CHAPTER- IV

SOIL COMPACTION

4.1 INTRODUCTION

The soil is commonly used as a fill material for many civil engineering projects such as road, airfield, levee and dam etc. Whenever soil is placed as a fill, it is always in a loose state. Therefore it has to be compacted to a dense state in order to obtain the required engineering properties. Compaction in the field is normally achieved by mechanical means, such as rolling, ramming or by vibration.

Compaction may be defined as the process of bringing soil particles closer to a dense state by mechanical means. The voids are reduced by expulsion of air, the particles are packed close to each other, and therefore the unit weight is increased. It is worth noting that by the process of compaction there is no significant change in the volume of water in the soil. Compaction is done to improve the engineering properties of soil. In general, higher the degree of compaction, higher will be the shear strength and hence greater will be the stability and the bearing capacity. Compaction is also done to reduce the compressibility, shrinkage, frost susceptibility and permeability of soil. For the compaction of deep soil layers to decrease the amount of undesirable settlement of structures, vibrofloat and dynamic compaction methods are employed. This is however beyond the scope of this chapter.

The selection of most efficient compaction plant depends on the site conditions and the type of soil to be compacted. For indoor and small area compaction rammers or tempers are commonly employed. Rollers are used when large areas are involved. Cohesive soil is compacted by means of rollers while non-cohesive soil is better compacted by vibration. Smooth-wheel rollers, sheep-foot rollers, rubber-tired rollers, and vibratory rollers are generally used in the field for soil compaction. Vibratory rollers are used mostly for densification of granular soils.

4.2 USE OF SOIL AS A FILL

The soil is commonly used as a fill material in the following cases.

1. To back fill an excavation e.g., for foundations.
2. To develop a made-up ground to support a structure.
   As a sub-grade or sub-base for roads, railways or airfields (runway, taxiway).
3. As an earth dam.
4. To raise the floor level to the required height in buildings.
5. As a back fill behind retaining walls.

6. To develop a site (residential, industrial, recreational etc.) in a difficult terrain (undulating topography) where substantial cutting and filling is involved.

4.3 OBJECTIVES OF COMPACTION

The main objective of compaction is the improvement of engineering properties of soil which are listed below.

1. To increase the shear strength.
   It provides higher bearing capacity for foundation support, higher CBR for pavement design and greater stability against landslides for natural or man-made slopes.
2. To lower compressibility, and hence smaller settlement of building structures and lesser deformation of earth structures.
3. To lower the permeability.

   It reduces the water absorption and the resulting loss of strength, (which always occurs due to increase of water content). It also reduces water percolation there by reducing the seepage quantities.
4. To lower the frost susceptibility. It reduces the risk of frost heave.
5. To reduce the degree of shrinkage. It reduces the possibility of formation of tension cracks.

4.4 FACTORS AFFECTING COMPACTION OF SOIL

Following are the important factors which affect the compaction of soil.

1. Moisture Content

Moisture content is the most important factor, which greatly influence the compaction of soil. For a given amount of compaction, there exist for each soil, a moisture content, known as the optimum moisture content at which the dry density of the soil is maximum.

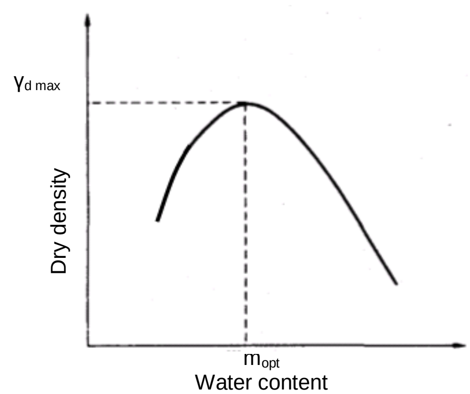


Figure 4.1 Dry density ~ moisture content relationship

At low moisture content, the soil is stiff and difficult to compact thus low dry densities and high air contents are obtained by compaction. When water is added to the soil, it acts as a lubricant causing the soil to soften and become more workable. Due to the film of water surrounding the soil particles, they slide over one another more easily and move into a densely packed position. This results in higher dry density and low air contents. For the same compaction energy, the dry density increases with the increase of moisture content. This occurs up to a limiting moisture content, which is known as the optimum moisture content. With further addition of moisture beyond the optimum value, the thickness of water film around the particles increases which tends to keep the particles apart and causes the dry density to fall. This is because the water takes up the space that would have been otherwise occupied by the solid particles. The effect of moisture change on dry density is shown in Fig 4.1. It should be noted that it is practically impossible to expel all the air from the voids by compaction.

2. Compaction Effort or Energy

Compaction effort means the mechanical energy applied to a soil mass for densification. Irrespective of the soil type and method of compaction, an increase in the amount of compaction (i.e., the energy applied per unit volume of soil) result in an increase in the maximum dry density and decrease in the optimum moisture content. Figure 4.2 shows a comparison of standard AASHTO and Modified AASHTO compaction tests performed on samples of the same soil.

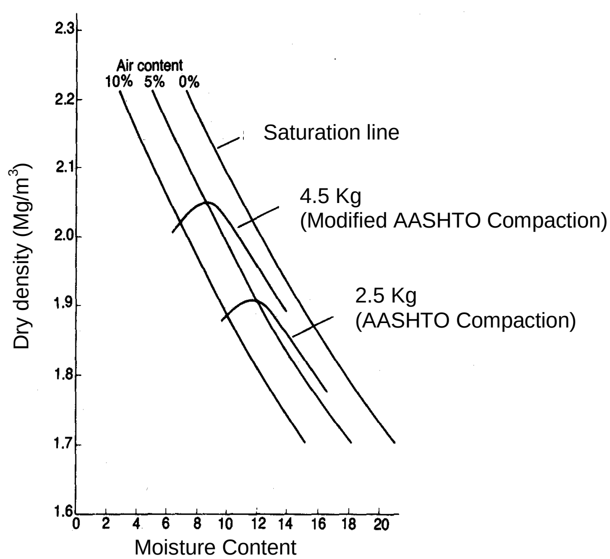


Fig: 4.2 Dry density ~ moisture content curves for different compaction efforts

The line joining the peaks (i.e., points of optimum moisture content) of the moisture ~ density curves of different compaction efforts, follows the general trend of the 100% saturation line, and corresponds to the saturation level of about 95% (Fig 4.2).

In the laboratory, compaction effort is usually applied by impact of hammer, while kneading or static compression methods are also used in some cases. During dynamic (impact) compaction a hammer of specified weight is dropped from a known height for a number of times on several layers of a soil sample in a mold of known volume.

The compaction energy per unit volume *"CE"* applied in a laboratory compaction test is calculated by the following equation.

$$CE = \frac{\begin{pmatrix} Number \\ of\ blows \\ per\ layer \end{pmatrix} \times \begin{pmatrix} Number \\ of \\ layers \end{pmatrix} \times \begin{pmatrix} Weight \\ of \\ hammer \end{pmatrix} \times \begin{pmatrix} Height \\ of\ drop\ of \\ hammer \end{pmatrix}}{volume\ of\ mold} \tag{4.1}$$

For the standard AASHTO test the compaction energy is calculated and given below.

$$\text{CE} = \frac{(25)(3)(5.5)(1)}{(1/30)} = 12375\text{ft} - \text{lb}/\text{ft}^3 (\cong 593\text{kJ}/\text{m}^3)$$

The amount of compaction energy applied in the laboratory tests by dynamic compaction methods is given in the Table 4.1.

Table: 4.1 Specifications for Standard and Modified AASHTO Tests

No.	Item	Specifications	
		Standard AASHTO	**Modified AASHTO**
1	Volume of mold	0.944×10^{-3} m^3 ($1/30ft^3$)	0.944×10^{-3} m^3 ($1/30$ ft^3)
2	Mass of hammer	2.495 kg (5.5 lb)	4.536 kg (10 lb)
3	Height of drop of the hammer	304.8 mm (12 in.)	457 mm (18 in.)
4	Number of hammer blows per layer of soil	25	25
5	Number of layers of compaction	3	5
6	Energy of compaction	593 kJ/m^3 (12,375 ft-lb/ft^3)	2698 kJ/m^3 (56,250 ft-lb/ft^3)

It should be noted that the degree of compaction is not directly proportional to the compaction effort. In other words the maximum dry density does not go on increasing indefinitely with increase in compaction effort. Initially when the soil is loose the affect of increased compaction effort is significant. But with the continued increase of compaction effort, the increase in the dry density becomes smaller and smaller. Finally a stage is reached beyond which there is no appreciable increase in the dry density with further increase in the compaction effort and the extra compaction effort is almost wasted. A qualitative relationship between dry density and compaction effort is shown in the Fig 4.3

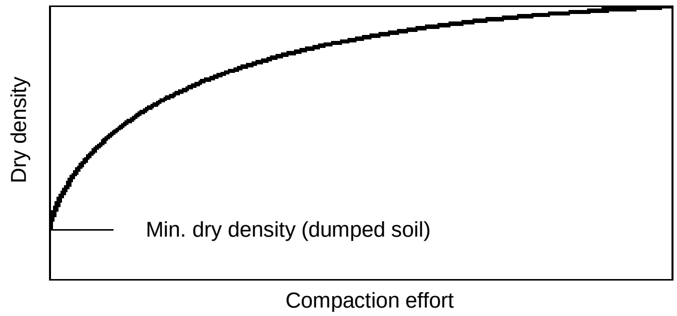


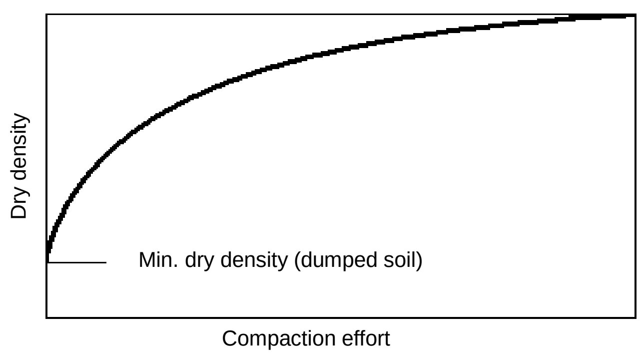
Fig: 4.3 Dry density ~ compaction effort

In the field compaction effort depends on the weight and number of passes of compaction roller. Since compaction effort in the field is very difficult to measure therefore it is never mentioned in the earthwork specification, rather a value of relative compaction is given in the specifications. Relative compaction is the ratio of the field dry density to the maximum Lab. dry density determined by the specified Laboratory Compaction test (standard or modified AASHTO Test).

For kneading compaction a punching device is used to produce a kneading action on the soil. In static compaction method a known volume of soil is compressed by mechanical jack in a specified mold as a single layer or number of layers. The compaction energy for kneading and static compaction method is not readily computed.

3. Soil Type

The soil type, based on particle-size distribution, shape of the particles, specific gravity of soil solids and amount and type of clay minerals present in the soil has a great influence on the maximum dry density and the optimum moisture content. Fig 4.4 shows typical compaction curves obtained for different soils, with laboratory tests conducted in accordance with ASTM Test Designation D-698.



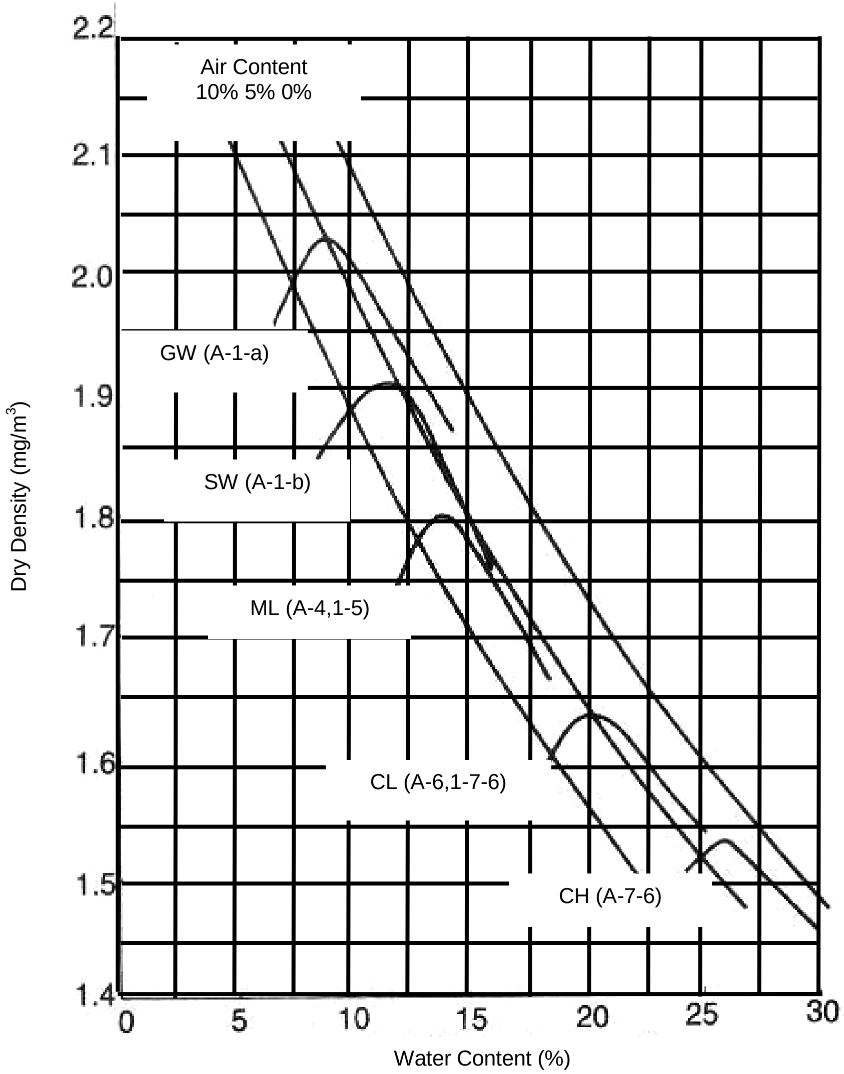


Fig: 4.4 Dry density ~ moisture content curves for different soils

It should be noted that both the shapes and the positions of the curves change as the texture of the soils varies from coarse to fine.

Maximum dry densities may range from about 60 Ib/ft^3 (9.42 kN/m^3) for organic soils to about 145 Ib/ft^3 (22.78 kN/m^3) for well-graded granular material consisting of sufficient fines to fill small voids. Optimum moisture contents may range from about 5% for granular material to about 35% for plastic silts and clays. Finer the soil grains higher will be the optimum moisture content. Higher optimum moisture contents are generally associated with lower dry densities. Higher dry densities and lower optimum moisture contents are achieved with well-graded granular materials. Uniformly graded sand, clays of high plasticity, and organic silts and clays typically show poor response to compaction.

4. Method of Compaction

The dry density obtained by compaction depends to some extent on the method of compaction. For the same amount of compaction energy, the dry density will depend upon whether the compaction is applied by kneading, dynamic or the static action. Different methods of compaction give different shapes of the compaction curves. Consequently the maximum dry densities and the optimum moisture contents are also different.

5. Admixture

The properties of soil are improved by adding other materials, known as admixtures. The most commonly used admixtures are lime, cement and bitumen. Some of the suitable waste materials (e.g., marble industry waste, steel industry waste etc.) are being used as admixtures. The dry density achieved by compaction depends upon the amount and the type of the admixture.

Other factors, which affect compaction of soil, but only slightly are as follows.

Processing amount, By thorough mixing of moisture in the soil higher dry density is achieved. Thorough mixing requires greater manipulation and curing time.

Energy distribution, Uniform distribution of blows on each layer gives better compaction and higher dry density is obtained.

4.5 LABORATORY COMPACTION TEST

The laboratory compaction test was originally developed by Proctor in 1933 to obtain the maximum dry density and the optimum moisture content. It is commonly known as standard proctor compaction test. Subsequent to the standard proctor test, modified proctor compaction test was developed to obtain higher dry densities. It was developed in response to the need for higher dry densities of pavement subgrades required for heavy traffic, airfields, embankments and earth dams. The original proctor methods were later standardised by the American Association of State Highway and Transportation Officials. Accordingly they are now-a-days more frequently known as Standard AASHTO compaction test and the modified AASHTO compaction test. The test procedures are given below.

4.5.1. Standard AASHTO Compaction Test

The apparatus required for the test are the standard mould and the hammer as shown in the Fig 4.5. During the test, the mould is attached to a base plate at the bottom and a collar at the top. The soil is mixed with varying amounts of water and then compacted in the mould in three approximately equal layers by the hammer. Each layer is given 25 blows of the hammer evenly spread on the surface of the layer. The hammer weighs 5.5 lb (2.5 kg) with a free fall of 12 in (304.8 mm). At least five samples at different moisture contents are compacted in the mould. For each sample, the bulk density 'γ_b' after compaction is determined as follows.

$$\gamma_b = \frac{W}{V_{(m)}} \tag{4.2}$$

Where, W = weight of the compacted sample in the mould
$V_{(m)}$ = volume of the mould = 1/30 ft^3

For each test, the moisture content of the compacted soil is determined by oven drying. The dry density γ_d can then be calculated as follows

$$\gamma_d = \frac{\gamma_b}{1 + \frac{m(\%)}{100}} \tag{4.3}$$

Where, m*(%)* = the moisture content in percentage

The values of γ_d are then plotted against the corresponding moisture contents to obtain the maximum dry density and the optimum moisture content for the soil. A typical moisture ~ density curve is shown in the Fig 4.6. The peak value on the y-axis gives the maximum dry density or unit weight and on the x-axis it gives the optimum moisture content.

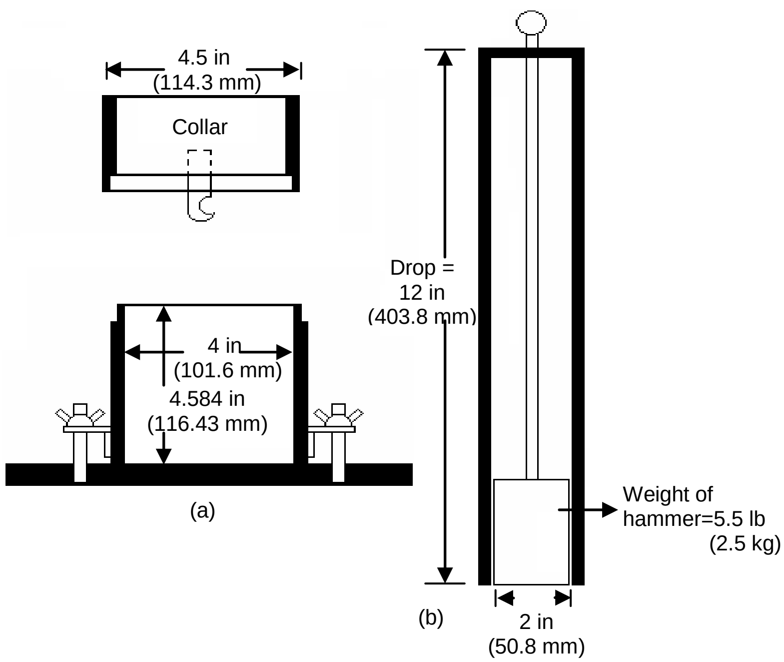


Fig: 4.5 Standard AASHTO test equipment: (a) mould; (b) hammer

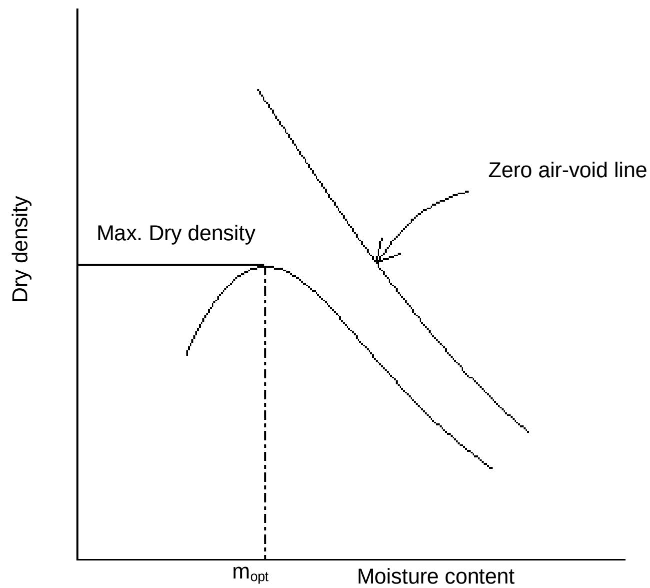


Fig. 4.6 Moisture-Dry density Curve

The detailed procedure is given in the ASTM Test Designation D-698 and the AASHTO Test Designation T -99.

For a given moisture content, the theoretical maximum dry density is obtained when there is no air in the void that is, when the degree of saturation equals 100%. Thus, the maximum dry density at a given moisture content with zero air voids can be given by the following equation.

$$\gamma_{zav} = \frac{G_s \gamma_w}{1+e} \qquad (4.4)$$

Where, γ_{zav} = Zero air-void dry density
γ_w = density of water
e = void ratio
G_s = specific gravity of soil solids

For 100% saturation, e = mG_s

$$\gamma_{zav} = \frac{G_s \gamma_w}{1+mG_s} = \frac{\gamma_w}{m+\frac{1}{G_s}} \qquad (4.5)$$

Where, m = moisture content

Fig 4.6 also shows the variation of zero air-void dry density (γ_{zav}) with moisture content and its relative location with respect to the laboratory compaction curve. Remember that for any type of soil, it is never possible for any part of the compaction curve to lie on the right of the zero- air-void curve.

4.5.2. Modified AASHTO Compaction Test

With the progress of the automobile industry heavy vehicles were manufactured. The traffic speed also increased due to manufacturing of high speed vehicles. Therefore the wheel loads as well as the impact loading increased which required stronger pavements to withstand the heavy wheel loads. The construction of stronger pavements was possible with heavy compaction rollers. The heavy rollers and their use in field compaction required improvement in the laboratory compaction standards for better representation of the field conditions. The standard Proctor test was modified. The modified test is commonly referred as the modified Proctor test or modified AASHTO compaction test (ASTM Test Designation D-1557 and AASHTO Test Designation T-180).

For the modified Proctor test, the same mould as in the case of the standard Proctor test is used. However, the soil is compacted in five layers with a hammer weighing 10 lb (4.54 kg). The drop of the hammer is 18 in. (457.2 mm). The number of hammer blows for each layer is 25 as in the case of the standard Proctor test. The compaction energy for the modified compaction test is given below,

$$CE = \frac{\text{(5 layers)(25 blows)(10 lb weight)(1.5 ft drop)}}{(1/30\ \text{ft}^3)}$$

$$= 56{,}250\ \text{ft-lb/ft}^3\ (2693.3\ \text{kJ/m}^3)$$

The compaction energy for modified compaction test (modified AASHTO test) as indicated in table 4.1 is 4.545 times higher than that of the standard proctor test (standard AASHTO test). It should be noted that the maximum dry density achieved with the modified compaction test is not 4.545 times of that obtained with the standard proctor compaction test rather it is only about 1.1 to 1.25 times higher than that of standard proctor compaction.

Because of higher compaction energy, the modified AASHTO compaction test results in an increase in the maximum dry density of the soil, which gives improved strength and stability of the pavement layers. The increase of maximum dry density however is accompanied by a decrease of the optimum moisture content. For pavement construction, the compaction of the layers is usually made with reference to the modified AASHTO test.

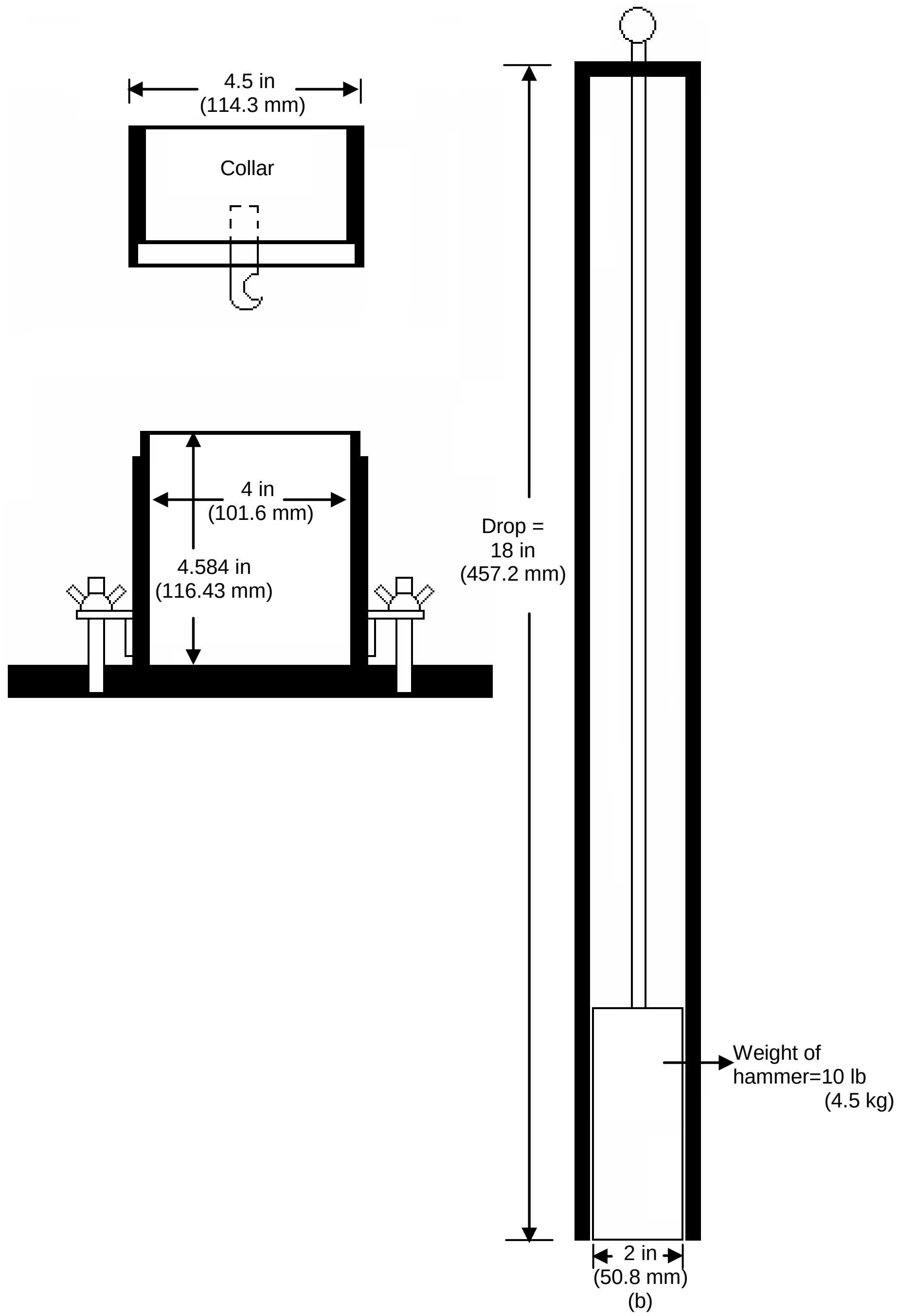


Fig 4.7 Modified proctor test apparatus (a) mould (b) hammer

4.6 COMPARISON OF AASHTO & MODIFIED AASHTO COMPACTION

The comparison is given in the following table:

Table 4.2 Comparison of AASHTO & modified AASHTO compaction

Standard AASHTO compaction	Modified AASHTO compaction
1- Volume of the mould is 1/30ft^3.	1- Volume of the mould is 1/30ft^3.
2- Weight of hammer is 5.5 lb.	2- Weight of hammer is 10 lb.
3- Height of fall is 12 in.	3- Height of fall is 18 in.
4- Number of layers is three.	4- Number of layers is five.
5- Number of blows is 25.	5- Number of blows is 25.
6- Maximum dry density is lower.	6- Maximum dry density is higher.
7- The optimum moisture content is higher.	7- The optimum moisture content is lower.
8- The compaction curve is below and to the right of modified AASHTO curve.	8- The compaction curve is above and to the left of standard AASHTO curve.
9- Compaction energy applied is 12375ft-lb/ft^3.	9- Compaction energy applied is 56250ft-lb/ft^3.
10- Compaction energy is 4.545 times lower than that of the modified AASHTO test, but the maximum dry density obtained is only about 1.1 to 1.25 times lower than that of the modified AASHTO test.	10- Compaction energy is 4.545 times higher than that of the standard AASHTO test, but the maximum dry density obtained is only about 1.1 to 1.25 times higher than that of the standard AASHTO test.
11- The degree of saturation at optimum moisture content for the AASHTO & Modified AASHTO test is almost same.	11- The degree of saturation at optimum moisture content for the AASHTO & Modified AASHTO test is almost same.

4.8 ASTM AND AASHTO SPECIFICATIONS FOR COMPACTION TESTS

The specifications for Proctor tests adopted by ASTM and AASHTO regarding the volume of the mould (1/30 ft^3) and the number of blows (25 blows/layer), as discussed in the preceding sections are commonly adopted for fine-grained soils that pass the U.S. No. 4 sieve. However, under each test designation, there are four different suggested methods which specify the mould size, the number of blows and the maximum particle-size in a soil sample used for testing. A summary of the test specifications is given in Table 4.3.

Table 4.3 Summary of compaction test specifications

		ASTM D-698; AASHTO T-99				ASTM D-1557; AASHTO T-180			
Description		**Method A**	**Method B**	**Method C**	**Method D**	**Method A**	**Method B**	**Method C**	**Method D**
Mould Volume	ft^3. cm^3.	1/30 943.9	1/13.33 2124.3	1/30 943.9	1/13.33 2124.3	1/30 943.9	1/13.33 2124.3	1/30 943.9	1/13.33 2124.3
Mould Height	in. mm.	4.58 116.33	4.58 116.33	4.58 116.33	4.58 116.33	4.58 116.33	4.58 116.33	4.58 116.33	4.58 116.33
Mould Diameter	in. mm.	4 101.6	6 152.4	4 101.6	6 152.4	4 101.6	6 152.4	4 101.6	6 152.4
Weight of hammer	lb. Kg.	5.5 2.5	5.5 2.5	5.5 2.5	5.5 2.5	10 4.54	10 4.54	10 4.54	10 4.54
Drop of hammer	in. mm.	12 304.8	12 304.8	12 304.8	12 304.8	18 457.2	18 457.2	18 457.2	18 457.2
Number of layers		3	3	3	3	5	5	5	5
Blows per layer		25	56	25	56	25	56	25	56
Soil passing sieve		No.4	No.4	¾ in	¾ in	No.4	No.4	¾ in	¾ in

4.9 DETERMINATION OF FIELD DENSITY

When the field compaction work is in progress, and a soil layer has been compacted by a contractor, it is important to know whether the dry density given in the specification has been achieved or not. If the specified dry density has not been attained, additional compaction would be required. The standard procedures for determination of field density of soil are as follows.

1. Drive cylinder method
2. Sand cone method
3. Rubber balloon method
4. Nuclear density meter

A brief description of each of the above methods is as follows.

1. Drive cylinder method (ASTM D-2937 or AASHTO T-204)

The apparatus consists of a steel drive cylinder, 85.7mm inside diameter and 108mm height with a cutting edge at the bottom (Fig 4.9). The volume of the drive cylinder is 620cc.

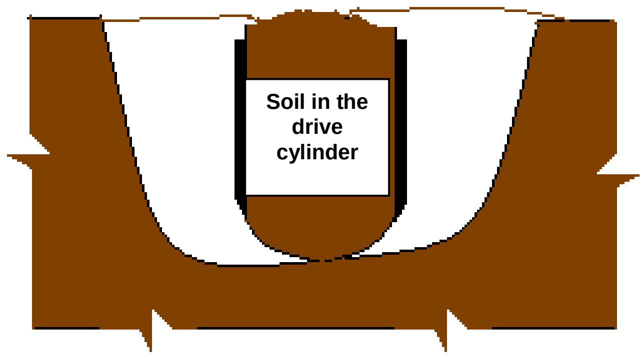


Fig 4.9 Drive cylinder pushed into the soil and the surrounding soil excavated to take out the cylinder

The soil surface at the test location is cleaned of all the loose particles. The drive cylinder is placed on the soil surface. Drive head is seated on the cylinder. Driving of the cylinder into the soil is accomplished by application of blows of the rammer. Driving is continued till the top of the cylinder is about 12mm below the surface. Drive head is removed and the cylinder along with the soil packed into it is dug out of the ground. Excess soil is trimmed off with a straight edge. The weight of soil sample in the cylinder and its moisture content is determined. With the volume of the soil (equal to volume of the cylinder) already known, the bulk density and hence the dry density is calculated. The detailed procedure can be seen in the ASTM or the AASHTO standards.

The drive cylinder method is not applicable for very hard soil or the soil containing gravels that cannot be easily penetrated. Neither is it suitable for low plasticity or cohesion-less soils which are not readily retained in the cylinder.

2. Sand-Cone Method (ASTM D-1556 or AASHTO T-191)

The sand-cone apparatus (Fig 4.10) consists of a glass or plastic jar with a metal cone attached at its top. The jar with the cone is filled with uniformly graded dry sand. The weight of the jar, cone, and the sand filling the jar is determined (W_1). A small hole is excavated at the test location and the weight of the soil excavated from the hole, (W_2) is determined. After excavation of the hole, the sand-cone apparatus filled with sand is placed over the hole (Fig 4.10). Sand is allowed to flow out of the jar to fill the hole and the cone. After that, the weight of sand cone apparatus and the remaining sand in the jar (W_3) is determined. Then the weight of sand to fill the hole and cone is calculated = $W4 = W_1 - W3$

The volume of the hole excavated can now be determined as

$$V = \frac{W_4 - W_c}{\gamma_{d(sand)}} \quad (4.6)$$

Where, W_c is the weight of sand to fill the cone only

$\gamma_{d(sand)}$ is the dry density of sand used

The values of W_c and $\gamma_{d(sand)}$ are separately determined in the laboratory.

The bulk density of the field compacted soil is determined as follows.

$$\gamma_b = \frac{W_2}{V} \quad (4.7)$$

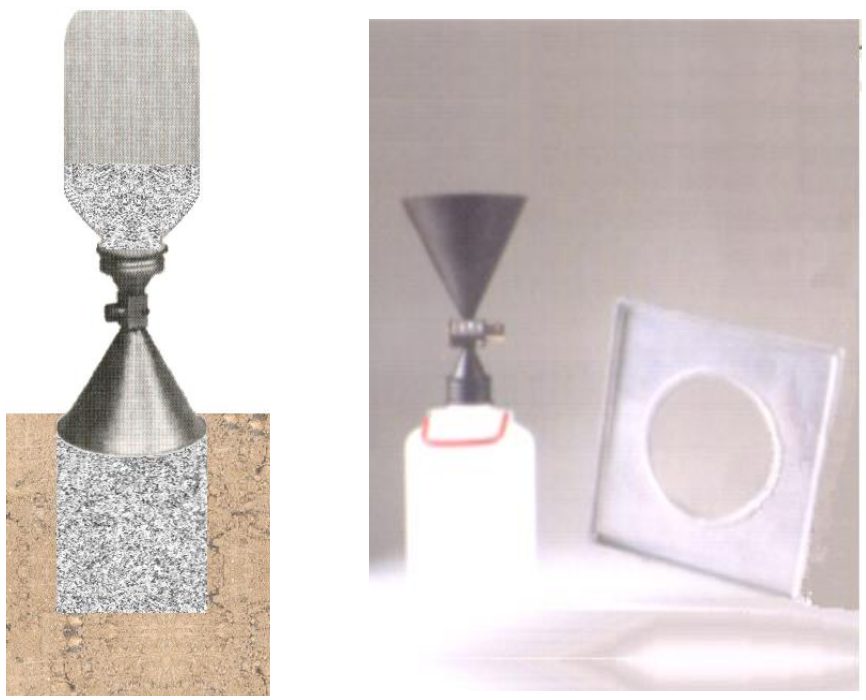


Fig 4.10 Sand-cone on the hole Sand-cone apparatus and base plate

The moisture content (*m*) of the soil excavated from the hole is also determined. The dry density of the field compacted soil is finally calculated as follows.

$$\gamma_d = \frac{\gamma_b}{1+m} \tag{4.8}$$

3. Rubber Balloon Method (ASTM D-2167 or AASHTO T-205)

The procedure for the rubber balloon method (RBM) is similar to the sand-cone method, in that a test hole is made and the weight of soil excavated from the hole and its moisture content are determined. However, the volume of the hole is determined by introducing into it a rubber balloon filled with water from a calibrated cylinder, from which the volume is read directly. The dry density of the field compacted soil is determined by dividing weight of excavated soil by the volume of hole. The rubber balloon apparatus is shown in the Fig: 4.11.

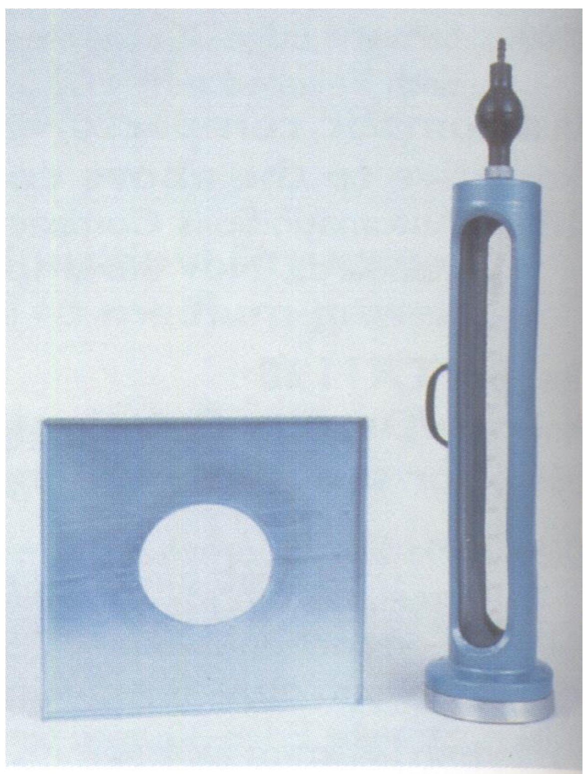


Fig 4.11 Rubber balloon apparatus with base plate

4. Nuclear Density Meter (ASTM D-2922 or AASHTO T-238)

Nuclear density meters (NDM) are now used in several large projects for determination of field dry density of soil. The density meters operate either in drilled holes or from the ground surface. The instrument measures directly the bulk density, dry density, moisture content and also the relative compaction of the soil if the laboratory dry density is already entered in the meter's memory. Fig 4.12 shows a photograph of a nuclear density meter.

Fig 4.12 Nuclear Moisture-Density Meter

It is a nondestructive method for determination of in-situ dry density and other relevant parameters for compaction control. During testing, the instrument is placed on the test location and emits gamma rays through the soil. Some of the gamma rays will be absorbed; others will reach a detector. Soil density is inversely proportional to the amount of radiation that reaches the detector. Through proper calibration, nuclear count rates received at the detector can be translated into values of bulk density of soil. Calibration curves are normally provided by the manufacturer. The nuclear apparatus also determines moisture content by emitting alpha particles that bombard a beryllium target, causing the beryllium to emit fast neutrons. Fast neutrons that strike hydrogen atoms in water molecules loose velocity; the resulting low-velocity neutrons are thermal neutrons. Thermal neutron counts are made, from which soil moisture content can be determined. The dry density can then be calculated by the common equation.

The nuclear method is considerably faster to perform than the sand-cone and rubber-balloon methods. It has the disadvantage, however, of potential hazards to individuals handling radioactive materials. The nuclear apparatus is also considerably more costly than the apparatus used in the other two methods.

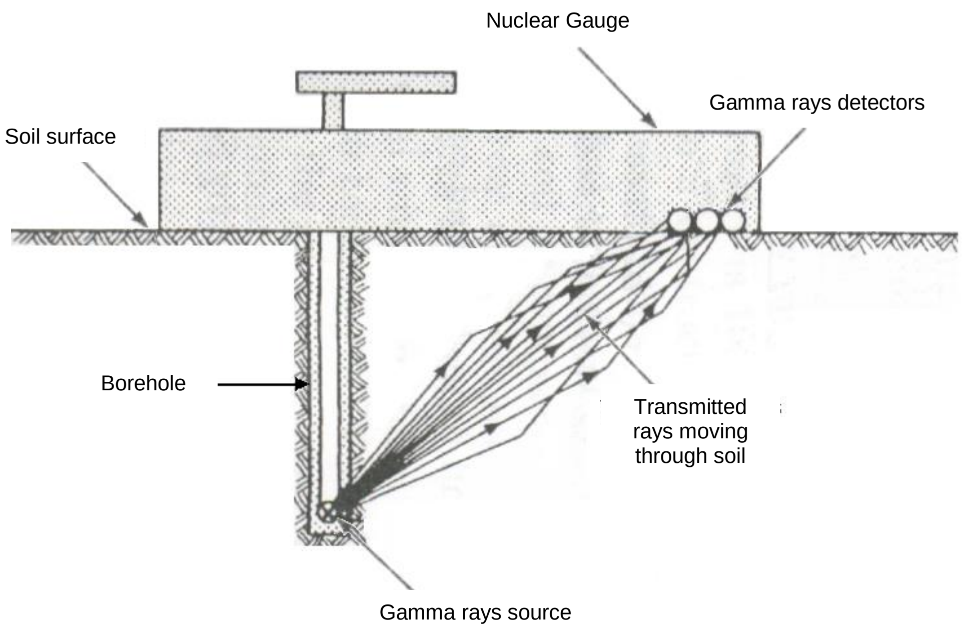


Fig 4.13 Determination of field density by direct transmission

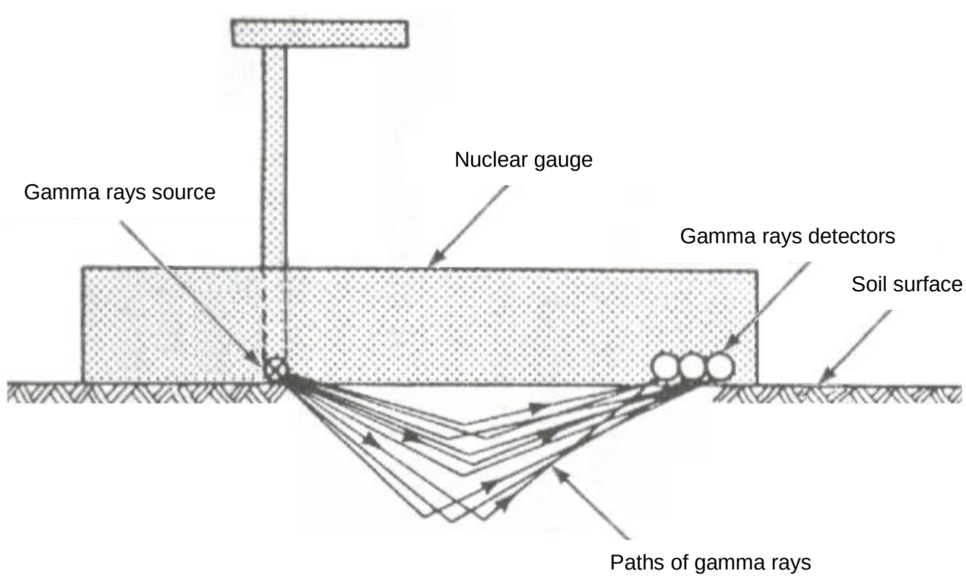


Fig 4.14 Measurement of field density by backscatter

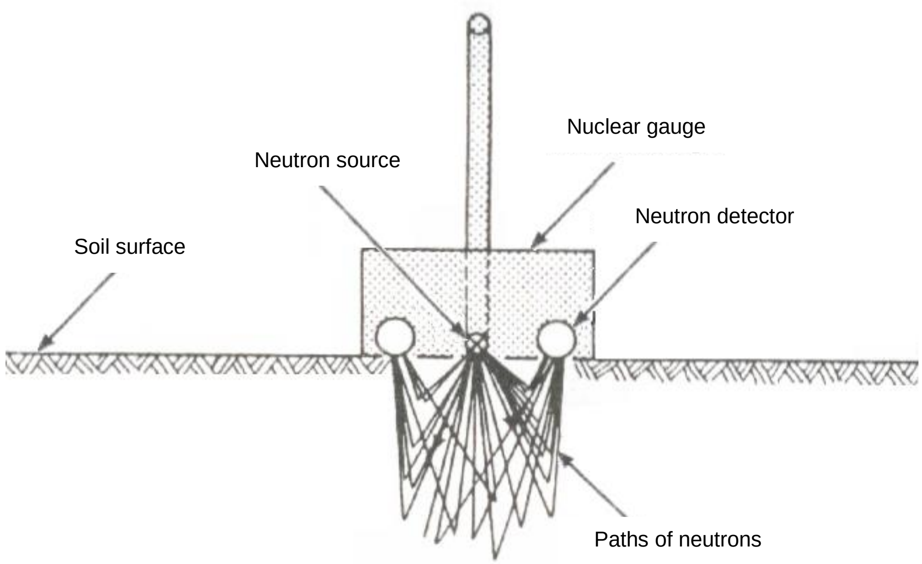


Fig 4.15

Measurement of moisture by backscatter

The advanced version of the instrument (Geo-test nuclear gauges) manufactured by the Seamen have the following unique advantages, which have made their use widespread and highly respected.

- Safest possible nuclear design as the source never leaves the meter. There is also automatic shielding when carried.
- Faster testing time.
- Larger samples tested: Using a new back scatter technology permits testing samples up to 20 times larger than direct transmission units.
- The factory set density calibration to eliminate operator error.
- The built-in brain and memory virtually eliminates need for special operator skills. The keyboard is used for all tests. The meter is factory calibrated for all materials.

The following features speed up testing.

- Separate systems take moisture and density reading simultaneously to cut time to half.
- Immediate display of wet and dry densities.
- Lab. densities can be entered and stored in memory bank.
- Immediate display of relative compaction as a % of laboratory dry density.
- Storage and display of previous contact, air gap, or moisture counts for subsequent reuse if new data is not needed.
- No charts or tables.
- No elaborate soil preparation or hole punching.
- No field calibration.

4.10 MERITS AND DEMERITS OF THE FIELD DENSITY METHODS

1. The Drive Cylinder method is easy and quick. The cutting edge is easily damaged and need re-sharpening. This method is best suited for soft and cohesive soil.
2. The Sand-Cone method is relatively slow, but it can be used for any type of soil.
3. The Rubber-Balloon method is easy and quick, but the results are not very reproducible owing to the difficulty of controlling the air pressure and ensuring that the balloon conforms to the shape of the hole. The method is not applicable to very stony soils.
4. The Nuclear Method is considerably faster to perform than the sand-cone and rubber-balloon methods. It has the disadvantage, however, of potential hazards to individuals handling radioactive materials. The nuclear apparatus is also considerably more costly than the apparatuses used in the other two methods.

4.13 FIELD CONTROL OF COMPACTION & INSPECTION

The results of laboratory compaction tests are not directly applicable to field compaction. The mode and amount of compaction efforts in the laboratory tests are different from those of the field compaction. Compaction in the field (wide area) is produced by moving compaction equipments, while laboratory compaction commonly is made by blows of rammer where the soil is confined in small metallic mould. Further, the laboratory tests are carried out only on material smaller than either 20mm or 37.5mm size. However, the maximum dry densities obtained in the laboratory tests AASHTO T 99, using the 2.5 kg rammer and AASHTO T 180, using 4.5 kg rammer cover the range of dry density normally produced by field compaction equipment. Therefore it is common to specify a value of relative compaction in the contract document. The required field dry density divided by the maximum laboratory dry density expressed as a percentage is called the relative compaction.

After a fill layer of soil has been compacted, a field density test is usually performed to determine whether the specified dry density has been achieved. For example, if the maximum dry density obtained from ASTM or AASHTO compaction test in the laboratory is 100 lb/ft^3 and the relative compaction specified is 95% according to the contract, a field dry density of 95 lb/ft^3 (or higher) would be acceptable.

Theoretically it looks very simple, but there are some practical considerations that must be taken into account. For example, the type of soil or compaction characteristics of soil taken from borrow areas may vary from one location to another. Also, the degree of compaction may not be uniform throughout. To deal with the problem of non-uniformity of soil from borrow areas, it is necessary to conduct the laboratory compaction tests to find the maximum dry density and the optimum moisture content for each type of soil encountered in a project. Then, as soil is transported from the borrow area and subsequently placed and compacted in the fill area, it is imperative that the results of each field dry density test be checked against the maximum laboratory dry density of the respective type of soil. For inspection it is common practice to specify a minimum number of field density tests. For example, for a dam embankment, it might be specified that one test be made for every 2000 m^3 (loose measure) of fill placed.

To ensure that the required field density is achieved by the field compaction, a specifications contract between the client and the contractor is prepared. The contract will normally specify the required relative compaction and minimum number of field density tests.

For compaction adjacent to a structure, where settlement is a serious matter, a higher value of relative compaction and a higher minimum number of tests may be specified than for example, the compaction of a parking area. The specifications contract may also include additional items, such as the maximum thickness of loose lifts (layers) prior to compaction, laboratory density test to determine the maximum dry density (e.g., ASTM D 698 or D 1557 or AASHTO T 99 or T 180) and the methods to determine field density (e.g., ASTM D 1556 or AASHTO T 191).

A soil engineer appointed by the client is responsible for ensuring that contract specifications are met precisely and completely. He is responsible for the testing and must see that the specified dry density is achieved. If a test on any particular location indicates that the required dry density has not been achieved, he must instruct the contractor for additional compaction, possibly including an adjustment in the field moisture content. The moisture will be added if the field moisture is below the optimum value, or the soil will be dried if the existing moisture is on the wet side of the optimum moisture.

4.19 EXAMPLES

Example-4.1 During construction of an embankment, a sand-cone test was performed in the field. The following data were obtained:

1. Weight of sand to fill test hole and funnel of sand-cone apparatus = 870g.
2. Weight of sand to fill funnel = 322g.
3. Density of sand = 98.0 Ib/ft^3.
4. Weight of wet soil from the test hole = 750g.
5. Moisture content of soil from test hole = 13.8%.

Solution: Given data

As above

Required

Dry density of the compacted soil = γ_d

Weight of sand in test hole = Weight of sand to fill test hole and funnel, minus the weight of sand to fill funnel

= 870 -322 = 548g

= 548/453.6 = 1.208*lb*

Volume of test hole = $\frac{1.208}{98.0} = 0.0123 ft^3$

Bulk density of soil in-place, γ_b = $\frac{750/453.6}{0.0123} = 134.42 lb/ft^3$

$$\gamma_d = \frac{\gamma_b}{1+m}$$

$$\gamma_d = \frac{134.42}{1+0.138} = 118.12\, lb/ft^3$$

γ_d = 118.12 *lb/ft³*

Example-4.2 For construction of an embankment, a soil from a borrow pit gave the following laboratory results when subjected to the ASTM D 698 Standard Proctor test.

Maximum dry unit weight = 120.5Ib/ft^3

Optimum moisture content = 13%

The contractor, during construction of the embankment, achieved the following

Dry density achieved by field compaction = 118.0Ib/ft^3

Actual field moisture content = 12.9%

Determine the relative compaction achieved by the contractor.

Solution: Given data

Maximum laboratory dry density ($\gamma_{d\,max}$) = 120.5 lb/ft^3

Field dry density ($\gamma_{d\,field}$) = 118.0 lb/ft^3

Relative compaction = $$\frac{\textit{Field dry}\text{ density }(\gamma_{\text{d field}})}{\textit{Maximum laboratory dry}\text{ density }(\gamma_{\text{d max}})} \times 100$$

$$= \frac{118.0 lb/ft^3}{120.5 lb/ft^3} \times 100 = 97.92\%$$

Relative compaction = 97.92%

4.20 PROBLEMS

Prob. 4.1 The following results were obtained from a standard AASHTO compaction test on a soil:

Weight (g)	2015	2092	2114	2100	2055
Water content (%)	13.0	14.5	15.6	16.8	19.2

The value of G is 2.66. Plot the dry density verses moisture content curve and find the optimum moisture content and maximum dry density. Plot also the curves of zero, 5% and 10% air voids and find the value of air voids at maximum dry density. The volume of the mould is 1000 cm^3.

Prob. 4.2 The following is the data obtained from a standard AASHTO compaction test:

Moisture content %	5.0	9.0	14.0	23.0	27.5	30.0
Wet soil weight (kg)	1.79	1.92	2.03	2.15	2.13	2.12

If the volume of the mould is 950 cc and specific gravity of the soil s 2.65, plot the curve showing moisture content versus dry density.

Prob. 4.3 The undisturbed soil from a pit has a moisture content of 15%, void ratio 0.61 and specific gravity of 2.71. The borrow soil is to be used to construct a rolled fill having a finished volume of 35500 m^3. The soil is to be transported from the pit to the construction site by trucks having a net carrying capacity of 6000kg. After compaction, the fill soil has a moisture content of 18% and a dry density of 1.70 g/cm^3. Calculate the total number of trips the truck will have to make to construct the rolled fill.

Prob. 4.4 Laboratory compaction test data is tabulated as follows. The test was conducted in accordance with the ASTM D 698 Standard Proctor test.

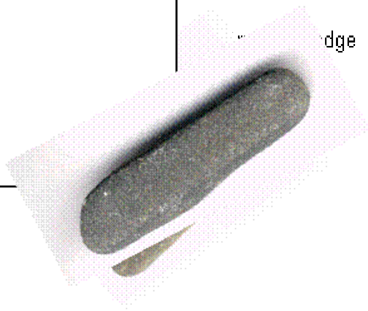
Sample Number	**1**	**2**	**3**	**4**	**5**
Dry density (lb/ft^3)	112	116.7	118.3	115.2	109
Moisture content (%)	7.1	10.0	13.4	16.7	20.1

Plot dry density versus moisture content curve and determine the maximum dry density and optimum moisture content.

Prob. 4.5 A Standard Proctor compaction test (ASTM D 698) was conducted in a soil laboratory. The weight of a compacted soil specimen plus mould was determined to be 3820 g. The volume and weight of the mould were 0.0333 ft^3 and 2050 g, respectively. The moisture content of specimen was 9.3%. Compute wet and dry density of compacted specimen.

Prob. 4.6 Results of the Standard Proctor test (AASHTO T 90) on a soil sample, taken from the site of a proposed borrow pit are given below: Plot moisture content versus dry density curve and determine the maximum dry density and optimum moisture content.

dge to face contact)



Sample Number	**1**	**2**	**3**	**4**	**5**
Dry density (lb/ft^3)	107	109.8	112	111.6	107.3
Moisture (%)	9.1	11.8	14.0	16.5	18.9

Prob. 4.7 Using the results of the test of Problem 4.5, determine the range of water content most likely to attain 95% or more of the maximum dry density.

Prob. 4.8 A laboratory compaction test was performed on a soil sample taken from a selected borrow area. The maximum dry density and optimum moisture content were determined to be 110.5 lb/ft^3 and 19.8%, respectively. Estimate the possible type (or classification) of soil for this sample.

Prob. 4.9 During construction of a highway project, a sand-cone test was performed on the compacted earth fill. The following data was obtained:

1. Weight of sand used to fill test hole and funnel of sand-cone apparatus=850g.
2. Weight of sand to fill funnel = 328 g.
3. Unit weight of sand = 100 lb/ft^3.
4. Weight of wet soil from test hole = 650 g.
5. Moisture content of soil from test hole = 15%.

Determine the dry density of the compacted earth fill.

Prob. 4.10 A soil sample was taken from a proposed borrow area for a highway construction project. The Standard AASHTO compaction test gave the following data.
Maximum dry density = 115.2*Ib/ft*^{3}
Optimum moisture content = 15.3%

The contractor, during construction of the embankment, achieved the following:
Dry density achieved by field compaction = 107.*1Ib/ft*^{3}
Actual field moisture content = 16.1%
Determine the percent compaction achieved by the contractor.

Prob. 4.11 Soil having a void ratio of 0.68 in a borrow pit is to be excavated and transported to a fill site where it will be compacted to a void ratio of 0.45. The volume of fill required is 3000 m^3. Determine the volume of soil to be excavated from the borrow pit to construct the fill of the required volume.

Prob. 4.12 Calculate the zero-air-void densities (i.e., theoretical maximum density) for a soil having G = 2.67 at moisture contents of 5, 10, 15, 20, and 25%. Plot a graph between theoretical maximum density and the moisture content.