

Chapter 6: Soil Compaction

In the construction of highway embankments, earth dams, and many other engineering structures, loose soils must be compacted to increase their unit weights. Compaction increases the strength characteristics of soils, which increase the bearing capacity of foundations constructed over them. Compaction also decreases the amount of undesirable settlement of structures and increases the stability of slopes of embankments.

6.1 Compaction — General Principles

Compaction, in general, is the densification of soil by removal of air, which requires mechanical energy. The degree of compaction of a soil is measured in terms of its dry unit weight. When water is added to the soil during compaction, acts as a softening agent on the soil particles. The soil particles slip over each other and move into a densely packed position. The dry unit weight after compaction first increases as the moisture content increases (See Figure 6.1). When the moisture content is gradually increased and the same compactive effort is used for compaction, the weight of the soil solids in a unit volume gradually increases.

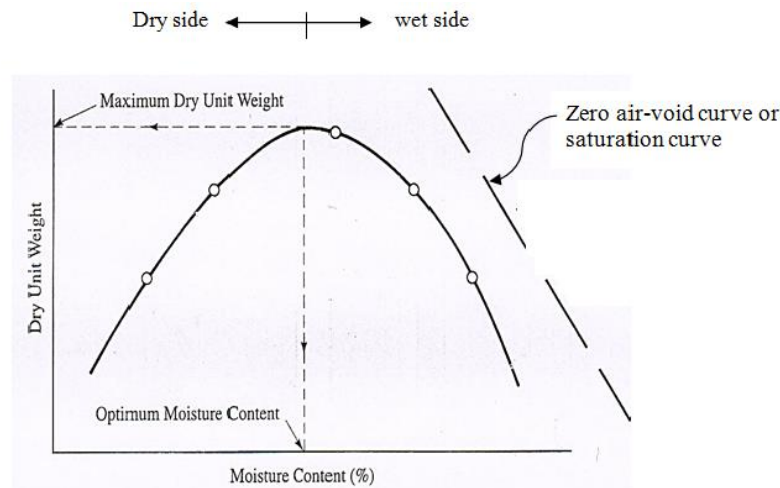


Figure 6.1 Principles of compaction

Beyond a certain moisture content, Figure (6.1), any increase in the moisture content tends to reduce the dry unit weight. This phenomenon occurs because the water takes up the spaces that would have been occupied by the solid particles. The moisture content at which the maximum dry unit weight is attained is generally referred to as the *optimum moisture content*.

The laboratory test generally used to obtain the maximum dry unit weight of compaction and the optimum moisture content is called the *Proctor compaction test* (Proctor, 1933).

6.2 Standard Proctor Test

In the Proctor test, the soil is compacted in a mold that has a volume of 944 cm³ (Figure 6.2). The diameter of the mold is 101.6 mm (4 in.). The soil is mixed with varying amounts of water and then compacted in three equal layers by a hammer (Figure 6.2b) that delivers 25 blows to each layer. The hammer has a mass of 2.5 kg (6.5 lb) and has a drop of 305 mm (12 in.). Figure 6.2c is a photograph of the laboratory equipment required for conducting a standard Proctor test.

For each test, the moist unit weight of compaction, γ , can be calculated as

$$\gamma = \frac{W}{V(m)} \quad (6.1)$$

where W = weight of the compacted soil in the mold

$V(m)$ = volume of the mold (944 cm³)

For each test, the moisture content of the compacted soil is determined in the laboratory. With the known moisture content, the dry unit weight can be calculated as

$$\gamma_d = \frac{\gamma}{1 + \frac{w(\%)}{100}} \quad (6.2)$$

where w (%) = percentage of moisture content.

The values of γ_d determined from Eq. (6.2) can be plotted against the corresponding moisture contents to obtain the maximum dry unit weight and the optimum moisture content for the soil. Figure (6.3) shows such a plot for a silty-clay soil.

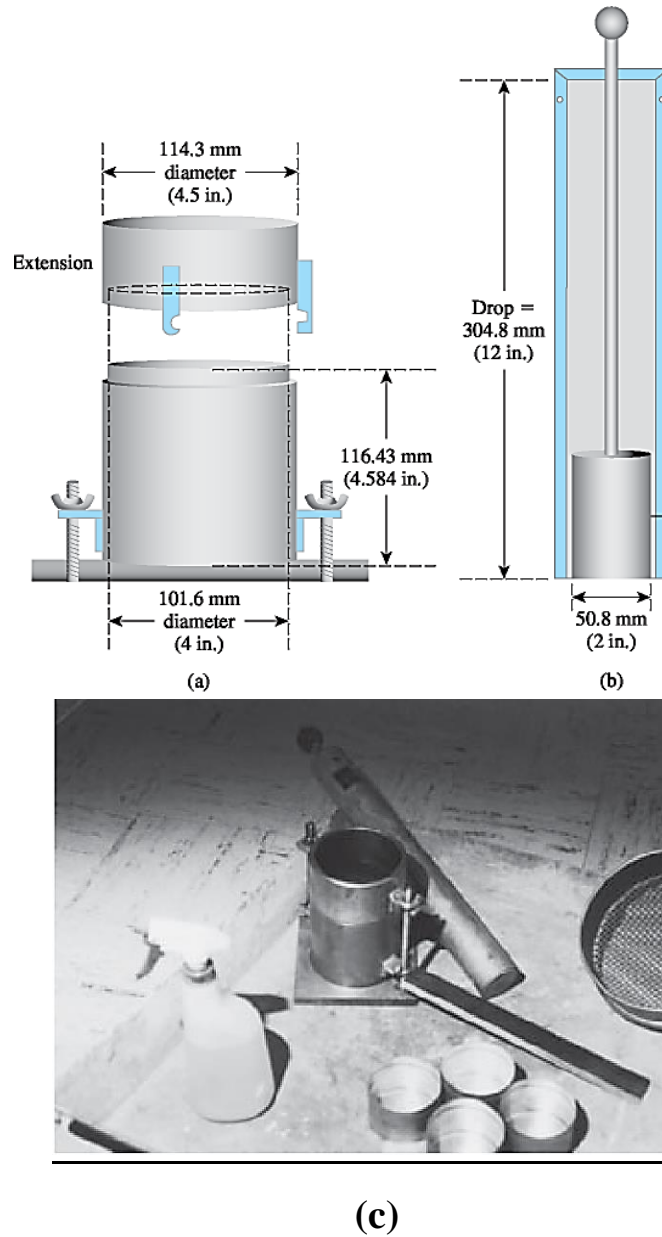


Figure 6.2 Standard Proctor test equipment: (a) mold; (b) hammer; (c) photograph of laboratory equipment used for test

The procedure for the standard Proctor test is elaborated in ASTM Test Designation D-698 (ASTM, 2007) and AASHTO Test Designation T-99 (AASHTO, 1982).

For given *moisture content* w and *degree of saturation* S , the dry unit weight of compaction can be calculated as follows. From Chapter 3 [Eq. (3.16)], for any soil,

$$\gamma_d = \frac{G_s \gamma_w}{1+e}$$

Where G_s = specific gravity of soil solids
 γ_w = unit weight of water
 e = void ratio

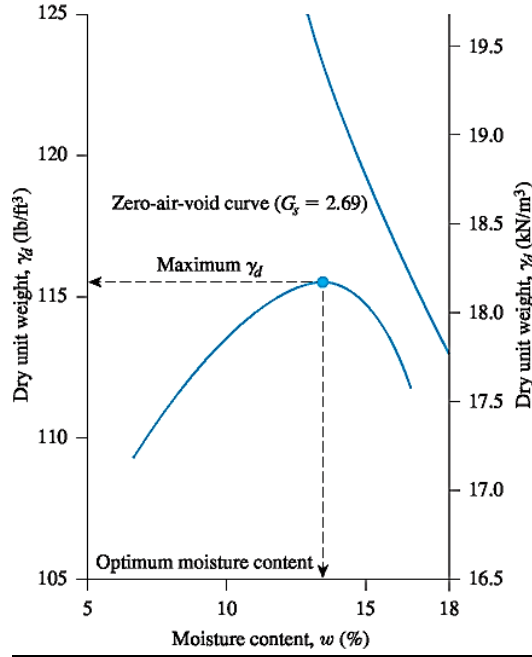


Figure 6.3 Standard Proctor compaction test results for a silty clay

and, from Eq. (3.18),

$$Se = G_s w$$

or

$$e = \frac{G_s w}{S}$$

Thus,

$$\gamma_d = \frac{G_s \gamma_w}{1 + \frac{G_s w}{S}} \quad (6.3)$$

For given moisture content, the theoretical maximum dry unit weight is obtained when no air is in the void spaces—that is, when the degree of saturation equals 100%. Hence, the maximum dry unit weight at a given moisture content with zero air voids can be obtained by substituting $S = 1$ into Eq. (6.3), or

$$\gamma_{zav} = \frac{G_s \gamma_w}{1 + w G_s} = \frac{\gamma_w}{w + \frac{1}{G_s}} \quad (6.4)$$

Where γ_{zav} = zero-air-void unit weight.

To obtain the variation of γ_{zav} with moisture content, use the following procedure:

1. Determine the specific gravity of soil solids.
2. Know the unit weight of water (γ_w).
3. Assume several values of w , such as 5%, 10%, 15%, and so on.
4. Use Eq. (6.4) to calculate γ_{zav} for various values of w .

Figure (6.3) also shows the variation of γ_{zav} with moisture content and its relative location with respect to the compaction curve. Under no circumstances should any part of the compaction curve lie to the right of the zero-air-void curve.

6.3 Factors Affecting Compaction

The preceding section showed that moisture content has a strong influence on the degree of compaction achieved by a given soil. Besides moisture content, other important factors that affect compaction are soil type and compaction effort (energy per unit volume).

Effect of Soil Type

The soil type—that is, grain-size distribution, shape of the soil grains, specific gravity of soil solids, and amount and type of clay minerals present—has a great influence on the maximum dry unit weight and optimum moisture content. Figure (6.4) shows typical compaction curves obtained from four soils. The laboratory tests were conducted in accordance with ASTM Test Designation D-698.

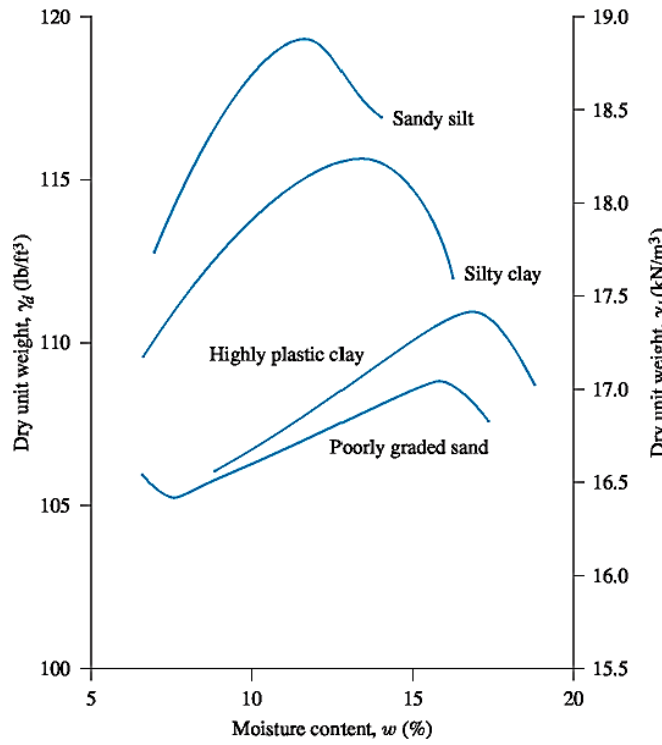


Figure 6.4 Typical compaction curves for four soils (ASTM D-698)

Effect of Compaction Effort

The compaction energy per unit volume used for the standard Proctor test described in Section 6.2 can be given as

$$E = \frac{\left(\frac{\text{Number of blows}}{\text{per layer}}\right) \times \left(\frac{\text{Number of}}{\text{layers}}\right) \times \left(\frac{\text{weight of}}{\text{hammer}}\right) \times \left(\frac{\text{Height of drop}}{\text{of hammer}}\right)}{\text{Volume of mold}} \quad (6.5)$$

or

$$E = \frac{(25)(3)\left(\frac{2.5 \times 9.81}{1000} \text{ kN}\right)(0.305 \text{ m})}{944 \times 10^{-6} \text{ m}^3} = 594 \text{ kN} \cdot \frac{\text{m}}{\text{m}^3} \cong 600 \text{ kN} \cdot \text{m}/\text{m}^3$$

If the compaction effort per unit volume of soil is changed, the moisture–unit weight curve also changes. This fact can be demonstrated with the aid of Figure (6.5), which shows four compaction curves for sandy clay. The standard Proctor mold and hammer were used to obtain these compaction curves. The number of layers of soil used for compaction was three for all cases. However, the number of hammer blows per each layer varied from 20 to 50, which varied the energy per unit volume.

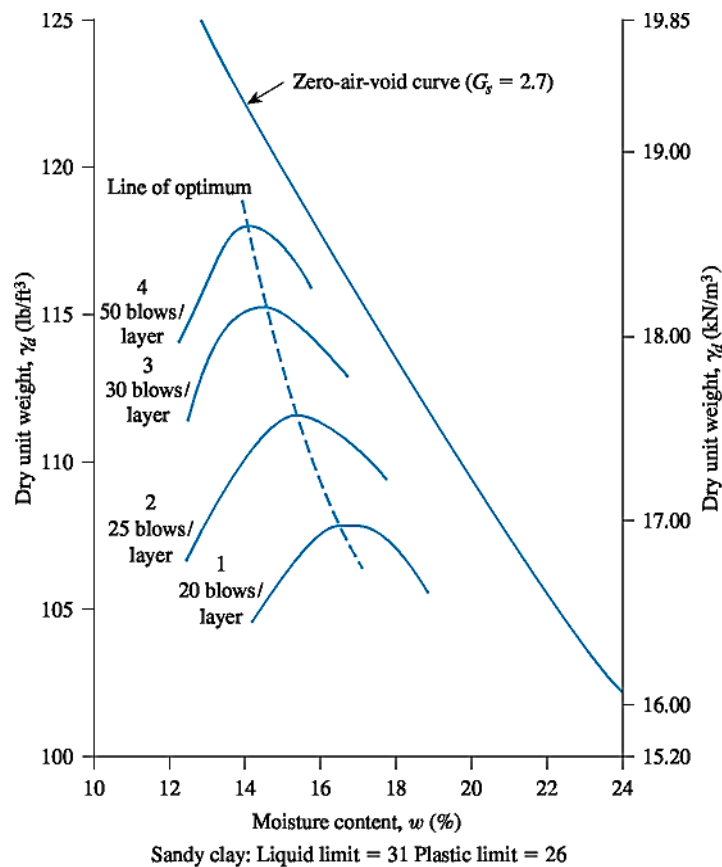


Figure 6.5 Effect of compaction energy on the compaction of a sandy clay

From the preceding observation and Figure (6.5), we can see that

1. As the compaction effort is increased, the maximum dry unit weight of compaction is also increased.
2. As the compaction effort is increased, the optimum moisture content is decreased to some extent.

6.4 Modified Proctor Test

With the development of heavy rollers and their use in field compaction, the standard Proctor test was modified to better represent field conditions. This revised version sometimes is referred to as the *modified Proctor test* (ASTM Test Designation D-1557 and AASHTO Test Designation T-180).

Table (6.1) Summarizes differences between standard and modified proctor tests

Specifications	Standard	Modified
Mold volume (cm^3)	944	944
No. of soil layers	3	5
Mass of rammer (kg)	2.5	4.5
Drop distance (mm)	305	457
No. of blows/ layer	25	25

Figure (6.6) shows a comparison between the hammers used in standard and modified Proctor tests. The compaction energy for this type of compaction test can be calculated as $2700 \text{ kN}\cdot\text{m}/\text{m}^3$.

Because it increases the compactive effort, the modified Proctor test results in an increase in the maximum dry unit weight of the soil. The increase in the maximum dry unit weight is accompanied by a decrease in the optimum moisture content.



Figure (6.6) Comparison between standard Proctor hammer (left) and modified Proctor hammer (right)

Example 6.1

The results of a standard compaction test are:

w(%)	6.2	8.1	9.8	11.5	12.3	13.2
γ (kN/m ³)	16.9	18.7	19.5	20.5	20.4	20.1

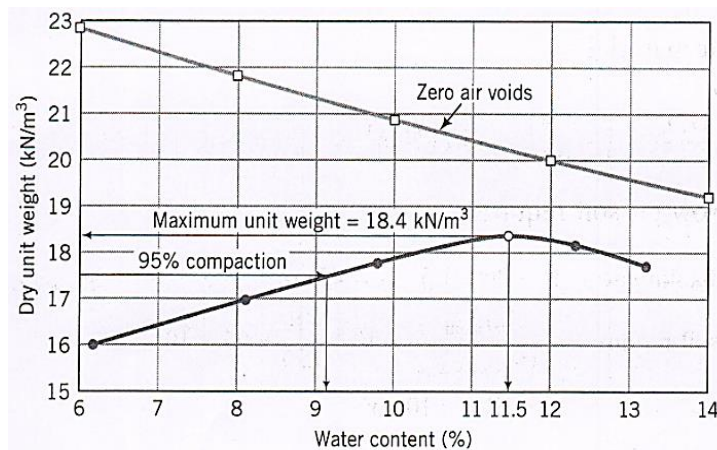
if $G_s = 2.7$, find

- The maximum dry unit weight and optimum water content.
- S at $(\gamma_d)_{max}$.
- γ_d and w at 95% compaction.
- Plot the zero-void line (or curve).

Solution;

a-

w %	γ (kN/m ³)	$\gamma_d = \frac{\gamma}{1+w} \left(\frac{kN}{m^3} \right)$
6.2	16.9	15.9
8.1	18.7	17.3
9.8	19.5	17.8
11.5	20.5	18.4
12.3	20.4	18.2
13.2	20.1	17.8



From the $(w-\gamma_d)$ graph, we get:

$$(\gamma_d)_{max} = 18.4 \text{ kN/m}^3 \quad \& \quad w_{opt.} = 11.5\%$$

b-

$$\gamma_d = \frac{G_s \gamma_w}{1 + \frac{G_s w}{S}}$$

or

$$S = \frac{w G_s (\gamma_d)_{max} / \gamma_w}{G_s - (\gamma_d)_{max} / \gamma_w} = \frac{0.115 \times 2.7 \times \left(\frac{18.4}{9.8} \right)}{2.7 - \left(\frac{18.4}{9.8} \right)} = 0.71 = 71\%$$

c-

at 95% compaction:

$$\gamma_d = 18.4 \times 0.95 = 17.5 \text{ kN/m}^3$$

$$w = 9.2 \% \quad (\text{From the graph})$$

d-

zero air-void line:

w (%)	6	8	10	12	14
$\gamma_d = \frac{G_s \gamma_w}{1 + \frac{G_s w}{S-1}}$	22.8	21.8	20.8	20.0	19.2

6.5 Field Compaction

Most of the compaction in the field is done with rollers. The four most common types of rollers are;

1. Smooth-Wheel (or smooth-drum) rollers (Figure 6.7):
 - Suitable for base coarse and for smooth finished grade (sandy and clayey soils)
 - Not suitable for producing high unit weights when used on thicker layers.
2. Pneumatic rubber-tired rollers (Figure 6.8):
 - Provide very high contact pressure.
 - Used for sandy and clayey soils.
 - Compaction is achieved by a combination of pressure and kneading.
3. Sheepsfoot rollers (Figure 6.9);
 - Most effective in compacting fine-grained soils by kneading action.
4. Vibratory rollers (Figure 6.10);
 - Most efficient in compacting granular soils.



Figure (6.7) Smooth-wheel roller



Figure (6.8) Pneumatic rubber-tired roller



Figure (6.9) Sheep's foot roller

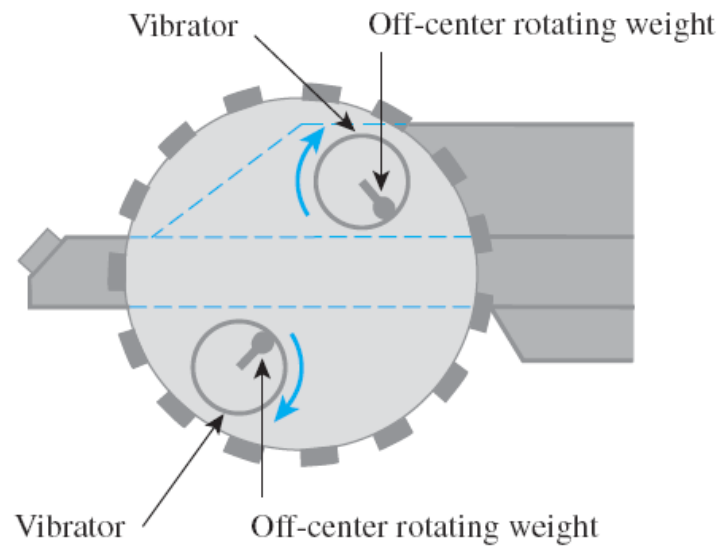


Figure (6.10) Principles of vibratory rollers

Handheld vibrating plates can be used for effective compaction of granular soils over a limited area. Vibrating plates are also gang-mounted on machines. These plates can be used in less restricted areas.

6.6 Specifications for Field Compaction

In most specifications for earthwork, the contractor is instructed to achieve a compacted field dry unit weight of 90 to 95% of the maximum dry unit weight determined in the laboratory by either the standard or modified Proctor test. This is a specification for relative compaction, which can be expressed as

$$R(\%) = \frac{\gamma_{d(field)}}{\gamma_{d(max-lab)}} \times 100 \quad (6.6)$$

where R = relative compaction.

For the compaction of granular soils, specifications sometimes are written in terms of the required relative density D_r or the required relative compaction. Relative density should not be confused with relative compaction. From Chapter 3, we can write

$$D_r = \left[\frac{\gamma_{d(field)} - \gamma_{d(min)}}{\gamma_{d(max)} - \gamma_{d(min)}} \right] \left[\frac{\gamma_{d(max)}}{\gamma_{d(field)}} \right] \quad (6.7)$$

Comparing Eqs. (6.6) and (6.7), we see that

$$R = \frac{R_0}{1 - D_r(1 - R_0)} \quad (6.8)$$

where

$$R_0 = \frac{\gamma_{d(min)}}{\gamma_{d(max)}} \quad (6.9)$$

6.7 Determination of Field Unit Weight

A geotechnical engineer needs to check that field compaction meets specifications. The standard procedures available to check the amount of compaction achieved in the field include:

1. Core cutter (ASTM D-2937)
 - Useful for fine-grained soils.
2. Sand cone method (ASTM D-1556) (Figure 6.11)
 - Used for both fine-grained and coarse-grained soils.
3. Rubber balloon method (ASTM D-2167) (Figure 6.12)

- Same as above, but water is used instead of sand.
4. Nuclear method (ASTM D-2922) (Figure 6.13)
- Nondestructive and fast approach to obtain the unit weight and water content of the soil.
 - More costly than the other apparatuses and of potential hazards to individuals handling radioactive materials.

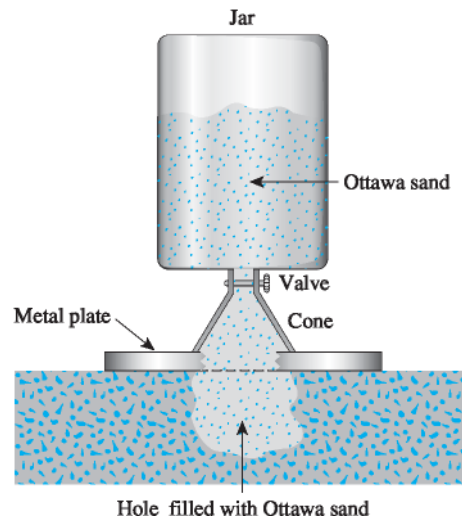


Figure (6.11) Field unit weight determined by sand cone method



Figure (6.12) Calibrated vessel used with rubber balloon



Figure (6.13) nuclear density meter

Problems

6.1 Given $G_s = 2.75$, calculate the zero-air-void unit weight for a soil in kN/m^3 at $w = 5\%$, 8% , 10% , 12% , and 15% .

Ans:

$w(\%)$	$\gamma_{zav} (kN/m^3)$
5	23.72
8	22.11
10	21.16
12	20.28
15	19.1

6.2 Repeat Problem **6.1** with $G_s = 2.65$.

Ans:

$w(\%)$	$\gamma_{zav} (kN/m^3)$
5	22.95
8	21.45
10	20.55
12	19.72
15	18.6

6.3 Calculate the variation of dry density (kg/m^3) of a soil ($G_s = 2.67$) at $w = 10\%$ and 20% for degree of saturation (S) = 80% , 90% , and 100% .

Ans:

$w(\%)$	ρ_d at S (%) (kg/m^3)		
	80	90	100
10	2002	2059	2107
20	1601	1676	1741

6.4 The results of a standard Proctor test are given in the following table. Determine the maximum dry density (kg/m^3) of compaction and the optimum moisture content.

Volume of Proctor mold (cm^3)	Mass of wet soil in the mold (kg)	Moisture content (%)
943.3	1.68	9.9
943.3	1.71	10.6
943.3	1.77	12.1
943.3	1.83	13.8
943.3	1.86	15.1
943.3	1.88	17.4
943.3	1.87	19.4
943.3	1.85	21.2

Ans: $\rho_{d(max)} = 1718 \text{ kg/m}^3$, $w_{opt.} = 15.8 \%$

6.5 A field unit weight determination test for the soil described in Problem 6.4 yielded the following data: moisture content = 10.5% and moist density = 1705 kg/m^3 . Determine the relative compaction.

Ans: $R = 89.81 \%$

6.6 The *in situ* moisture content of a soil is 18% and the moist unit weight is 16.5 kN/m^3 . The specific gravity of soil solids is 2.75. This soil is to be excavated and transported to a construction site for use in a compacted fill. If the specifications call for the soil to be compacted to a minimum dry unit weight of 16.3 kN/m^3 at the same moisture content of 18%, how many cubic meters of soil from the excavation site are needed to produce $10,000 \text{ m}^3$ of compacted fill? How many 20-ton truckloads are needed to transport the excavated soil?

Ans: $N = 981$

6.7 A proposed embankment fill requires 8000 m^3 of compacted soil. The void ratio of the compacted fill is specified as 0.7. Four borrow pits are available as described in the following table, which lists the respective void ratios of the soil and the cost per cubic meter for moving the soil to the proposed construction site. Make the necessary calculations to select the pit from which the soil should be bought to minimize the cost. Assume G_s to be the same at all pits.

Borrow pit	Void ratio	Cost (\$/m ³)
A	0.82	8
B	1.1	5
C	0.90	9
D	0.78	12

Ans: Pit B

6.8 The maximum and minimum dry unit weights of a sand were determined in the laboratory to be 16.3 kN/m^3 and 14.6 kN/m^3 , respectively. What would be the relative compaction in the field if the relative density is 78%?

Ans: $R = 97.4\%$

6.9 The maximum and minimum dry densities of a sand were determined in the laboratory to be 1682 kg/m^3 and 1510 kg/m^3 , respectively. In the field, if the relative density of compaction of the same sand is 70%, what are its relative compaction (%) and dry density (kg/m^3)?

Ans: $R = 96.7\%$

6.10 The relative compaction of a sand in the field is 90%. The maximum and minimum dry unit weights of the sand are 17.0 kN/m^3 and 14.65 kN/m^3 , respectively. For the field condition, determine

- Dry unit weight
- Relative density of compaction
- Moist unit weight at a moisture content of 12%

Ans: (a) $\gamma_{d(\text{field})} = 15.3 \text{ kN/m}^3$ (b) $D_r = 31.08\%$ (c) $\gamma_{(\text{field})} = 17.14 \text{ kN/m}^3$