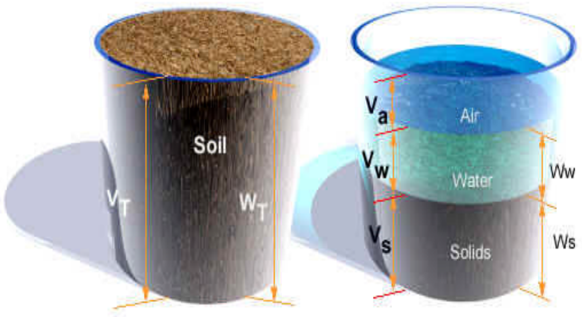
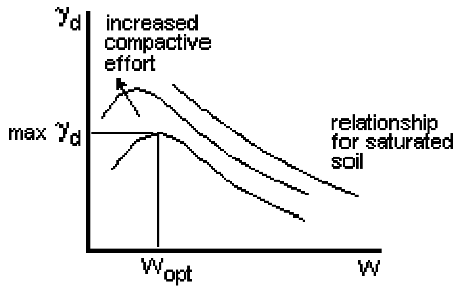
Compaction :

is the process of increasing soil dry unit weight by forcing soil solids into a tighter state and reducing the air voids .Compaction is measured in terms of dry unit weight.



Phase Diagram



The objective of compaction :

Content exhibits different engineering properties (strength ,compressibility and permeability) depending on their dry density .

-Water added to permit the soil particles to slip relative to one another (water acts as a lubricant)

-Water added to soil + compaction (energy)→rearrangement of the solid particles in to a denser state .

Compaction can be applied to improve the properties of an existing soil or in the process of placing fill. The main objectives are to:

- increase shear strength and therefore bearing capacity
- increase stiffness and therefore reduce future settlement
- decrease voids ratio and so permeability, thus reducing potential frost heave

Factors affecting compaction

A number of factors will affect the degree of compaction that can be achieved:

- Nature and type of soil, i.e. sand or clay, grading, plasticity
- Water content at the time of compaction
- Site conditions, e.g. weather, type of site, layer thickness
- Compactive effort: type of plant (weight, vibration, number of passes)

Types of compaction plant

Smooth-wheeled roller

- Self-propelled or towed steel rollers ranging from 2 - 20 tonnes
- Suitable for: well-graded sands and gravels
  silts and clays of low plasticity
- Unsuitable for: uniform sands; silty sands; soft clays

Grid roller

- Towed units with rolls of 30-50 mm bars, with spaces between of 90-100 mm
- Masses range from 5-12 tonnes
- Suitable for: well-graded sands; soft rocks; stony soils with fine fractions
- Unsuitable for: uniform sands; silty sands; very soft clays

Sheepsfoot roller

- Also known as a 'tamping roller'
- Self propelled or towed units, with hollow drum fitted with projecting club-shaped 'feet'
- Mass range from 5-8 tonnes
- Suitable for: fine grained soils; sands and gravels, with >20% fines
- Unsuitable for: very coarse soils; uniform gravels

Pneumatic-tyred roller

- Usually a container on two axles, with rubber-tyred wheels.
- Wheels aligned to give a full-width rolled track.
- Dead loads are added to give masses of 12-40 tonnes.
- Suitable for: most coarse and fine soils.

Unsuitable for: very soft clay; highly variable soils

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Vibrating plate

- Range from hand-guided machines to larger roller combinations
- Suitable for: most soils with low to moderate fines content
- Unsuitable for: large volume work; wet clayey soils

Power rammer

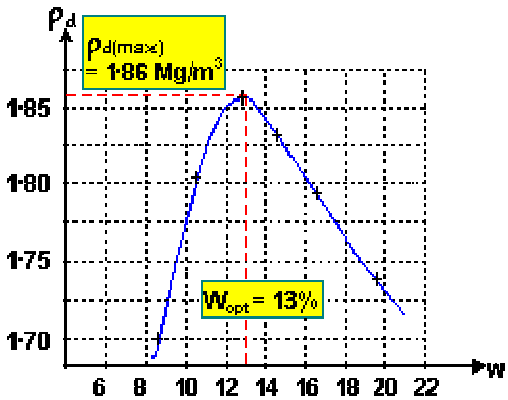
- Also called a 'trench tamper'
- Hand-guided pneumatic tamper
- Suitable for: trench back-fill; work in confined areas
- Unsuitable for: large volume work

Standard laboratory tests:

- Standard protect Test (ASTMD - 698)
- Modified Protect Test (ASTMD-1557)

Carried out on soil passing the No.40 sieve (opening size=0.425)

		Standard	Modified
Hammer wt.	(Ib)	5.5	10
	(Kg)	2.49	4.54
Drop	(in)	12	18
	(mm)	305	457
Vol.	(ft^3)	1/30	1/30
	(m^3)	0.944×10^{-3}	0.944×10^{-3}
No. of layers		3	5
No. of blows		25	25
Comp.energy			
	(Kilo Joules/m^3)	593	2693
	(Ft-Ib/ft^3)	12375	56250



$$E = \frac{\text{Number of blows per layer} \times \text{Number of layers} \times \text{Weight of hammer} \times \text{Height of drop of hammer}}{\text{volume of mold}}$$

Higher comp. energy→ { higher γ_d
Smaller opt. moisture content

Since :

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

$$S.e = G_s.w_c$$

$$\therefore \gamma_d = \frac{G_s}{1+\frac{G_s.w_c}{S}}\gamma_w$$

Total or wet density ρ :

$$\rho = \frac{M_t}{V_t} = \frac{M_s + M_w}{V_t}$$

Solid density ρ_s

$$\rho_s = \frac{M_s}{V_s}$$

dry density ρ_d

$$\rho_d = \frac{M_s}{V_t}, \quad \because V_t > V_s \quad \therefore \rho_d < \rho_s$$

Also we have

$$\rho_d = \frac{M_s}{V_t} = \frac{M_t - M_w}{V_t} = \frac{M_t}{V_t} - \frac{M_w}{V_t} = \rho - \left(\frac{M_w}{M_s}\right)\left(\frac{M_s}{V_t}\right) = \rho - w\rho_d$$

$$so \quad that \quad \rho_d + w\rho_d = \rho \quad and \quad \rho_d = \frac{\rho}{1+w}$$

Hence for a given(ω_c) ,layer values of γ_d can be obtained by the use of higher comp. energy.

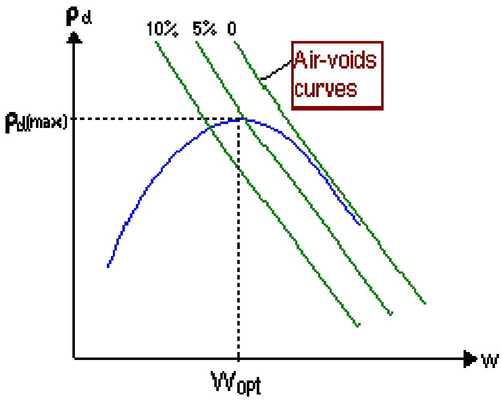
Example: A compacted soil sample has been weighed with the following results:
Mass = 1821 g Volume = 950 ml Water content = 9.2%
Determine the bulk and dry densities.

Bulk density ρ = 1821 / 950 = 1.917 g/ml or Mg/m³

Dry density ρ_d = 1.917 / (1+0.092) = 1.754 Mg/m³

Dry density and air-voids content

A fully saturated soil has zero air content. In practice, even quite wet soil will have a small air content



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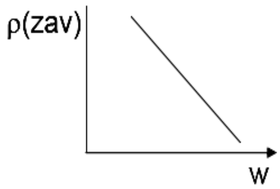
$$\text{Air - voids content, } A_v = \frac{\text{Volume of air}}{\text{Total volume}}$$

The maximum dry density is controlled by both the water content and the air-voids content. Curves for different air-voids contents can be added to the ρ_d / w plot using this expression:

$$\rho_d = \frac{G_s \rho_w}{1 + wG_s}(1 - A_v)$$

The air-voids content corresponding to the maximum dry density and optimum water content can be read off the ρ_d/w plot or calculated from the expression.

$$\rho(z.a.v) = \frac{G_s \rho_w}{1 + wG_s}$$



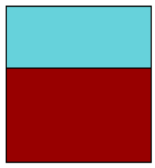
$$V_s = 1$$

$$\rho_s = M_s / V_s, then \quad M_s = V_s \rho_s = V_s G_s \rho_w$$

$$w = M_w / M_s, then \quad M_w = wM_s = wG_s \rho_w, by \quad V_s = 1$$

$$M_w = V_w \rho_w, or \quad V_w = M_w / \rho_w = wG_s \rho_w / \rho_w = wG_s$$

$$\rho_{dry} = \frac{\rho}{1+w} = \frac{M_t}{V_t(1+w)} = \frac{(1+w)\rho_w G_s}{(1+w)(1+wG_s)} = \frac{\rho_w G_s}{1+wG_s}$$



Example: Determine the dry densities of a compacted soil sample at a water content of 12%, with air-voids contents of zero, 5% and 10%. (G_s = 2.68).

$$\text{For } A_v = 0: \quad \rho_d = \frac{2.68 \times 1.0}{1 + 2.68 \times 0.12} = 2.03 \text{ Mg/m}^3$$

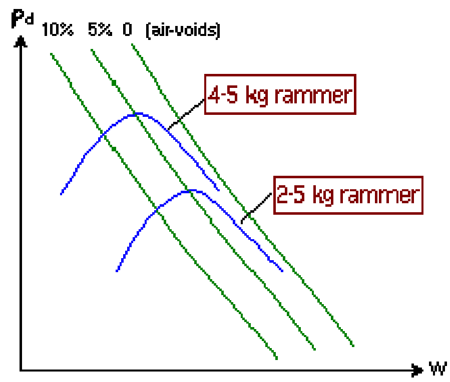
$$\text{For } A_v = 5\%: \quad \rho_d = \frac{2.68 \times 1.0}{1 + 2.68 \times 0.12}\left(1 - \frac{5}{100}\right) = 1.93 \text{ Mg/m}^3$$

$$\text{For } A_v = 10\%: \quad \rho_d = \frac{2.68 \times 1.0}{1 + 2.68 \times 0.12}\left(1 - \frac{10}{100}\right) = 1.83 \text{ Mg/m}^3$$

Effect of increased compactive effort

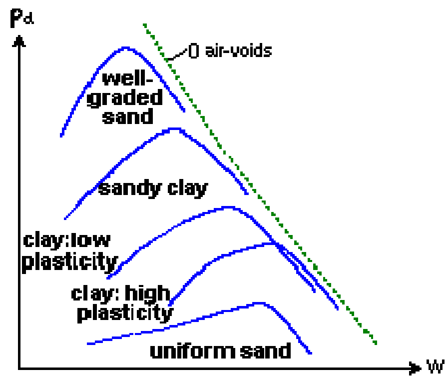
The compactive effort will be greater when using a heavier roller on site or a heavier rammer in the laboratory. With greater compactive effort:

- maximum dry density increases
- optimum water content decreases
- air-voids content remains almost the same.



Effect of soil type

- Well-graded granular soils can be compacted to higher densities than uniform or silty soils.
- Clays of high plasticity may have water contents over 30% and achieve similar densities (and therefore strengths) to those of lower plasticity with water contents below 20%.
- As the % of fines and the plasticity of a soil increses, the compaction curve becomes flatter and therefore less sensitive to moisture content. Equally, the maximum dry density will be relatively low



Interpretation of laboratory data

Example data collected during test

In a typical compaction test the following data might have been collected:
Mass of mould, M_o = 1082 g
Volume of mould, V = 950 ml
Specific gravity of soil grains, G_s = 2.70

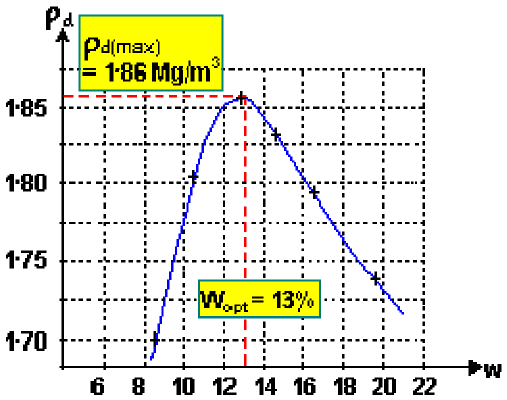
Mass of mould + soil (g)	2833	2979	3080	3092	3064	3027
Water content (%)	8.41	10.62	12.88	14.41	16.59	18.62

Calculated densities and density curve

The expressions used are:

$$\rho = \frac{M - M_o}{V} \quad \text{and} \quad \rho_d = \frac{\rho}{1 + w}$$

Bulk density, ρ (Mg/m³)	1.84	2.00	2.10	2.12	2.09	2.05
Water content, w	0.084	0.106	0.129	0.144	0.166	0.186
Dry density, ρ_d (Mg/m³)	1.70	1.81	1.86	1.851	1.79	1.73

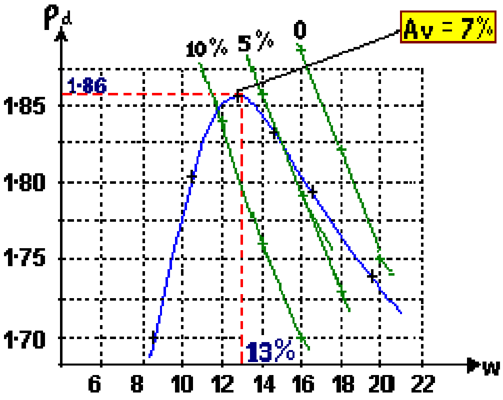


Air-voids curves

The expression used is:

$$\rho_d = \frac{G_s \rho_w}{1 + wG_s}(1 - A_v)$$

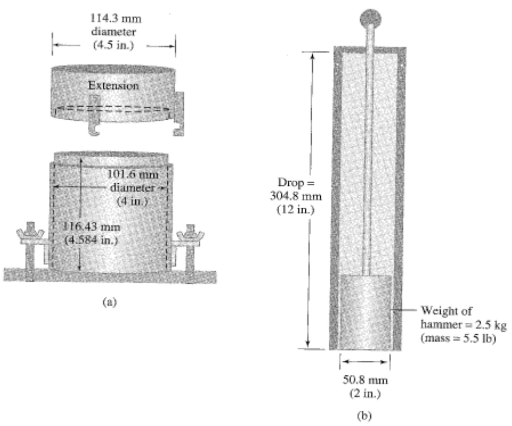
Water content (%)	10	12	14	16	18	20
ρ_d when A_v = 0%	2.13	2.04	1.96	1.89	1.82	1.75
ρ_d when A_v = 5%	2.02	1.94	1.86	1.79	1.73	1.67
ρ_d when A_v = 10%	1.91	1.84	1.76	1.70	1.64	1.58

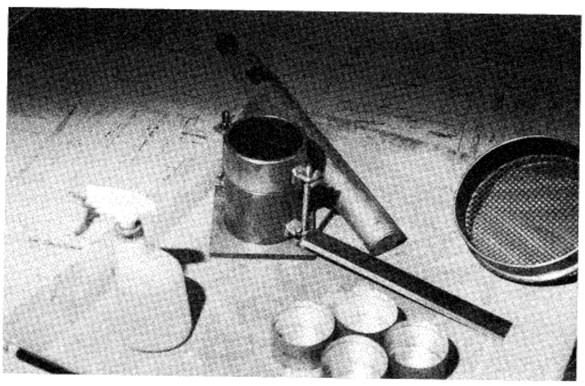


The **optimum air-voids content** is the value corresponding to the maximum dry density (1.86 Mg/m³) and optimum water content (12.9%).

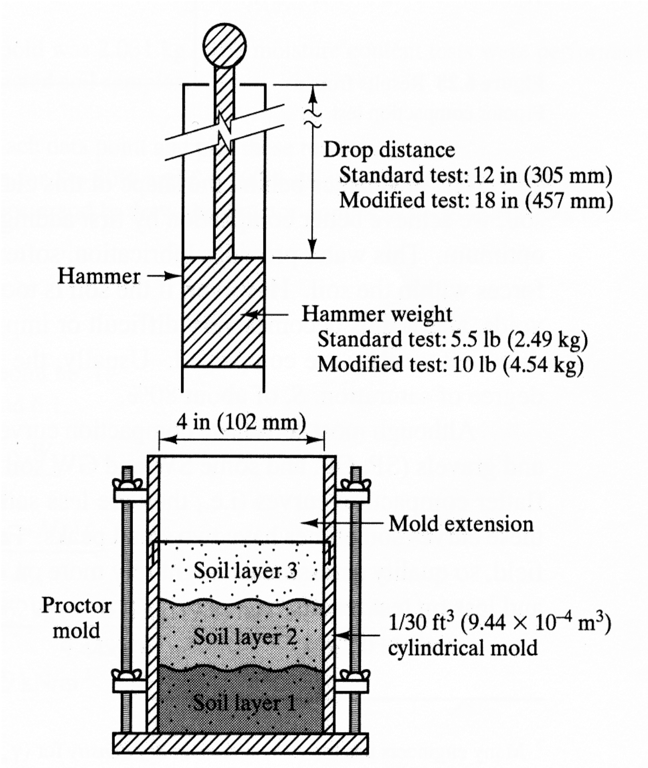
$$A_{v(opt)} = 1 - \frac{1.86}{2.70 \times 1.0}(1 + 0.129 \times 2.70) = 0.071 \quad (7.1\%)$$

Procedure





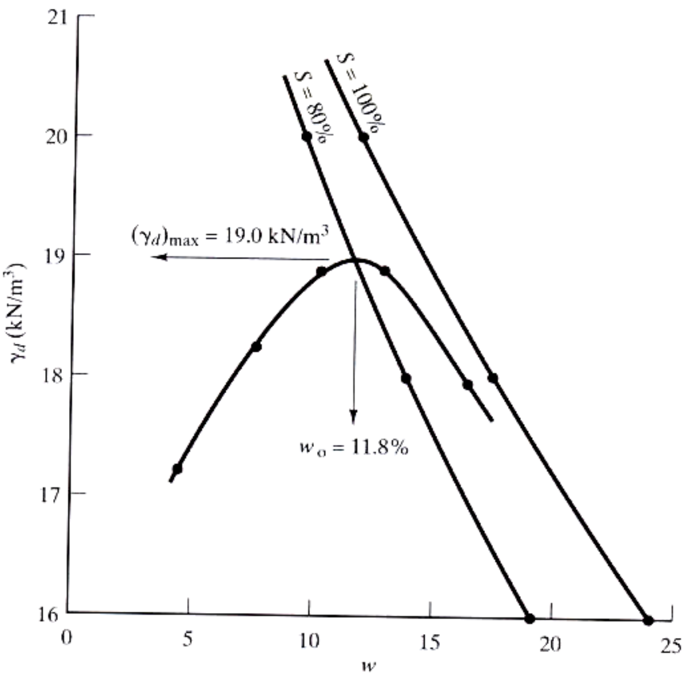
(c)



1. Obtain 10 lbs of soil passing No. 4 sieve
2. Record the weight of the Proctor mold without the base and the (collar) extension, the volume of which is 1/30 ft3.
3. Assemble the compaction apparatus.
4. Place the soil in the mold in 3 layers and compact using 25 well distributed blows of the Proctor hammer.
5. Detach the collar without disturbing the soil inside the mold
6. Remove the base and determine the weight of the mold and compacted soil.
7. Remove the compacted soil from the mold and take a sample (20-30 grams) of soil and find the moisture content
8. Place the remainder of the molded soil into the pan, break it down, and thoroughly remix it with the other soil, plus 100 additional grams of water.

Results

- Plot of dry unit weight vs moisture content
- Find gd (max) and *w*opt
- Plot Zero-Air-Void unit weight
  (only S=100%)



Specification for Field Compaction

- Specifications will refer to % Relative Compaction
- Relative to what?
  - Proctor Test – standard or modified

- % Relative Compaction

- If R > 100 % use Modified Proctor Test
- Soil will be compacted to 98% relative compaction as compared to a standard proctor test, ASTM D-698
- The soil moisture content will be ± 2% of optimum.
- 98% means the soil in the field should be 98% of the lab result
- For example, if the peak of the curve is at 100 pcf and 22% moisture
- The field compaction must be at least 98 pcf and within the stated moisture range (20 ~24%)

<u>Measurement of Field Compaction</u>

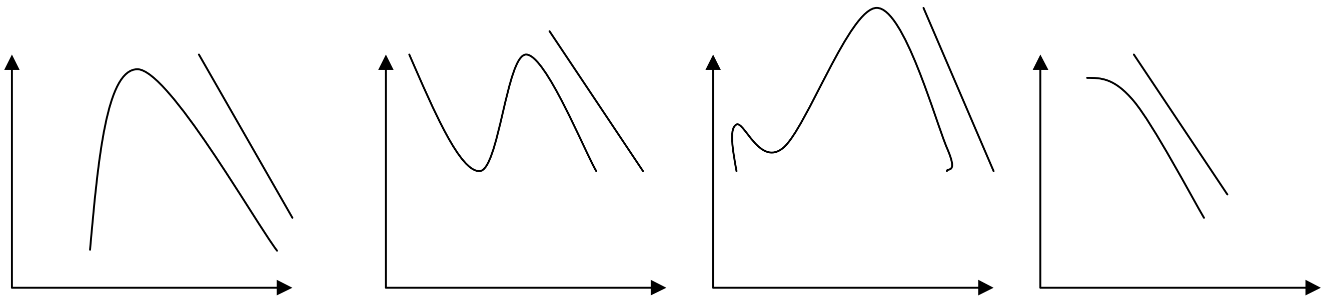
- Most common methods are
  - Nuclear Method
  - Sand Cone method
  - Rubber Balloon method

$$R(\%) = \text{Relative Compaction}$$

$$R(\%) = \frac{\gamma_d \text{ in the field}}{\text{maximum } \gamma_d \text{ from the Proctor test}}$$

Value of RC is specified according to importance and type of the project (about 90-95%)

Types of Compaction Curves



Single peak $30 < L.L < 70$ | irregular Shape $L.L < 30$ | double peak $L.L < 30$ & > 70 | oddly Shape $L.L > 70$

Properties of Compacted Soils :

Effect of molding moisture cont on **soil structure** :

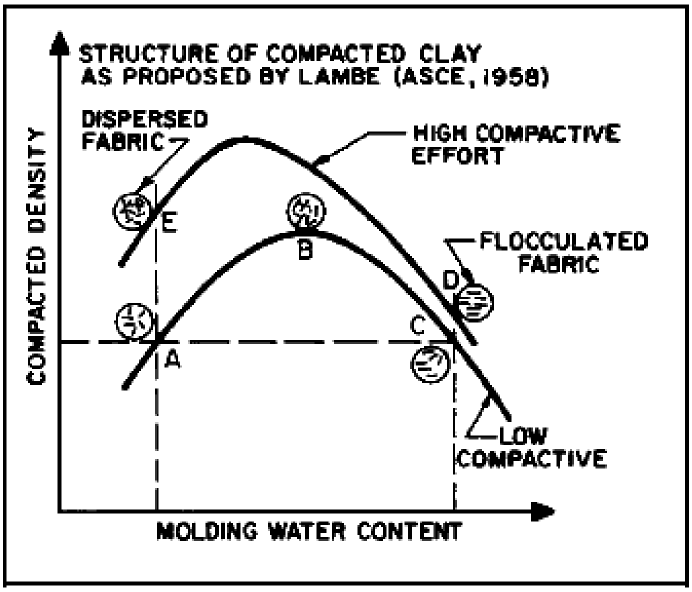
increasingWc for a given compaction effort tends to increase the repulsions and permitting a more orderly arrangement of the soil particles

Effect of molding moisture content on **permeability** :

increasing Wc results in a decrease in permeability on the dry of optimum and a slight increase in permeability on the wet side of optimum .(K1 > K2 since for dry side of opt.(flocculated st),the doainage paths are smaller then of the wet side of opt .(dispersed st .in which the drainage paths are longer)

Effect of molding moisture content on **stress-strain relationship** :

samples compacted dry of optimum tend to be more rigid and stronger than samples compacted wet of optimum



Note :

In designing the **earth dam** , the engineer must consider not only the strength and compressibility of the soil element as compacted ,but also its properties after it has been subjected to increased total stresses and saturated by permeating water .

effect of moisture content on **compression characteristics** :

1-at **low. Stress consolidation** : the sample compacted on the wet side is more compressible than the one compactedon the dry side

2-at high-stress consolidation : the sample compacted on the dry side is more compressible than the compacted on the wet side .

Moisture condition value

This is a procedure developed by the Road Research Laboratory using only one sample, thus making laboratory compaction testing quicker and simpler. The minimum compactive effort to produce near-full compaction is determined. Soil placed in a mould is compacted by blows from a rammer dropping 250 mm; the penetration after each blow is measured.

Apparatus and sizes

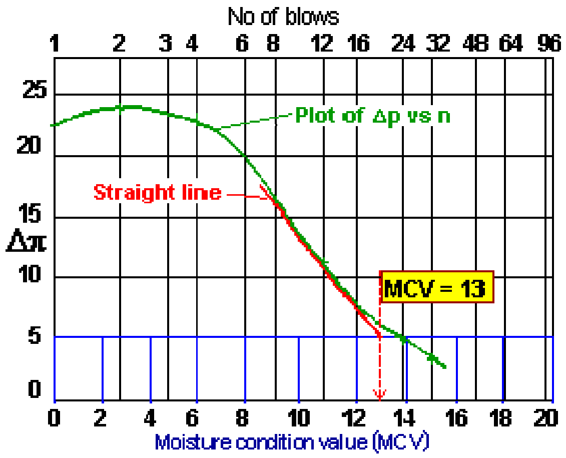
Cylindrical mould, with permeable base plate:
    internal diameter = 100 mm, internal height at least 200 mm
Rammer, with a flat face:
    face diam = 97 mm, mass = 7.5 kg, free-fall height = 250 mm
Soil:
    1.5 kg passing a 20 mm mesh sieve

Test procedure and plot

- Firstly, the rammer is lowered on to the soil surface and allowed to penetrate under its own weight
- The rammer is then set to a height of 250 mm and dropped on to the soil
- The penetration is measured to 0.1 mm
- The rammer height is reset to 250 mm and the drop repeated until no further penetration occurs, or until 256 drops have occurred
- The change in penetration ($\Delta\pi$) is recorded between that for a given number of blows (**n**) and that for **4n** blows

- A graph is plotted of $\Delta\pi$ / **n** and a line drawn through the steepest part
- The **moisture condition value (MCV)** is give by the intercept of this line and a special scale

Example plot and determination of MCV



After plotting $\Delta\pi$ against the number of blows n, a line is drawn through the steepest part.

The intercept of this line and the 5 mm penetration line give the MCV

The defining equation is:**MCV = 10 log B**
(where B = number of blows corresponding to 5 mm penetration)

On the example plot here an MCV of 13 is indicated.

Significance of MCV in earthworks

The MCV test is rapid and gives reproducible results which correlate well with engineering properties. The relationship between MCV and water content for a soil is near to a straight line, except for heavily overconsolidated clays.A desired value of undrained strength or compressibility can be related to limiting water content, and so the MCV can be used as a control value after calibrating MCV vs w for the soil. An approximate correlation between MCV and undrained shear strength has been suggested by Parsons (1981).

$\text{Log } s_u = 0.75 + 0.11(\text{MCV})$

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Examples

1. The natural water content of a borrow material is known to be 10%. Assuming 6000 g of wet soil is used for each laboratory compaction test point, compute how much water is to be added to each of the other 6000 g samples to bring their water contents up to 13, 17, 20, 24, and 28%

Answer

GIVEN 6000 g samples at natural m/c = 10%

$$w = \frac{M_w}{M_s} = 0.1$$

$$M_t = M_s + M_w = 6000\ g$$

$$M_s = \frac{6000}{1.1} = 5455\ g$$

$$But\ M_w = w \times M_s$$

$$If\ w = 0.10\ then\ M_w = 545\ g$$

$$If\ w = 0.13\ then\ M_w = 709\ g$$

$$If\ w = 0.17\ then\ M_w = 927\ g$$

$$If\ w = 0.20\ then\ M_w = 1091\ g$$

$$If\ w = 0.24\ then\ M_w = 1309\ g$$

$$If\ w = 0.28\ then\ M_w = 1527\ g$$

water added given by

$$(M_w)_{moisture} - (M_w)_{0.10}$$

$$If\ w = 0.13\ water\ added = 164\ g$$

$$If\ w = 0.17\ water\ added = 382\ g$$

$$If\ w = 0.20\ water\ added = 546\ g$$

$$If\ w = 0.24\ water\ added = 764\ g$$

$$If\ w = 0.28\ water\ added = 982\ g$$

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2. For the data given below ($\rho S = 2.64\ Mg/m^3$):

C (Low Compaction)		B (Standard Proctor)		A (Modified Proctor)	
w (%)	ρd (Mg/m3)	w (%)	ρd (Mg/m3)	w (%)	ρd (Mg/m3)
10.9	1.627	9.3	1.691	9.3	1.873
12.3	1.639	11.8	1.715	12.8	1.910
16.3	1.740	14.3	1.755	15.5	1.803
20.1	1.707	17.6	1.747	18.7	1.699
22.4	1.647	20.8	1.685	21.1	1.641
		23.0	1.619		

(a) Plot the compaction curves.
(b) Establish the maximum dry density and optimum water content for each test.
(c) Compute the degree of saturation at the optimum point for the Modified Proctor test data.
(d) Plot the 100% saturation (zero air voids) curve. Also plot the 70, 80, and 90% saturation curves. Plot the line of optimums.

Answer:

(A) Plot Dry Density v Moisture Content

(B)From graph plot of DRY DENSITY V MOISTURE CONTENT

Data "A" $\rho_d = 1.91\ t/m^3$ $w_{opt} = 12.5\ \%$

Data "B" $\rho_d = 1.76\ t/m^3$ $w_{opt} = 15.5\ \%$

Data "C" $\rho_d = 1.75\ t/m^3$ $w_{opt} = 17.3\ \%$

(C)

$\rho=\rho_d(1+w);$

$$S=\frac{V_w}{V_v}=\frac{w\,\rho_d}{1-\frac{\rho_d}{\rho_s}}$$

Data "A"

$$S = \frac{0.125 \times 1.91}{1 - \frac{1.91}{2.64}} = 0.863 \text{ or } 86.3\%$$

Data "B" gives S = 81.8%

Data "C" gives S = 89.8%

(D) For selected values of ρ_d and for s = 100% calculate w.

Then plot on graph. ρ_d (t/m^3)

ρ_d (t/m^3)	w (%)
2.0	12.1
1.9	14.8
1.8	17.7
1.7	10.9
1.6	24.6

3. A soil proposed for a compacted fill contains 40% fines and 60% coarse material by dry weight. When the coarse fraction has w = 1.5%, its affinity for water is completely satisfied (that is, it is saturated but surface dry). The Atterberg limits of the fines are LL = 27 and PL = 12. The soil is compacted by rolling to a ρd = 2.0 Mg/m^3 at w = 13%. Note: This is the water content of the entire soil mixture.

(a) What is the water content of the fines in the compacted mass?

(b) What is the likely USCS classification of the soil?

(c) What is the liquidity index of the fines?

(d) What can you say about the susceptibility of the fill to

(i) shrinkage-swelling potential?

(ii) potential for frost action?

(e) Is there a certain type of compaction equipment you would especially recommend for this job? Why?

Answer

Given: $\rho_d = 2.0\ t/m^3$ *and* $w = 13\%$

$[\rho]_{coarse} = 0.60 \times 2.0 = 1.2 t/m^3$

$[\rho]_{fines} = 0.40 \times 2.0 = 0.8 t/m^3$

Mass of water = 13% = .13 x 2.0 = 0.26 *t*

Mass of water in coarse = 1.5% = 0.15 x 1.2 = 0.018 t

Mass of water in fines = 0.26 − 0.018 = 0.242 t

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(a)

$$[w]_{fines} = \frac{M_w}{[M_s]_{fines}} 100 = \frac{0.242}{0.80} 100 = 30.3\%$$

(b)

Unified Classification = *GC or SC*

(c)

$$\text{Liquidity Index} = \frac{w_L - w_p}{w_L - w_p} = \frac{30.25 - 12}{27 - 12} = 1.22$$

(d)

Shrinkage - Swell
Shrinkagefrom Plastic Limit = 12 *LOW*
Swell from page 55 *of notes Table* 1 *PI*<18 *LOW*
Frost from Figure 6-11 *of Holtz p* 183 *LOW - MODERATE*

(e)

Fines are CL. From page 159 *of Holtz*
Sheepsfoot or rubber tired roller
or page 37 *of notes (d) use:*
Sheepsfoot

4. As an earthwork construction control inspector you are checking the field compaction of a layer of soil. The laboratory compaction curve for the soil is identical to the test for the Standard Test of Question 4-2. Specifications call for the compacted density to be at least 95% of the maximum laboratory value and within ± 2% of the optimum water content. When you did the sand cone test, the volume of soil excavated was 1153 cm^3. It weighted 2209 g wet and 1879 g dry.

(a) What is the compacted dry density?
(b) What is the field water content?
(c) What is the relative compaction?
(d) Does the test meet specifications?
(e) What is the degree of saturation of the field sample?
(f) If the sample were saturated at constant density, what would be the water content?

Answer

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(a)

$$[\rho_d]_{field} = \frac{1879}{1153} = 1.63\ g/cm^3$$

(b)

$$[w]_{field} = 100\ \frac{2209 - 1879}{1879} = 17.6\%$$

(c)

$$[Rel\ Comp] = \frac{[\rho_d]_{field}}{[\rho_d]_{max}}\ 100 = \frac{1.63}{1.73}\ 100 = 94.2\%$$

(d)

Spec.: Rel Comp > 95 % and m/c = $w_{opt} \pm 2$ %

Rel Comp at 94.2% FAILS

m/c at 17.6% PASSES

(e) $\rho_w S e = w \rho_s$ and $\rho_d = \dfrac{\rho_s}{1 + e}$

Assuming $\rho_s = 2.65$ [e = 0.63] $S = 74.4\%$

Assuming $\rho_s = 2.70$ [e = 0.66] $S = 72.2\%$

(f)

Assuming $\rho_s = 2.65$ [e = 0.63] $w = 23.6\%$

Assuming $\rho_s = 2.70$ [e = 0.66] $w = 24.4\%$

5. The following results were obtained from a standard Proctor Test in performed in Lab.

Weight of wet soil (lb)	Moisture content (%)
3.65	12.2
3.95	13.4
4.25	15.3
4.15	19.1

(a) Calculate dry unit weight for each set of the data

(b) Calculate dry unit weight for Zero-Air-Void (ZAV) at each moisture content assuming G_s to be 2.70.

(c) Plot moisture-unit weight relationship along with ZAV line. Also calculate and plot (on the same diagram) dry unit weight versus moisture content for S = 70 and 80 percent (assume G_s = 2.70)

(d) Determine maximum unit weight, $\gamma_{d(max)}$ and OMC from the diagram

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(e) If the specifications call for field compaction to be minimum of 95 percent of maximum dry unit weight of the soil, recommend the range of moisture content to be used in the field.

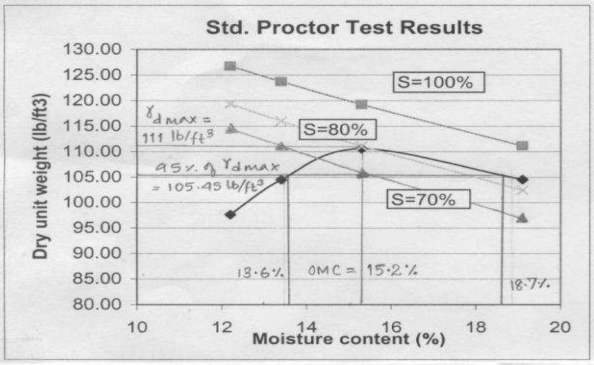
Draw the diagram to scale

(Note: If you select to use spreadsheet, please show at least one set of hand calculations for each problem)

PROBLEM #1

Wet wt.(lb)	Volume (ft3)	Wt unit wt.(lb/ft3)	Moisture (%)	Dry unit wt.(lb/ft3)	Zero void unit wt. (lb/ft3)
3.65	1/30	109.5	12.2	97.59	126.7338649
3.95	1/30	118.5	13.4	104.50	123.7186077
4.25	1/30	127.5	15.3	110.58	119.2272309
4.15	1/30	124.5	19.1	104.53	111.1565613

Dry unit wt (S=70%)	Dry unit wt (S=80%)
114.567709	119.341243
111.071765	116.013083
105.952745	111.107081
97.0107757	102.442806



Equations used

Wet unit wt, $\gamma_t = \dfrac{\text{wet wt}}{\text{Volume}} \Rightarrow$ eg. $\gamma_t = \dfrac{3.65\ lb}{1/30\ ft^3} = 109.5\ lb/ft^3$

(a) Dry unit wt, $\gamma_d = \dfrac{\gamma_t}{1+w} \Rightarrow$ eg. $\gamma_d = \dfrac{109.5}{1+0.122} = 97.59\ lb/ft^3$

(b) $\gamma_{zero\ air\ void} = \dfrac{\gamma_w}{w + 1/G_s} \Rightarrow$ eg. $\gamma_{zav} = \dfrac{62.4}{0.122 + 1/2.7} = 126.73\ lb/ft^3$

(c) $\gamma_{zav\ (s=70\%)} = \dfrac{G_s \gamma_w}{1 + \frac{G_s w}{s}} \Rightarrow$ eg. $\gamma_{zav\ (s=70\%)} = \dfrac{2.7 \times 62.4}{1 + \frac{2.7 \times 0.122}{0.70}} = 114.57\ lb/ft^3$

(d) From the figure, $\gamma_{d(max)} = 111\ lb/ft^3$

OMC = 15.2%

(e) For 95% of $\gamma_{d(max)}$, $\gamma_d = 0.95 \times 111 = 105.45\ lb/ft^3$

Equivalent MC range = 13.6% to 18.7%