the optimum the use of heavier compaction machinery will have only a small effect on increasing dry unit weights. For this reason it is important to have good control over moisture content during compaction of soil layers in the field.

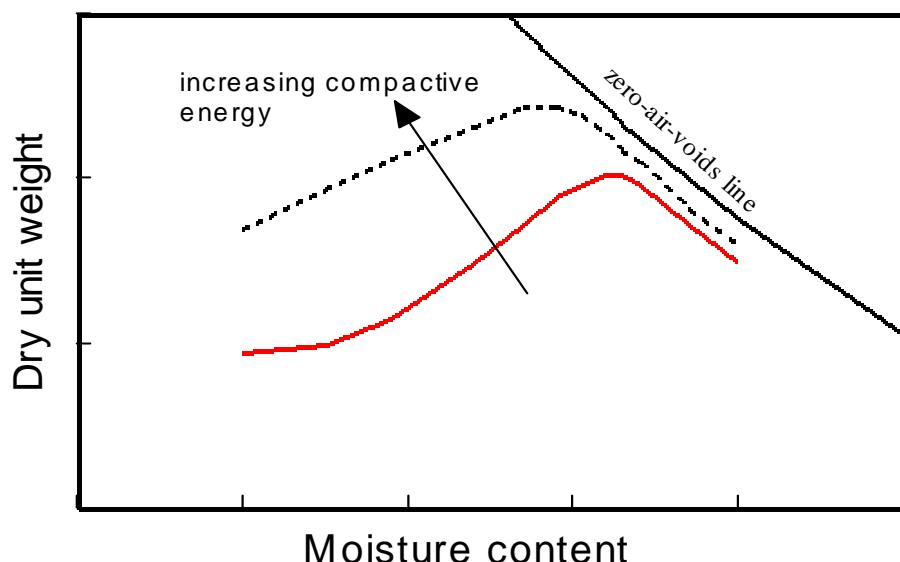


Figure 4 Effects of compactive effort on compaction curves

It can be seen from this figure that the compaction curve is not a unique soil characteristic. It depends on the compaction energy. For this reason it is important when giving values of $(\gamma_{dry})_{max}$ and m_{opt} to also specify the compaction procedure (for example, standard or modified).

3.7 Effects of soil type

The table below contains typical values for the different soil types obtained from the Standard Compaction Test.

		Typical Values	
		$(\gamma_{dry})_{max}$ (kN/m ³)	m_{opt} (%)
Well graded sand	SW	22	7
Sandy clay	SC	19	12
Poorly graded sand	SP	18	15
Low plasticity clay	CL	18	15
Non plastic silt	ML	17	17
High plasticity clay	CH	15	25

Note that these are typical values. Because of the variability of soils it is not appropriate to use typical values in design, tests are always required.

3.8 Field specifications

To control the soil properties of earth constructions (e.g. dams, roads) it is usual to specify that the soil must be compacted to some pre-determined dry unit weight. This specification is usually that a certain percentage of the maximum dry density, as found from a laboratory test (Standard or Modified) must be achieved.

For example we could specify that field densities must be greater than 98% of the maximum dry unit weight as determined from the Standard Compaction Test. It is then up to the Contractor to select machinery, the thickness of each lift (layer of soil added) and to control moisture contents in order to achieve the specified amount of compaction.

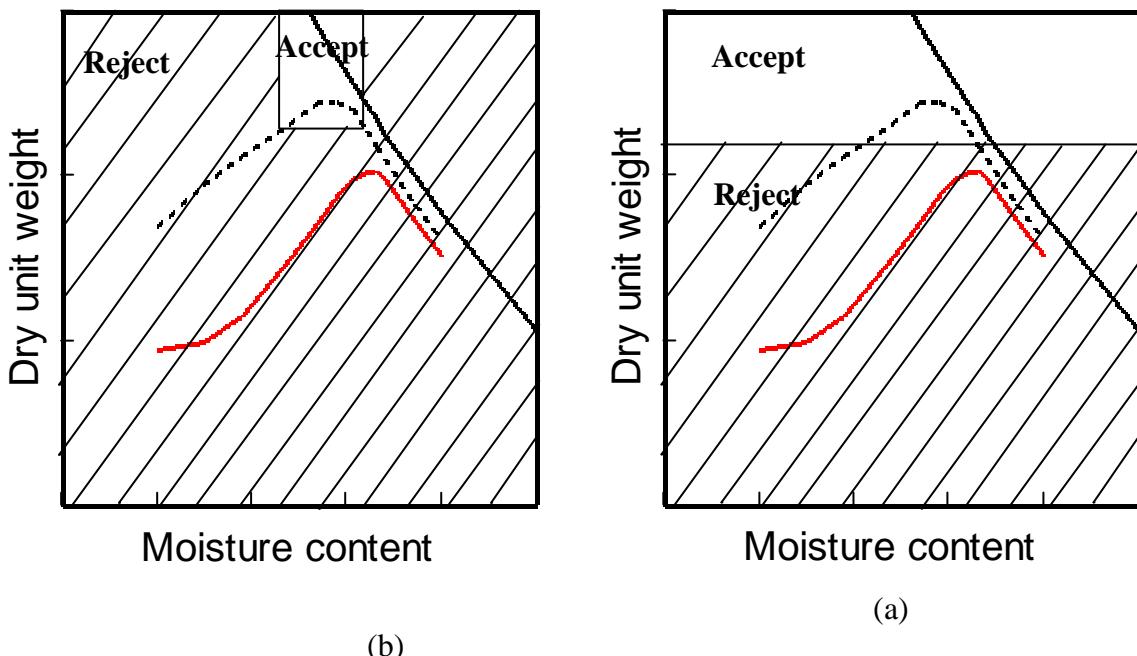


Figure 5 Possible field specifications for compaction

There is a wide range of compaction equipment. For pavements some kind of wheeled roller or vibrating plate is usually used. These only affect a small depth of soil, and to achieve larger depths vibrating piles and drop weights can be used. The applicability of the equipment depends on the soil type as indicated in the table below

Equipment	Most suitable soils	Typical application	Least suitable soils
Smooth wheeled rollers, static or vibrating	Well graded sand-gravel, crushed rock, asphalt	Running surface, base courses, subgrades	Uniform sands
Rubber tired rollers	Coarse grained soils with some fines	Pavement subgrade	Coarse uniform soils and rocks
Grid rollers	Weathered rock, well graded coarse soils	Subgrade, subbase	Clays, silty clays, uniform materials
Sheepsfoot rollers, static	Fine grained soils with > 20% fines	Dams, embankments, subgrades	Coarse soils, soils with cobbles, stones
Sheepsfoot rollers, vibratory	as above, but also sand-gravel mixes	subgrade layers	
Vibrating plates	Coarse soils, 4 to 8% fines	Small patches	clays and silts
Tampers, rammers	All types	Difficult access areas	
Impact rollers	Most saturated and moist soils		Dry, sands and gravels

3.9 Sands and gravels

For soils without any fines (sometimes referred to as cohesionless) the standard compaction test is difficult to perform. For these soil types it is normal to specify a relative density, I_d , that must be achieved. The relative density is defined by

$$I_d = \frac{e_{\max} - e}{e_{\max} - e_{\min}}$$

where e is the current voids ratio,

e_{\max} , e_{\min} are the maximum and minimum voids ratios measured in the laboratory from Standard Tests (AS 1289-5.1)

Note that if $e = e_{\min}$, $I_d = 1$ and the soil is in its densest state
 $e = e_{\max}$, $I_d = 0$ and the soil is in its loosest state

The expression for relative density can also be written in terms of the dry unit weights associated with the various voids ratios. From the definitions we have

$$e = \frac{G_s \gamma_w}{\gamma_{dry}} - 1$$

and hence

$$I_d = \frac{\frac{1}{\gamma_{dry_{min}}} - \frac{1}{\gamma_{dry}}}{\frac{1}{\gamma_{dry_{min}}} - \frac{1}{\gamma_{dry_{max}}}} = \frac{\gamma_{dry_{max}}(\gamma_{dry} - \gamma_{dry_{min}})}{\gamma_{dry}(\gamma_{dry_{max}} - \gamma_{dry_{min}})}$$

The description of the soil will include a description of the relative density. Generally the terms loose, medium and dense are used where

Loose	$0 < I_d < 1/3$
Medium	$1/3 < I_d < 2/3$
Dense	$2/3 < I_d < 1$

Note that you cannot determine the unit weight from knowing I_d . This is because the values of the maximum and minimum dry unit weights (void ratios) can vary significantly. They depend on soil type (mineralogy), the particle grading, and the angularity.