CHAPTER SEVEN
SOIL COMPACTION

6.1. THEORY OF COMPACTION

Compaction of a soil is the pressing of the soil close to each other by mechanical means. During compaction air is expelled from the void spaces. Thus compaction results in an increase in the density of the soil. Compaction improves the engineering properties of soils. It increases the shear strength of the soil & consequently the bearing capacity. It also reduces the compressibility & permeability of soil.

The difference b/n compaction & consolidation is as follows even though both cause reduction in volume.

a) Compaction is a rapid process by which a reduction in volume takes place by mechanical means whereas consolidation is a gradual process of volume reduction by static and uniform load.

b) Compaction is the reduction in volume of a partially saturated soil mass which takes place as a result of expulsion of air from the voids at the same water content where as consolidation is the reduction in volume of a saturated soil mass as a result of expulsion of water from the soil.

c) Compaction is done artificially to increase the engineering properties of the soils where as consolidation takes naturally when soils are subjected to static loads.

To determine the amount of compaction required in the field and the water content required, it is necessary to perform compaction tests in the laboratory on the same soil sample. From these tests the relationships b/n ρdry and water content can be plotted.

6.2. COMPACTION IN THE LAB.

Standard Proctor Test

In standard proctor test a mould of internal diameter of 100 mm and height of 127.30 mm is used. The capacity of the mould is 1000ml. The mould has a detachable base plate & a removable collar. The soil in the mould is compacted in three layers by giving 25 blows of the rammer, which falls through a height of 310 mm and a face diameter of 50 mm to each equal layer. The rammer has a mass of 2 kgs and collar height is 60 mm.

COMPACTION TEST

Objective

To obtain the moisture content – dry density relationship for a soil and hence to determine the optimum moisture content and maximum dry density.

Introduction

Soil compaction can be a very economical method of soil improvement, and it is often used to make ground suitable for the foundations of roads and buildings. It is also used in the placing of soil fills and in the construction of earth dams to ensure suitable soil properties. The compaction is normally achieved through the input of energy into the soil by impact, kneading, vibration or static means.

The extent of compaction depends on the moisture content of the soil and the compactive effort used. In a compaction test the object is to determine the optimum moisture content and maximum dry density achievable with a given compactive effort. A plot of dry density versus moisture content (Figure 1) indicates that compaction becomes more efficient up to a certain moisture content, after which the efficiency decreases. The maximum dry density is obtained at this optimum moisture content.

If the compaction process were completely efficient, it would be possible (but not necessarily desirable) to expel all the air from the voids, in which case the dry density would correspond to a zero-air voids state (ie. the sample would be saturated with water). Since perfect compaction is not possible (except at high moisture contents and low dry density) the compaction curve will always fall below the ideal or zero-air voids curve (Figure 1).

It should be noted that there are a number of standards for compaction tests, each differing in the amount of energy input into compaction. For a given soil the different tests will produce different maximum dry densities and optimum moisture contents (ie. these parameters are NOT soil properties). The maximum dry density and optimum moisture content are only relevant for a specified compaction procedure which should be stated when presenting the results.

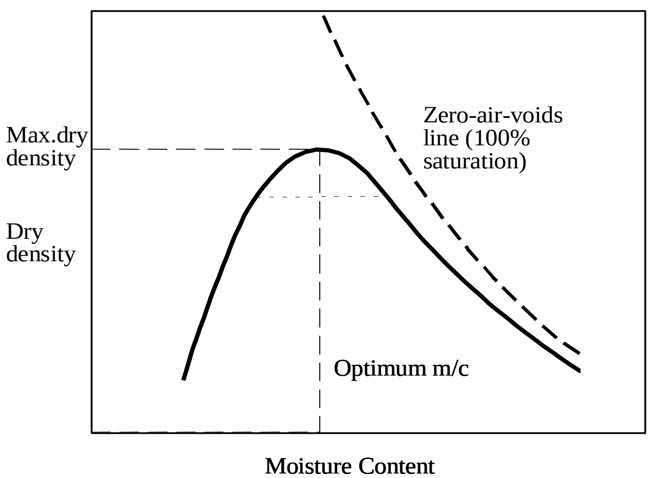
In earthworks it is common to specify a dry density within a certain percentage of the maximum determined from a specified compaction test. For this to be a sensible procedure it is important that the compactive effort used in the laboratory is comparable to that supplied by the field equipment.

Procedure

About 2.5 kg of the soil is provided that it will pass through a No. 4 sieve. The soil sample should be mixed with water and placed in the standard mould provided in 3 approximately equal layers. Each layer is to be compacted with 25 blows from a special compaction hammer. When the mould is full the weight of soil should be measured and then two moisture content samples should be taken for drying in the oven. The volume of the mould is approximately 944 cm^3 (1/30 ft^3) and should be checked by measurements of cylinder height and diameter. The remaining soil should be removed from the mould, broken down until it will again pass a No. 4 sieve (determine visually), remixed with more water added, and then re-compacted into the mould.

The compaction test should be repeated five times with the assumed moisture content used in calculations to ensure that the dry density versus moisture content plot has points on both sides of the optimum moisture content. This assumed dry density and moisture content plot that must be produced during the session, will later be replaced in the report by a plot with the calculations based upon the average of the moisture contents measured with the sample tins.

The two groups performing the experiment will use different compaction hammer weights. To complete the report, you will need to use the dry density versus moisture content data for both hammer weights.



Compaction Test Procedure

1. Weigh the empty mould (with the base but without the collar)

2. Break soil lumps and sieve the soil through a No. 4 sieve

3. Add the required amount of water to the soil

4. Form a 50 to 75 mm layer of soil in the mould, and gently press the soil to smooth its surface

5. Compact the soil with 25 evenly distributed full height blows of the hammer.

6. Repeat the procedure with a second and third layer. After the compaction of the third layer, the surface of the soil must be slightly above the top rim of the mould.

7. Remove the collar and trim off the soil above the top of the mould.

8. Weigh the mould and the sample

9. Remove the soil from the mould and obtain representative samples for moisture content determinations.

10. Break the removed soil from the mould, remix with the original sample, and raise its water content by 2 – 3%.

11. Keep repeating the compaction process until 5 runs have been made.

Calculations

1. The dry unit weight γ_d can be computed from $\gamma_d = \frac{\gamma_t}{1+m}$

Where γ_t =wet unit weight of the soil

$= \frac{W(g) \times 9.81}{V(cm^3)}$ (kN/m^3)

W = mass of the wet compacted soil sample

V = volume of soil

m = moisture content of the compacted soil

$m = \frac{W_w}{W_s} = \frac{W - W_s}{W_s}$

W_s = mass of the dry soil sample

W_w = mass of water

2. to plot the zero air void curve $\gamma_d = \frac{G\gamma_w}{1+(mG/S)}$

Where G =specific gravity of the soil (assume G =2.70)

γ_w =unit weight of water 9.81 kN/m^3 (or density 1.0 g/cm^3)

S =degree of saturation

For zero-air-voids or 100% saturation, S = 1.

3. To calculate the amount of water to be added to the soil assume the initial moisture content is 1.5%, and the mass of the soil is 2500g. Then

$$1.5\% = \frac{2500 - W_s}{W_s}$$

This may be solved for the mass of dry soil Ws which we take to remain constant. Recalling that the assumed initial weight of water in the soil $W_w = 0.015\ W_s$ and that W_s is constant, if the first required water content is 10%, the extra mass of water required W_w can be calculated

$$10\% - 1.5\% = \frac{W_w}{W_s} = 0.085$$

Subsequent water to be added to change the moisture content by 3% can be found from

$$3\% = \frac{W_w}{W_s} = 0.03$$

MOISTURE CONTENT

Determination No.	1	2	3	4	5
Container No.					
Container & Wet soil (g)					
Container & Dry soil (g)					
Container (g)					
Water W_w (g)					
Dry soil W_s (g)					
Moisture content (%)					

DRY DENSITY

Determination No.	1	2	3	4	5
Mass mould & Compacted soil					

(g)					
Mass mould (g)					
Mass Compacted soil (g)					
Wet density ρ_t (g/cm^3) or (t/m^3)					
Dry Density ρ_d (g/cm^3) or (t/m^3)					

To complete the laboratory session each student must show the demonstrator:

- A completed compaction curve. This will require the use of the nominal moisture contents.
- On the plot with the compaction curve show the no-air-voids (NAV) line
- A comment on the significance of any point plotting above the NAV line
- The maximum dry unit weight and optimum moisture content

Report Format

Your report should include the following:

1. A description of the soil.

2. A sample of the calculations used to determine dry density and moisture content.

3. A plot showing the variations of dry density with moisture content for both hammer weights (draw both sets of data on the same graph).

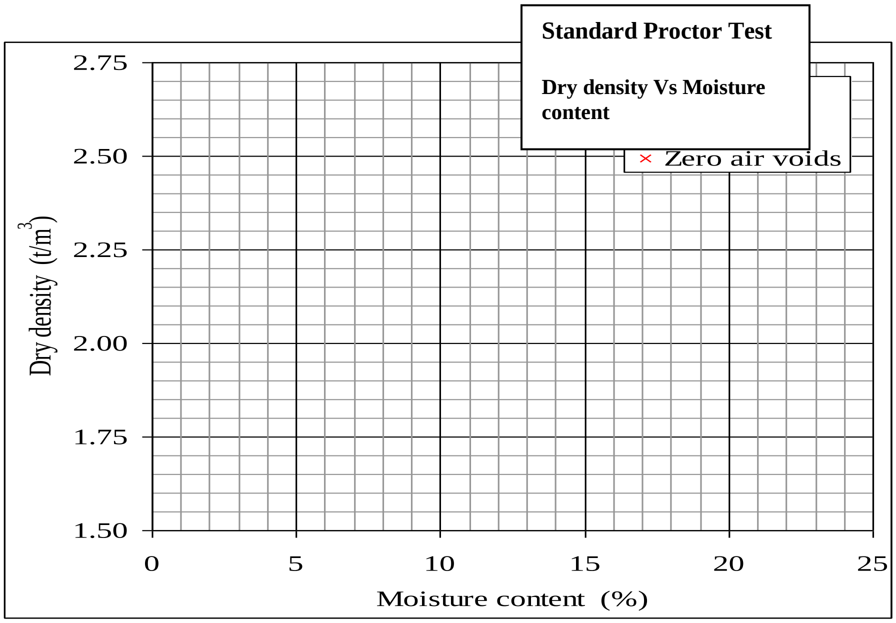
4. On the same plot draw the zero-air voids line for this soil.

5. The optimum moisture contents and maximum dry densities.

6. A comment on the effects of increasing compactive effort observed in the experiment.

7. Discussion of the benefits of increasing compactive effort in engineering practice. Are there any disadvantages?

8. Calculate the degree of saturation of the soil at the optimum moisture content.



Compaction curve

A compaction curve is a curve obtained from the compaction test results. It is a curve obtained by plotting the water content as abscissa versus the corresponding dry density as ordinate for each test.

It was observed that the dry density initially increases with an increase in moisture content till the ρd (max) is attained. But with further increase in water content, the Sd decreases. The water content that corresponds to the ρd (max) is known as optimum moisture content (OMC)

When the water content is lower than the optimum, the soil will be stiff & has much void spaces resulting in low dry density. Also at a water content higher than the optimum, the water occupies more space that is occupied by solid particles and results in reduction of dry density.

Any compaction methods cannot remove all the air voids.

Thus the soil will never become fully saturated.

$$\rho d = \frac{G.\rho w}{1+e} \Rightarrow \rho d = \frac{G.\rho w}{1+(wG/s)}$$

The theoretical maximum density, which is obtained at 100 % saturation, can be determined for any value of w & known G. The hidden line in the figure below indicated the theoretical maximum dry density.

The compaction in the field should be approximately similar to the compaction in the laboratory test. The water content at which the soil is compacted in the field is controlled by the value of optimum moisture content determined in the laboratory. The O, M, C. obtained in laboratory is used as control criterion for compaction in the field. The amount of compaction in the field should be approximately equal to that in the laboratory.

Factors Affecting Compaction:

The increase in dry density of the soil achieved as a result of compaction depends upon the following factors.

A) Water content: At water content lower than O. M. C, the soil is stiff and is not workable offering resistance to compaction. As the water content increases, the particles become lubricated and are easier to expel air from the voids. Thus the dry density increases till the optimum amount of water is applied. With further increase in moisture content the water starts to occupy more pore spaces and results in an increase of the total voids (air and water). This results in an increase in the total volume of the soil. Hence this in turn will bring about reduction in the dry density of soil.

B) Amount of Compaction: -At moisture content less than the optimum, increasing the compactive effort brings about an increase in the dry density. But at water content more than the optimum, the volume of air voids is almost constant & thus increasing the compactive effort has no effect on the dry density. Even at moisture content less than the optimum, the dry density will not go on increasing with an increase in compactive effort. With an increase in compaction the increase in ρdry becomes smaller and smaller and finally no change in ρdry will be observed with an increase in compactive effort.

C) Type of Soil: -Generally coals grained soils can be compacted to a higher dry density then fine gained soils for some compaction effort. When some fines are added to the coarse grained soils to file the voids, the maximum dry density further increases, but it the amount of fines is too much, more than required to fill the voids, it results in reduction of dry density, well graded soils can attain higher dry density then poxes graded soils. High plasticity cays attain much less dry density than low plasticity clays for some completive effort.

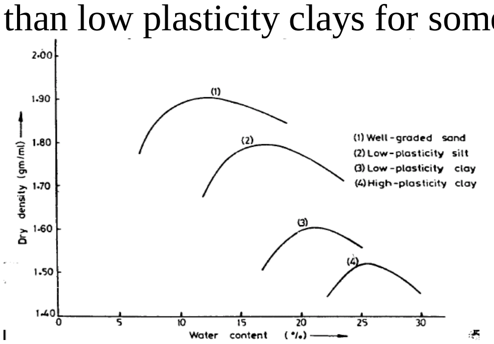


Fig. Compaction curves for different soils.

(D) Method of compaction ÷ the increase in dry density for a given compaction effort depends also on method of compaction i-e whether the method of compaction utilizes kneading action static action or dynamic.

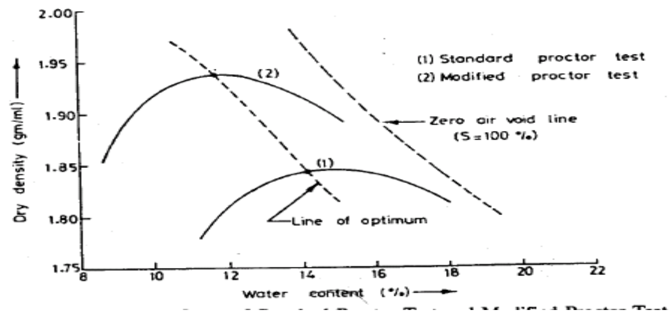


Fig. Compaction curves for different compacting effect.

Relative compaction

This is the ratio of the dry density achieved in the field to the maximum dry density obtained from the standard proctor test.

i e relative compaction = $\dfrac{\rho\text{dry in the field}}{\text{pdry (max) in laboratory}} \times 100$

- About 95% relative compaction can be attained by sheep toot refers or pneumatic tyred rollers.
- For cohesion less soils, relative compaction of about 100 % can be achieved using pneumatic typed rollers & vibratory rollers.

Control of Compaction

During compaction in the field, it is necessary to check the dry density and the water content in order to get proper results. Compaction can be controlled by measuring the dry density and the water content of the compacted soil. The sample of the compacted soil should be taken and the dry density is determined. For the same sample the water content is also determined. If the water content is less than the optimum moisture content (OMC) some more water is added and compacted again. When OMC is attained and a dry density nearly maximum dry density is obtained, the compaction is satisfactory.

Example: - The in-situ density of a soil is to be determined by the proctor method. The volume of the mold is 1000 ml. Its weight when empty is 1864 gm and when filled with the soil is 3646 gm. The soil has G = 2.67, S = 58 % & the in-situ void ratio is found to be 0.85, determine

a) The in-situ dry density of the soil

b) The theoretical dry density of the soil for zero air voids.

Properties of Soils

The physical properties have a direct effect on the ease or difficulty of handling earth, the selection of equipment, and the production rates of the equipment.

Swell and shrinkage

Because of the changes in volume and density when the earth is excavated, hauled, placed and compacted, it is necessary to specify whether the volume is measured in its original position, in the loose condition, or in the fill after compaction.

The bank-measure volume is the volume of the earth measured in the borrow pit, trench, canal, or cut prior to loosening. This is the volume on which payment usually is based.

The loose-measure volume is the volume of the earth after it has been removed from its natural position and deposited in trucks scrapers, or spoil piles.

The compact volume, or fill volume, is the volume of the earth after it has been placed in a fill, such as a dam or road, and compacted. For projects requiring compacted earth fill the volume in the fill may be used as the basis of payment.

The increase in volume of earth as a result of loosening is defined as ***swell***. It is expressed as a parent of the original undisturbed volume.

The reduction in volume of earth from the bank measure volume due to compaction is defined as ***shrinkage***. It is expressed as a percent of the original undisturbed bed volume.

For any given class of earth, the percent of shrinkage will vary with the extent and degree of compaction and the amount of moisture present during compaction.

The percent swell and shrinkage may be determined as follows, respectively.

$$S_w = \left(\frac{B}{L} - 1\right) * 100$$

$$S_h = \left(1 - \frac{B}{C}\right) * 100$$

Where, S_w=% swell

S_h= % Shrinkage.

B = density of undisturbed earth

L= density of loose earth

C = density of compacted earth

Example:

A given soil weighs $17.3 KN/m^3$ in situ $15.1 KN/m^3$ when loose and $18.5 KN/m^3$ when compacted in a fill. Determine the percent swell and shrinkage for the soil.

Solution

$B = 17.3 \, KN/m^3$

$L = 15.1 \, KN/m^3$

$C = 18.5 \, KN/m^3$

$$Swell \, S_w = \left(\frac{B}{L} - 1\right)100 = \left(\frac{17.3}{15.1} - 1\right) * 100 = 14.6\%$$

$$Shrinkage S_h = \left(1 - \frac{B}{C}\right) * 100 = \left(1 - \frac{17.3}{18.5}\right) * 100 = 6.5\%$$

Soil Stabilization

In engineering construction, stabilization is most often referred to compaction of soil preceded by the addition and mixing of an inexpensive admixture termed a stabilization agent, which alters the chemical make-up of the soil, resulting in a more stable material.

Stabilization prevents the soil from differential expansion and shrinkage due to changes in moisture content. Also soil movement and rutting under moving wheel loads is prevented.

Stabilization may be applied in place to a soil in its natural position or as it is placed in a fill. Also, stabilization may be applied in a plant and then transported to the job site for placement and compaction.

Methods of stabilizing soils include, but are not limited to, the following operations.

1. Blending and mixing heterogeneous soils to produce more homogeneous soils.
2. Incorporating lime or lime fly ash in to soils that are high in clay content.
3. Blending asphalt with the soil.
4. Incorporating Portland cement (with or without fly ash) in to soils.
5. Incorporating various salts in to the soil.
6. Incorporating certain chemicals in to the soil.
7. Compacting the soils after they are processed.

Blending and mixing soils

Heterogeneous soils in their original states, such as in a borrow pit, may be mixed during excavation by using equipment such as a power shovel to excavate through several layers in one operation. When such material is placed on a fill, it may be subjected to further blending by several passes with a disk harrow.

Stabilizing soils with lime

Soil stabilization with lime involves a chemical process. Unless stabilized, clay soils usually become very soft when water is introduced.

Lime, in its hydrated form [C_a $(OH)_2$] , will rapidly cause cation exchange and flocculation /agglomeration, provided it is intimately mixed with the soil. The clay type soil will then behave much more like a silt type soil.

Lime fly ash stabilization

Fly ash is a byproduct in the production of electricity using coal. The resulting fly ash is extremely fine in size (often finer than Portland cement) and contains the silicates and aluminates necessary to combine with the lime in the soil stabilization. Laboratory and field results indicate that fly ash, of suitable quality; can replace a portion of the lime necessary to stabilize a clay type soil.

Asphalt Soil stabilization

When asphalts, such as an emulsion or a cut back, are mixed with granular soil, usually in amount of 5 to 7 percent of the volume of the soil, this treatment will produce a much more durable and stable soil.

The moisture content of the soil must be low at the time the asphalt is added. Also, it is necessary to allow the volatile oils to evaporate from the bitumen before finishing and rolling the material.

Cement Soil Stabilization

The use of Portland cement has been found to be effective for soils predominantly granular with only minor amounts of clay particles. A good rule of thumb is that soils with PI less than about 10 are likely candidates for this type of stabilization.

The terms “soil cement” and “cement treated base” are often used interchangeably, and generally describe this type of stabilization. The amount of cement in the soil is usually 5 to 7 percent by dry weight of the soil. Like lime stabilization, fly ash can be effectively utilized to replace a portion of the Portland cement in soil cement. Replacement percentages on an equal weight basis or on a **1.25: 1.0** fly ash/Portland cement replacement basis have been used.

Soil Compaction

Soil for use as a sub grade under a pavement structure or other foundation is strengthened by compaction at optimum moisture. Typically, a uniform layer, or lift, of from 4 to 12in. of soil is compacted by means of several passes of heavy mechanized compaction equipment.

Types of Compacting Equipment

Compaction is attained by applying energy to a soil by one or more of the following methods:

1. Kneading action
2. Static weight
3. Vibration
4. Impact
5. Explosives

Many types of compacting equipment are available, including the following:

1. Tamping rollers
2. Smooth-wheel rollers
3. Pneumatic-tired rollers
4. Vibrating rollers, including tamping, smooth wheel, and pneumatic
5. Self-propelled vibrating plates and/or shoes
6. Manually propelled vibrating plates.
7. Manually propelled compactors
8. Vibratory compactors for deep sand

Types of equipment suited for compacting soils

Type compactor	**Soil best suited for**	**Maximum effect in loose lift, in.**	**Density gained in lift**	**Maximum weight, tons**
Sheep's foot	Clay, silty clay, gravel with clay binder	7 to 12	Nearly uniform	20
Steel tandem two-axle	Sandy silts, most granular material with some clay binder	4 to 8	Average*	16
Steel tandem three-axle	Same as above	4 to 8	Average*	20
Steel three-wheel	Granular or granular-plastic material	4 to 8	Average* to uniform	20
Pneumatic, small-tire	Sandy silts, Sandy clays, gravely sand and clays with few fines	4 to 8	Average* to uniform	12
Pneumatic, large-tire	All types	? to 24	Uniform	50
Vibratory	Sand, silty sands, silty gravels	3 to 6	Uniform	30
Combinations	All	3 to 6	Uniform	20

Tamping rollers
These are sheep's-foot type or modifications thereof. On the outer surface of the hollow steel drum there are a number of welded projecting steel feet. A unit may consist of one or several drums mounted on one or more horizontal axles. The

weight of a drum may be varied by adding water or sand to produce unit pressures under the feet up to 750 psi or more.
As a tamping roller moves over the surface, the feet penetrate the soil to produce a kneading action and a pressure to mix and compact the soil from the bottom to the top of the layer.

The specifications may prescribe one of the following as a means of attaining the desired compaction:
(i) The number of passes of a roller, producing a specified unit pressure under the feet, over each layer of the soil.
(ii) Repeated passes of a roller, producing a specified unit pressure under the feet, over each layer of soil until the penetration of the feet does not exceed a stated depth.
(iii) Repeated passes of a roller over each layer until the soil is compacted to a specified density. Sheep's-foot rollers are quite effective in compacting clays and mixtures of sand and clay. However, they cannot compact granular soils such as sand gravel. Also the depth of a layer of soil to be compacted is limited to approximately the length of the feet.

Modified tamping rollers
It is a modified tamping roller designed as a grid roller. When this roller is ballasted with concrete blocks, it is capable of producing very high soil pressures, and when it is used to compact soil containing rocks, the high concentration of pressure on rocks projecting above the surface of the soil is effective in shattering the rocks and forcing the broken pieces into the soil to produce a relatively smooth surface.
Smooth-wheel rollers
Classification can be based on type or weight.
The rollers are steel drums, which may be ballasted with water or sand to increase the weights.
Specifications governing these rollers may be of two types, one type simply designating the weight, and the other type designating the weight per linear inch of roll.

When compacting cohesive soils, these rollers tend to form a crust over the surface, which may prevent adequate compaction in the lower portions of a lift. However, these rollers are effective in compacting granular soils, such as sand, gravel, and crushed stone, and they are also effective in smoothing surfaces of soils that have been compacted by tamping rollers.

Pneumatic-tired rollers

These rollers apply the principle of kneading action to effect compaction below the surface.

The small-tired units usually have two tandem axles with four to nine tires on each axle. Complete coverage of the surface is ensured as the rear wheels are spaced to travel over the surfaces between the front wheels. Usually the weight of a unit may be varied by adding ballast to suit the material being compacted.

Large-tired rollers utilize two or more big earth-moving tires on a single axle. Because of heavy loads and high tire pressures, they are capable of compacting all types of soils to greater depths. These units are frequently used to proof roll sub grades and bases on airfields and earth-fill dams.

Because of the variation of the contact area between a tire and the ground surface, a more definitive method of designating the compacting ability is to specify the gross weight, the number and sizes of tires, and the tire inflation pressure.

Pneumatic-tire rollers with variable inflation pressures

Several manufacturers produce rollers that are equipped to permit the operator to vary the tire pressure without stopping the machine. The first passes are made with relatively low tire pressures. As the soil is compacted, the tire pressure is increased to suit the particular conditions of the soil.

Vibrating compactors

Certain type of soils such as sand, gravel, and relatively large stones respond quite well to compaction produced by a combination of pressure and vibration. When these material are vibrated, the particles shift their position and nestle more closely with adjacent particles to increase the density of the mass.

Equipments include:

(i) Vibrating sheep’s-foot rollers

(ii) Vibrating steel-drum rollers

(iii) Vibrating pneumatic-tired rollers

(iv) Vibrating plates or shoes

Vibrating sheep’s-foot, steel-drum, pad-type, and pneumatic-tired rollers are actuated by separate engines mounted on the rollers, or in some cases by hydraulic drives which rotate horizontal shafts on which one or more eccentric weights are mounted.

In general, better compaction efficiencies and economy are obtained by moving vibrating compactors at relatively slow speeds, 1.5 to 2.5 mph. slow speeds permit a greater flow of vibratory energy into the soil.