ENCE 3610 Soil Mechanics

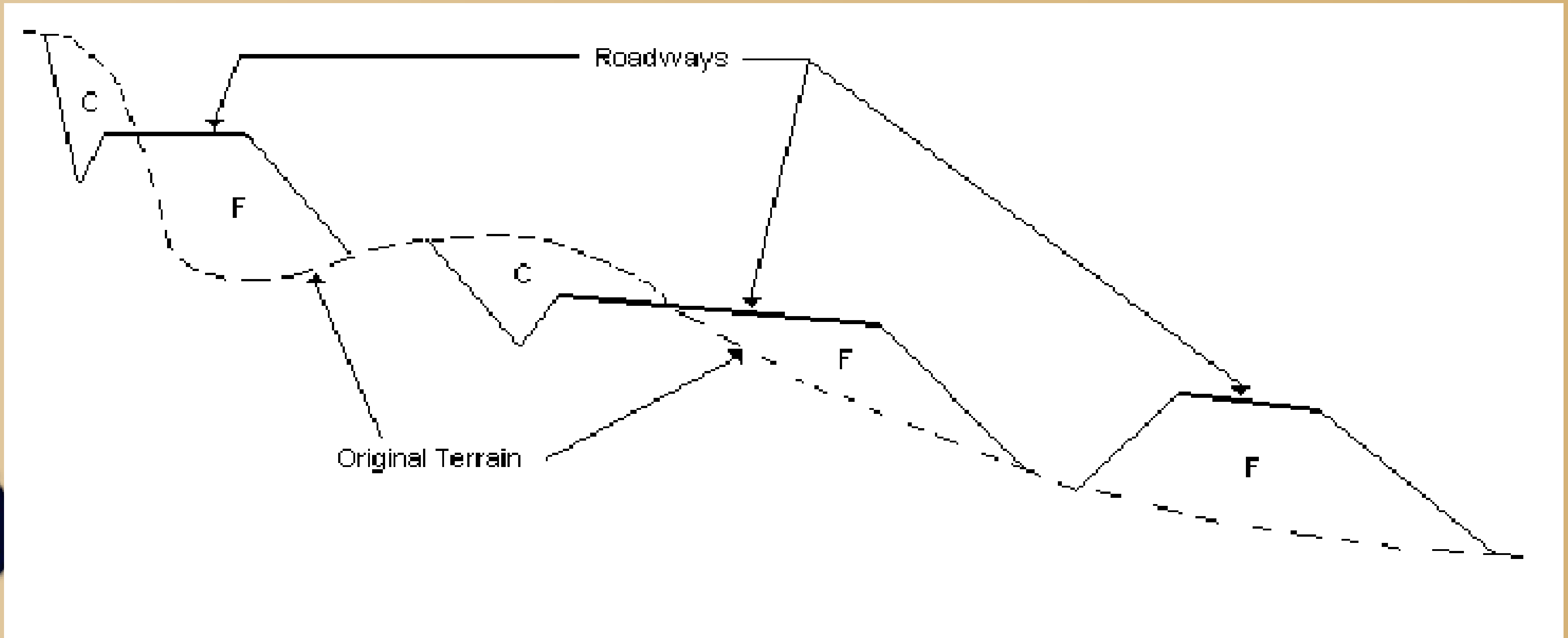
Soil Compaction

Proctor Test

Overview of Earthwork and Compaction

Objectives of earthwork

- To move the soil where it is needed
- To improve the quality of the soil so that it will support structures



Overview of Earthwork and Compaction

- To change the ground surface from some initial configuration to a final configuration
- The final configuration is generally defined by a grading plan
- Earthwork must not create slope stability problems, either temporary or permanent
- Additional objectives of compacted fills
  - Fills must have sufficient strength to support both their own weight and external loads, such as foundations or vehicles
- Additional objectives of compacted fills
  - Fills must be sufficiently stiff to avoid excessive settlement
  - Fills must satisfy the first two requirements even if they become wet
  - Fills for the cores of earth dams or liners for sanitary landfills must have hydraulic conductivity low enough to restrict the flow of water
  - Fills for bases of pavements must have hydraulic conductivity high enough to enable drainage of the roadway
  - Fills should not be frost heave susceptible

Construction Methods and Equipment

- Historic methods
  - Large earthmoving and compaction projects were possible in ancient times, but required a great deal of labour and time to execute
  - Soil compaction was known in ancient times; in the Roman world, large logs (with handles and, in some cases, iron shoes) were simply picked up and dropped to compact soil
  - Introduction of steam power in the nineteenth century made possible the introduction of "modern" mechanised earth moving equipment
  - Panama Canal: Excavation of the Culebra Cut (1907) required the movement of 75,000,000 m^3 of earth

- Historic methods
  - Hydraulic fills
    - Popular technique between 1900 and 1940 for moving large amounts of earth
    - Involved mixing the soil with large quantities of water, conveying the mixture through pipes to the sites and depositing it at desired locations
    - No compaction was done, which insured unstable fills with high settlement potential
    - 3,800,000 m^3 landslide at the last large hydraulic fill job (Ft. Peck Dam, Montana, 1938) helped to end this practice
    - Higher capacity earthmoving equipment has made hydraulic fills unnecessary in any case

Earthmoving Equipment

- Key development: the tractor or crawler
  - Basic task: to convert engine power into traction
  - First tractors were developed in early 20th century for agricultural and military (tanks) applications
- Mounting
  - All early tractors were track mounted
  - Modern track mounted equipment is powerful and mobile, but operates at slow speeds (< 11 kph or 7 mph)
  - Wheel mounted tractors are available for speeds up to 50 kph (30 mph), but has less traction and not as well suited for rough terrain

Earthmoving Equipment

- Tractors or Crawlers
  - Based on a "modular" concept, starting with a tractor base and adding attachments for various jobs
  - Bulldozer is most common; the movable steel blade can cut, move, spread, and mix soil along with other operations

Earthmoving Equipment

- Tractors or Crawlers
  - Loader can pick up, transport, and deposit soil
  - Hoe type earthmoving equipment
  - Special tractors with a loader on one end and a hoe on the other are backhoes
  - Larger tractors without the loader are excavators

Earthmoving Equipment

- Tractors or Crawlers
  - Hoe type earthmoving equipment
  - Excavators and backhoes are versatile types of equipment that can be used for a wide variety of tasks
  - Shown is a special attachment for piece lifting and detailed clearing

Conventional Earthwork

- Definition of conventional earthwork
  - The excavation, transport, placement and compaction of soil or soft rock in areas where equipment can move freely
- Clearing and Grubbing
  - Involves removal of vegetation, trash, debris and other undesirable materials from areas to be cut or filled
  - Clearing is the above-ground portion of the work
  - Grubbing is the below-ground portion of the work
  - Mix of materials to be moved varies from site to site
- Stripping
  - Removing and storing the topsoil; topsoil is valuable for growing plants
- Oversize Items
  - Limited quantities of inorganic debris such as chunks of concrete, bricks or asphalt do not need to be hauled away if they are no larger than 250 mm (10")
  - Items larger than this are oversize and need to be hauled away
  - This is especially important with areas for pile foundations and in the upper 3 m of the soil

Conventional Earthwork

- Excavation
  - Most excavation takes place at the construction site
  - If insufficient material exists on site, material may be obtained from offsite borrow pits
  - Areas to be filled need to have the loose upper soils removed
  - Although loaders can be used with trucks to haul dirt, scrapers are more efficient, as they load, move, and unload dirt
  - If ground is too hard for scrapers or loads, it can be loosened using a ripper

- Excavation
  - When rippers do not work, it may become necessary to blast; this is especially important in rock
  - Chemicals that expand and break rocks apart can sometimes be used in lieu of blasting
  - Rippability or excavatability at a site can generally be evaluated from a visual inspection
  - At questionable sites, measurement of seismic wave velocity can help in selecting proper equipment
  - Soil and rock with seismic velocities of less than 500 m/sec (1600 ft/sec) can be excavated without ripping

Conventional Earthwork

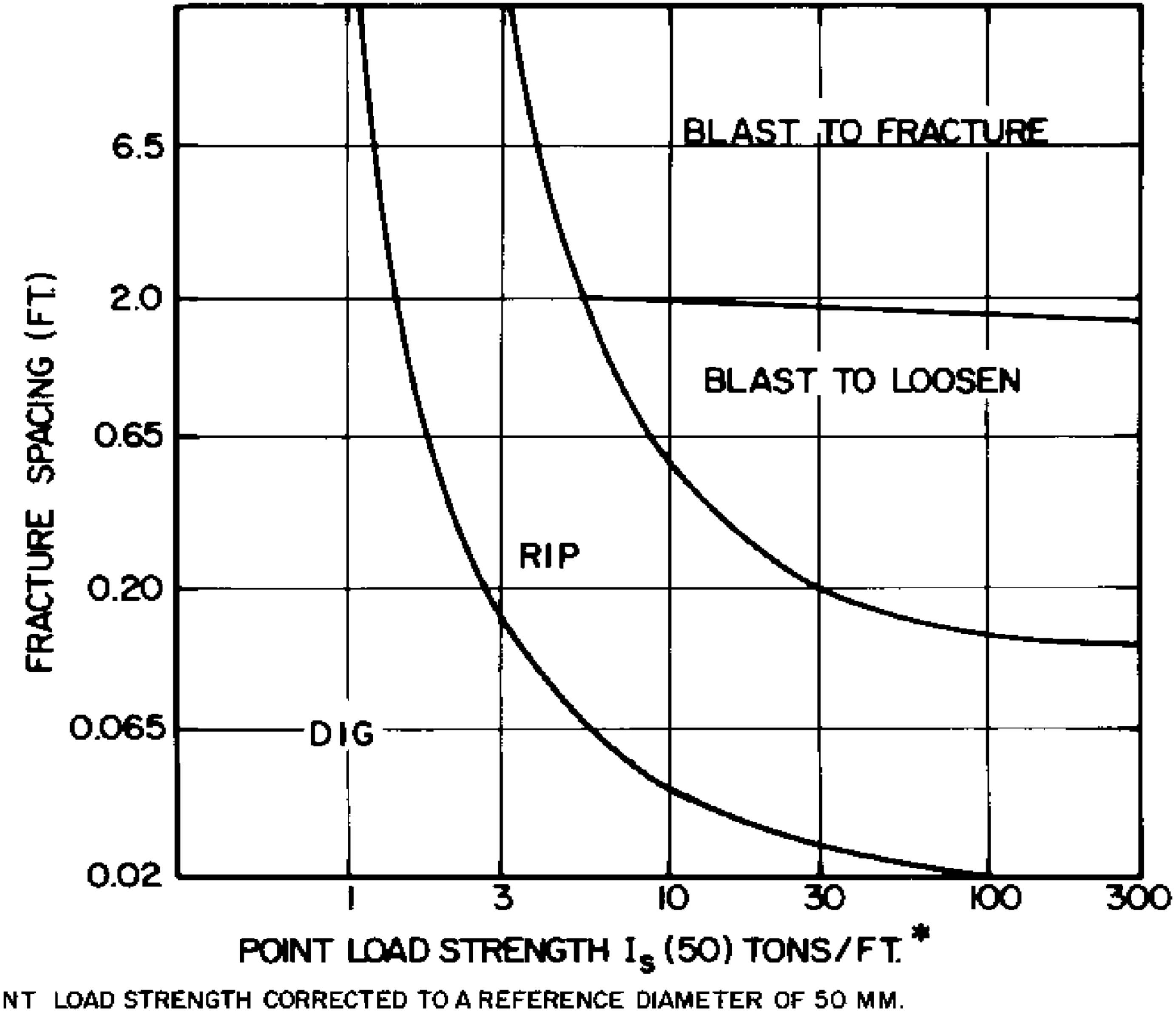


FIGURE 9
Suggested Guide for Ease of Excavation

Conventional Earthwork

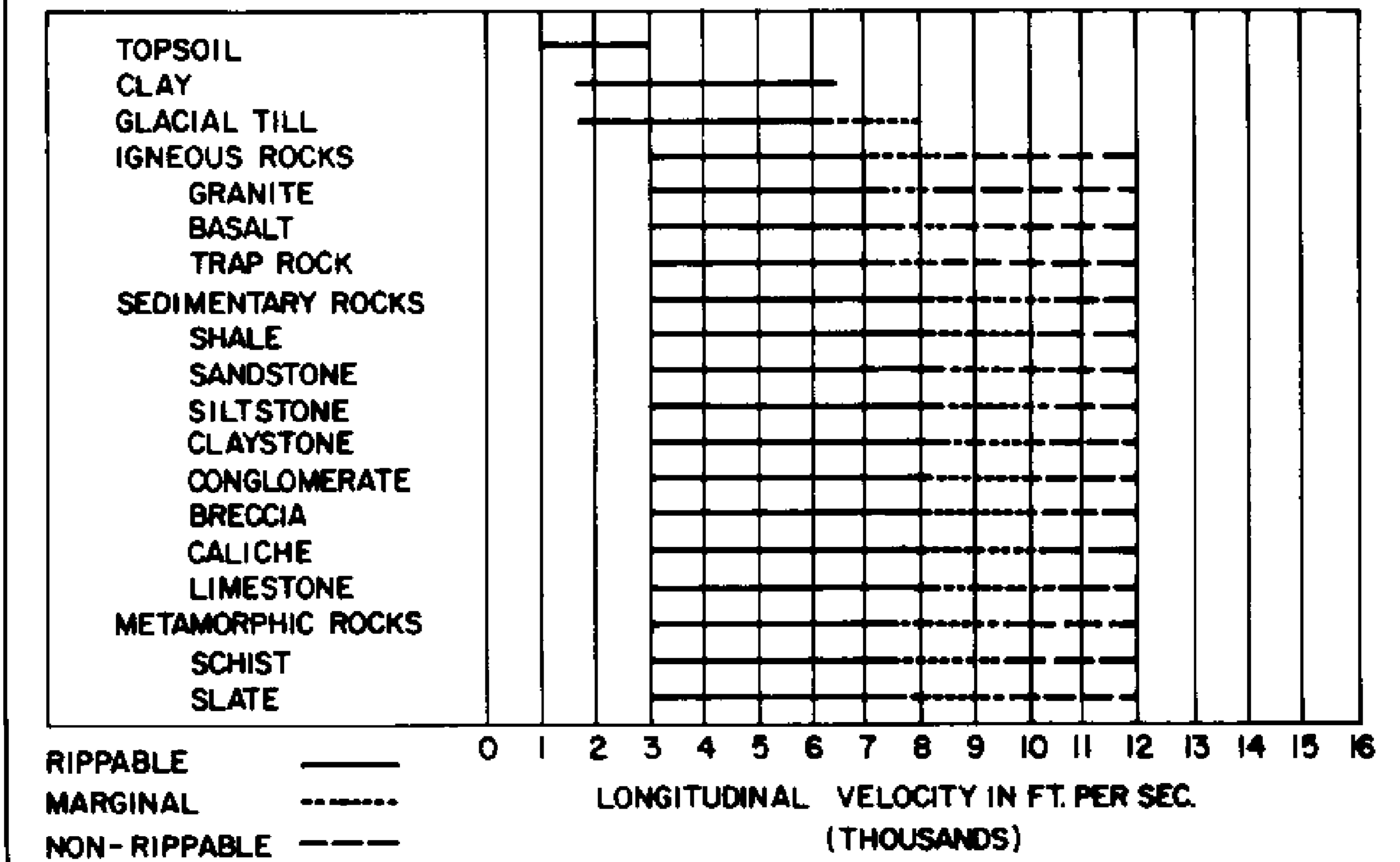


FIGURE 8
Rippability of Subsurface Materials Related to Longitudinal Seismic Velocity for a Heavy Duty Ripper (Tractor-Mounted)

Conventional Earthwork

- The method of excavation can determine the way in which the job is paid for
  - Unclassified: contractor receives the same unit price for all materials
  - Classified: price depends on ease of excavation
  - Common: soil
- Rock
  - To avoid problems, specifications for a classified excavation need to clearly define each category
- Transport and Placement
  - Scrapers can be used for moderate length hauls, but cannot be used to haul over public highways
  - Dump trucks can be used when the soil is loaded with loaders; they usually can move over public highways, and are faster than scrapers
  - For long distance hauling, wagons can be used; these are towed by semi tractors and are self-unloading when the site is reached
  - Conveyor belts are used on very large jobs and the soil is transported to a confined area

Conventional Earthwork

- Transport and Placement
  - Once soil arrives on site, it must be laid out in thin horizontal lifts
  - Each lift must be moisture-conditioned and compacted before the next lift is placed
  - If compaction specifications require it, additional moisture needs to be added, usually by water trucks spraying each lift
  - Clay soils can be especially difficult to mix soil and water
- Compaction
  - Compaction equipment is used to compress the soil into a smaller volume, increasing the dry unit weight and improving its engineering properties
  - Soil compaction results in the reduction of the volume of the air in the soil
  - Early compaction equipment included animals, logs used as rammers, and rollers hauled by horses or steam tractors
  - Although construction equipment does some compaction while going over the site, it is generally not enough

Overview of Compaction

- Definition
  - The densification of soil by removal of air, and the rearrangement/reorientation of the particles
- Purpose
  - To increase the load bearing capacity of the soil
  - To reduce settlement
- Early compaction equipment included animals, logs used as rammers, and rollers hauled by horses or steam tractors
- Although construction equipment does some compaction while going over the site, it is generally not enough

Basic Procedure

- Once soil arrives on site, it must be laid out in thin horizontal layers (lifts)
- Each lift must be moisture-conditioned and compacted before the next lift is placed
- If compaction specifications require it, additional moisture needs to be added, usually by water trucks spraying each lift
- Clay soils can be especially difficult to mix soil and water

Methods of compaction

- Pressure: contact pressure between equipment and ground compacts soil; sheepsfoot roller has a contact of pressure of around 3500 kPa (500 psi)
- Impact: blows to the soil give a very high pressure in a short period of time; repeated rapidly, this can induce compaction
- Vibration: Vibratory compaction rearranges the soil particles, thus compacting them. Uses frequencies from 1000-3500 RPM
- Manipulation: Shearing forces can also compact. Also called kneading. Can be detrimental with very wet fills.

TABLE 5
Compaction Equipment and Methods

Equipment Type	Applicability	Requirements for Compaction of 95 to 100 Percent Standard Proctor Maximum Density			Possible Variations in Equipment
		Compacted Lift Thickness, in.	Passes or Coverages	Dimensions and Weight of Equipment	
Sheepsfoot Rollers	For fine-grained soils or dirty coarse-grained soils with more than 20 percent passing No. 200 sieve. Not suitable for clean coarse-grained soils. Particularly appropriate for compaction of impervious zone for earth dam or linings where bonding of lifts is important.	6	4 to 6 passes for fine-grained soil. 6 to 8 passes for coarse-grained soil.	Soil Type / Foot Contact Area sq. ft. / Foot Contact Pressures psi Fine-grained soil PI>30 / 5 to 12 / 250 to 500 Fine-grained soil PI<30 / 7 to 14 / 200 to 400 Coarse-grained soil / 10 to 14 / 150 to 250 Efficient compaction of soils wet of optimum requires less contact pressure than the same soils at lower moisture contents.	For earth dam, highway and airfield work, articulated self propelled rollers are commonly used. For smaller projects, towed 40 to 60 inch drums are used. Foot contact pressure should be regulated so as to avoid shearing the soil on the third or fourth pass.
Rubber Tire Roller	For clean, coarse-grained soils with 4 to 8 percent passing the No. 200 sieve.	10	3 to 5 coverages	Tire inflation pressures of 35 to 130 psi for clean granular material or base course and subgrade compaction. Wheel load 18,000 to 25,000 lbs.	Wide variety of rubber tire compaction equipment is available. For cohesive soils, light-wheel loads, such as provided by wobble-wheel equipment, may be substituted for heavy-wheel load if lift thickness is decreased. For granular soils, large-size tires are desirable to avoid shear and rutting.
Do.......	For fine-grained soils or well graded, dirty coarse-grained soils with more than 8 percent passing the No. 200 sieve.	6 to 8	4 to 6 coverages	Tire inflation pressures in excess of 65 psi, for fine-grained soils of high plasticity. For uniform clean sands or silty fine sands, use large size tires with pressures of 40 to 50 psi.	
Smooth Wheel Rollers	Appropriate for subgrade or base course compaction of well-graded sand-gravel mixtures.	8 to 12	4 coverages	Tandem type rollers for base course or subgrade compaction 10 to 15 ton weight, 300 to 500 lbs per lineal in. of width of rear roller.	3-wheel rollers obtainable in wide range of sizes. 2-wheel tandem rollers are availabe in the range of 1 to 20 ton weight. 3-Axle tandem rollers are generally used in the range of 10 to 20 tons weight. Very heavy rollers are used for proof rolling of subgrade or base course.
Do....	May be used for fine-grained soils other than in earth dams. Not suitable for clean well-graded sands or silty uniform sands.	6 to 8	6 coverages	3-wheel roller for compaction of fine-grained soil; weights from 5 to 6 tons for materials of low plasticity to 10 tons for materials of high plasticity.	

TABLE 5 (continued)
Compaction Equipment and Methods

Equipment Type	Applicability	Requirements for Compaction of 95 to 100 Percent Standard Proctor Maximum Density			Possible Variations in Equipment
		Compacted Lift Thickness, in.	Passes or Coverages	Dimensions and Weight of Equipment	
Vibrating Sheetsfoot Rollers	For coarse-grained soils sand-gravel mixtures	8 to 12	3 to 5	1 to 20 tons ballasted weight. Dynamic force up to 20 tons.	May have either fixed or variable cyclic frequency.
Vibrating Smooth Drum Rollers	For coarse-grained soils sand-gravel mixtures - rock fills	6 to 12 (soil) to 36 (rock)	3 to 5 4 to 6	- do -	- do -
Vibrating Baseplate Compactors	For coarse-grained soils with less than about 12 percent passing No. 200 sieve. Best suited for materials with 4 to 8 percent passing No. 200 sieve, placed thoroughly wet.	8 to 10	3 coverages	Single pads or plates should weigh no less than 200 lbs. May be used in tandem where working space is available. For clean coarse-grained soil, vibration frequency should be no less than 1,600 cycles per minute.	Vibrating pads or plates are available, hand-propelled, single or in gangs, with width of coverage from 1-1/2 to 15 ft. Various types of vibrating-drum equipment should be considered for compaction in large areas.
Crawler Tractor	Best suited for coarse-grained soils with less than 4 to 8 percent passing No. 200 sieve, placed thoroughly wet.	6 to 10	3 to 4 coverages	Vehicle with "Standard" tracks having contact pressure not less than 10 psi.	Tractor weight up to 85 tons.
Power Tamper or Rammer	For difficult access, trench backfill. Suitable for all inorganic soils.	4 to 6 in. for silt or clay, 6 in. for coarse-grained soils.	2 coverages	30-lb minimum weight. Considerable range is tolerable, depending on materials and conditions.	Weights up to 250 lbs., foot diameter 4 to 10 in.

Sheepsfoot Roller

- Developed by a Los Angeles contractor after a flock of sheep compacted a roadway
- As rolled, projecting feet by a combination of tamping and kneading
- Pressures vary from 100 – 500 psi (700 – 3500 kPa)
- Will compact layers on the order of 150 mm (6") in 4-6 passes
- Most suitable for fine grained soils (clays and silts)

Pneumatic Tire and Vibratory Rollers

- Pneumatic Tire Rollers
  - Compact primarily by kneading
  - Usually outfitted with a weight box for additional compression
  - Small equipment will compact 150 mm (6") layers
  - Large equipment will compact 300 mm (12") layers
  - Useful in a wide variety of soils
- Vibratory Compactors
  - Compact soils by densify soils through shaking
  - Attempt to find the resonant frequency of soils with units that can vary the frequency
  - Can be mounted on smooth drum, sheepsfoot, and pneumatic tire units
  - The finer the material, the thickness of the layer to be compacted can be reduced
  - Best used in granular soils but applicable to all soil types

Smooth Drum and Impact Rollers

- Smooth Drum Rollers
  - Misnamed "steamrollers"; no longer powered by steam
  - Not well suited for compacting fill
  - Can be utilized for compacting limited thicknesses of material, such as highway and airfield (paving) work
  - Provides a smooth surface so that rain will run off of the worksite

- Impact Rollers
  - A conventional tractor pulls a heavy prism-shaped mass, consisting of steel or concrete.
  - The impact generated by the rotation of the heavy mass (up to 50 tons) transfers sufficient energy to achieve medium compaction to a depth of several meters.

Soil Classification and Compaction Requirements

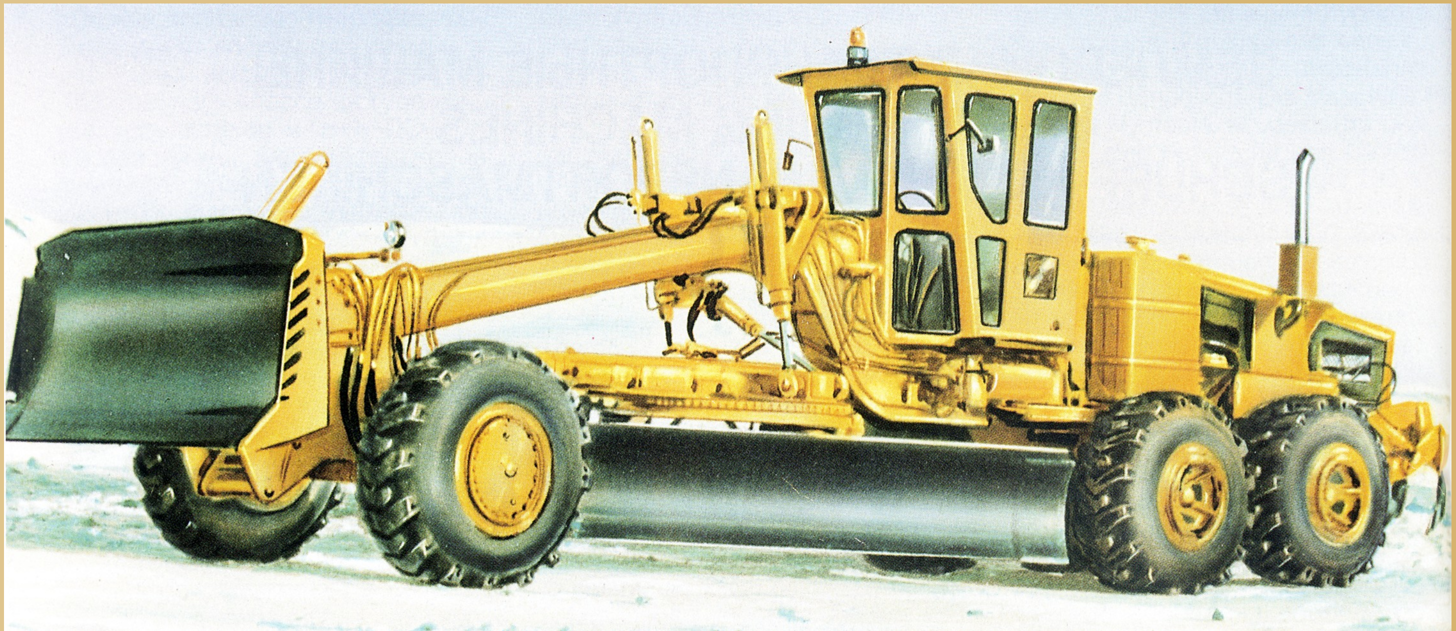
Soil Classification						Sheepsfoot, Standard With Ballast (Towed by Dozer) Single Drum: 4 ft Dual Drum: 8 ft			Self-Propelled Vibratory Roller Rolling Width = 7 ft		
Major Divison		Symbol	Description	Value as a Base, Subbase, or Subgrade	Potential Frost Action	Compacted Lift Thickness (Inches)	Rolling Speed (mph) (vpm)	Number of Passes	Compacted Lift Thickness (Inches)	Rolling Speed (mph) (vpm)	Number of Passes
Coarse-grained soils with 50% or more larger than No 200 sieve opening	Gravel and/or gravelly soils	GW	Well-graded gravels or gravel-sand mixture with 5% or less amount of fines	Good to excellent for subbase and subgrade. Fair to good for **base.**	None to very slight	*	N/A	N/A	Best 18	4 mph 1,400 vpm or more	8
		GP	Poorly graded gravels or gravel-sand mixture with little or no fines	Fair to good for **all.**	None to very slight	*	N/A	N/A	Best 18	4 mph 1,400 vpm or more	8
		GM	Silty gravel, gravel-sand-silt mixtures	**Not** suitable for **base,** 15% or less less of fines with PI of 5 or less. 50% or less of fines for subbase and subgrade.	Slight to medium	*	N/A	N/A	12	4 mph 1,100 vpm	6
		GC	Clayey gravel, gravel-sand-clay mixture	**Not** suitable for **base,** 15% or less of fines with PI of 5 or less. Poor to good for subbase and subgrade.	Slight to medium	6	3	10	12	4 mph 700 vpm to none	6
	Sand and/or sandy soils	SW	Well-graded sands or gravelly sand mixture with 5% or less amount of fines	**Poor** for **base.** Fair to good for subbase and subgrade.	None to very slight	*	N/A	N/A	Best 18	4 mph 1,400 vpm or more	8
		SP	Poorly graded sands or gravelly sand mixture with 5% or less amount of fines	Poor to not suitable for **base.** Poor to fair for subbase and subgrade.	None to very slight	*	N/A	N/A	Best 18	4 mph 1,400 vpm or more	8
		SM	Silty sands, sand-silt mixture	**Not** suitable for **base.** Poor to good for subbase and subgrade.	Slight to high	*	N/A	N/A	12	4 mph 1,100 vpm	6
		SC	Clayey sands, sand-clay mixture	**Not** suitable for **base.** Poor to fair for subbase and subgrade.	Slight to high	Best 6	3	10	12	3 mph 700 vpm to none	7
Fine-grained soils with more than 50% smaller than No 200 sieve opening	Silt and clays with LL < 50	ML	Inorganic silt, silty fine sands	**Not** suitable for **base** or **subbase.** Poor to fair for subgrade.	Medium to very high	6	3	10	8	3 mph 700 vpm to none	7
		CL	Inorganic clay of low to medium plasticity, lean clays	**Not** suitable for **base** or **subbase.** Poor to fair for subgrade.	Medium to high	Best 6	2	12	8	3 mph 700 vpm to none	7
		OL	Organic silt and organic silt-clay of low plasticity	**Not** suitable for **base** or **subbase.** Poor to very poor for subgrade.	Medium to high	6	2	12	*	N/A	N/A
	Silt and clays with LL > 50	MH	Inorganic silt micaeous or diatomaceous silty soil	**Not** suitable for **base** or **subbase.** Poor to fair for subgrade.	Medium to very high	6	2	12	*	N/A	N/A
		CH	Inorganic clay of high plasticity, fatty clays	**Not** suitable for **base** or **subbase.** Poor to fair for subgrade.	Medium	Best 6	2	14	*	N/A	N/A
		OH	Organic clay of medium to high plasticity	**Not** suitable for **base** or **subbase.** Poor to very poor for subgrade.	Medium	6	2	14	*	N/A	N/A

Symbol	Compactor, High Speed, Tamping Foot, Self-Propelled, BOMAG Model Rolling Width = 5 ft (Not Recommended for Finish Grade)			13-Wheel Pneumatic Compactor With Ballast (Wheel Towed) 100 psi Rolling Width = 7 ft			50-Ton Pneumatic Compactor With Ballast (Wheel Towed) 100 psi Rolling Width = 7 ft			9-Wheel Pneumatic, Self-Propelled With Ballast 100 psi Rolling Width = 6 ft			Vibratory Roller (Wheel Towed) Rolling Width = 4 ft		
	Compacted Lift Thickness (Inches)	Rolling Speed (mph) (vpm)	Number of Passes	Compacted Lift Thickness (Inches)	Rolling Speed (mph)	Number of Passes	Compacted Lift Thickness (Inches)	Rolling Speed (mph)	Number of Passes	Compacted Lift Thickness (Inches)	Rolling Speed (mph)	Number of Passes	Compacted Lift Thickness (Inches)	Rolling Speed (mph) (vpm)	Number of Passes
GW	12	10	5	6	5	10	18	5	10	6	6	5	12	4 mph 1,400 vpm or more	8
GP	12	10	5	6	5	10	18	5	10	6	6	6	12	4 mph 1,400 vpm or more	8
GM	9	10	6	6	4	10	12	4	8	6	6	7	9	4 mph 1,100 vpm	8
GC	9	8	7	6	4	10	12	3	8	6	5	7	9	4 mph 700 vpm to none	9
SW	12	10	5	6	5	10	18	5	9	6	6	7	12	4 mph 1,400 vpm or more	8
SP	12	10	5	6	5	10	18	5	9	6	6	7	12	4 mph 1,400 vpm or more	8
SM	9	10	6	6	4	10	12	4	7	6	6	8	9	4 mph 1,100 vpm	6
SC	9	8	6	6	3	12	12	3	7	6	5	8	9	3 mph 700 vpm to none	10
ML	6	8	5	4	3	7	9	4	6	4	4	6	6	3 mph 700 vpm to none	10
CL	6	4	5	4	3	7	9	3	6	4	4	6	6	3 mph 700 vpm to none	10
OL	6	4	5	4	3	7	9	3	6	4	4	6	*	N/A	N/A
MH	6	4	6	4	3	8	9	3	6	4	4	6	*	N/A	N/A
CH	6	3	6	4	2	9	9	3	7	4	3	6	*	N/A	N/A
OH	6	3	6	4	2	9	9	3	7	4	3	6	*	N/A	N/A

* NOT recommended

Earthwork After Compaction

- Fine Grading
  - Once all lifts are in place, rough grading is done
  - Fine grading consists of carefully trimming and filling to produce the desired configuration
  - Motor grader or blade is often used for this purpose



Proctor Compaction Test

- In the laboratory compaction test, a soil at a known water content is placed in a specified manner in a mould of given dimensions and subjected to a compactive effort of controlled magnitude after which the resulting unit weight of the soil is determined.
- The procedure is repeated at various water contents until a relation between water content and unit weight of the soil is established.

- **Maximum dry density** ($\gamma_{d\text{-}max}$) is the dry density corresponding to the peak of the compaction curve for a given type and amount of input energy. Note from Figure 5-31, that the SPC $\gamma_{d\text{-}max}$ is less than the MPC $\gamma_{d\text{-}max}$. Note from Table 5-13 that although the type of energy (impact) is the same for both SPC and MPC, the amount of energy in the MPC test is 4.5 times that of the SPC test.

- **Optimum moisture content** (w_{opt}) is the compaction water content at which the soil attains its maximum dry density for a given input energy. Note from Figure 5-31, that the SPC w_{opt} is greater than the MPC w_{opt}.

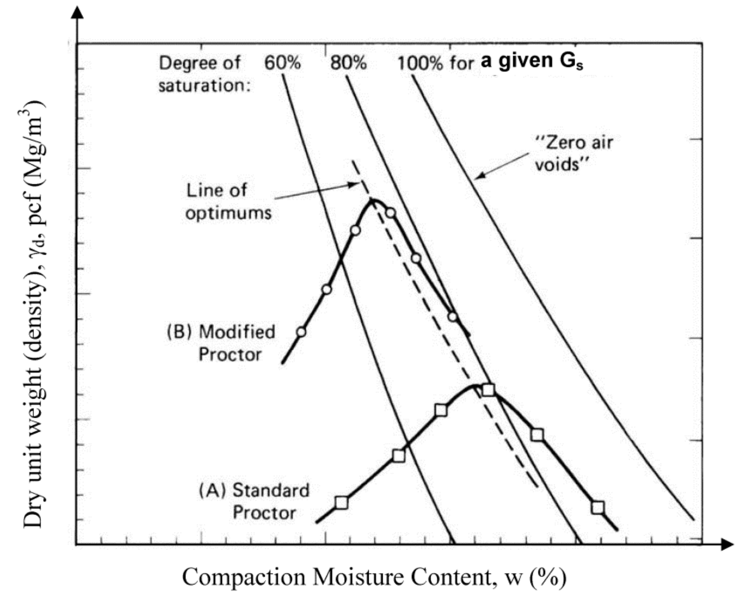


Figure 5-31. Compaction curves (after Holtz and Kovacs, 1981).

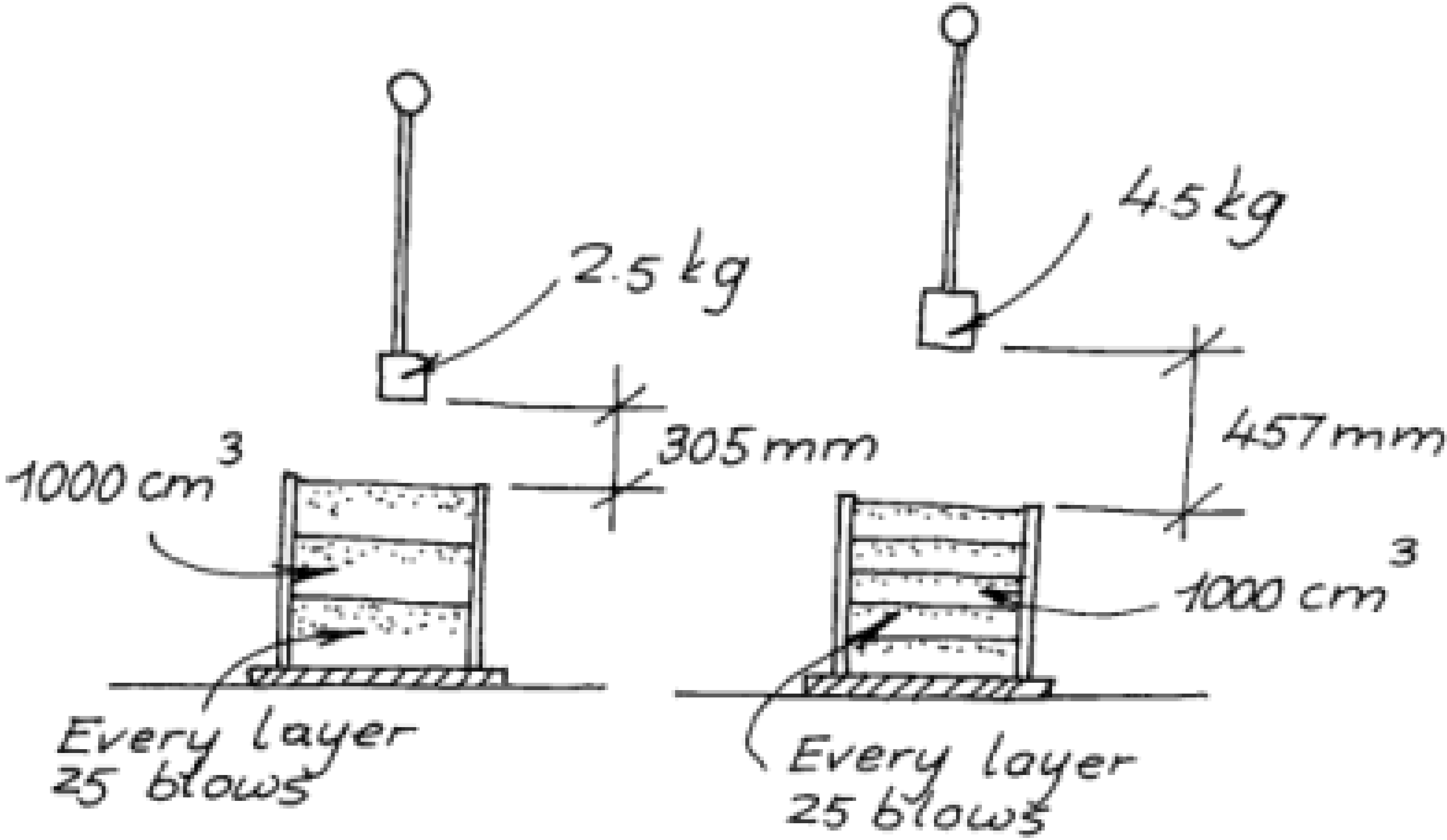
Apparatus

- **Cylindrical, metal moulds**

Rammer

TABLE 8.1 Comparison of Compaction Test Procedures

Designation	*Standard* *ASTM D698*	*Modified* *ASTM D1557*
Mold		
Diameter (in.)	4	4
Height (in.)	4 5/8	4 5/8
Volume (ft^3)	1/30	1/30
Tamper		
Weight (lb)	5.5	10.0
Free drop (in.)	12	18
Face diameter (in.)	2	2
Face area ($in.^2$)	3.1	3.1
Layers		
Number, total	3	5
Surface area, each ($in.^2$)	12.6	12.6
Compacted thickness, each (in.)	1 5/8	1
Effort		
Tamper blows per layer	25	25
$\cancel{(ft\text{-}lb/ft^3)}$ ft-kip/ft^3	12.375	56.250



Standard Proctor Modified Proctor.

Preparation of Samples

- Sample Sizes
  - Soils Passing #4 Sieve
    - Use 4" mould
    - 20 pounds of material required
  - Samples containing gravel
    - Use 6" mould
    - 75 pounds of material required
- Drying
  - Samples should be air dried, or heated not to exceed 60 º C.
- Addition of water
  - To each sample a different amount of water is mixed, corresponding with different water content

Procedure Overview

- Obtain a bulk soil sample
- Add a specified amount of moisture to the sample
- Place some of the prepared sample into the mould until about 40% full
- Compact the soil by applying blows from the rammer

Procedure and Results

Procedure

- Place a second layer into the mould until it is 75% full; compact with blows from rammer
- Place third layer into mould; compact with blows from rammer
- Trim the sample so that its volume is exactly 1/30 ft^3. The unit weight can thus be readily computed
- Perform a moisture (water) content test on a representative portion of the compacted sample
- Repeat procedure three or four times, each with soil at a different moisture content

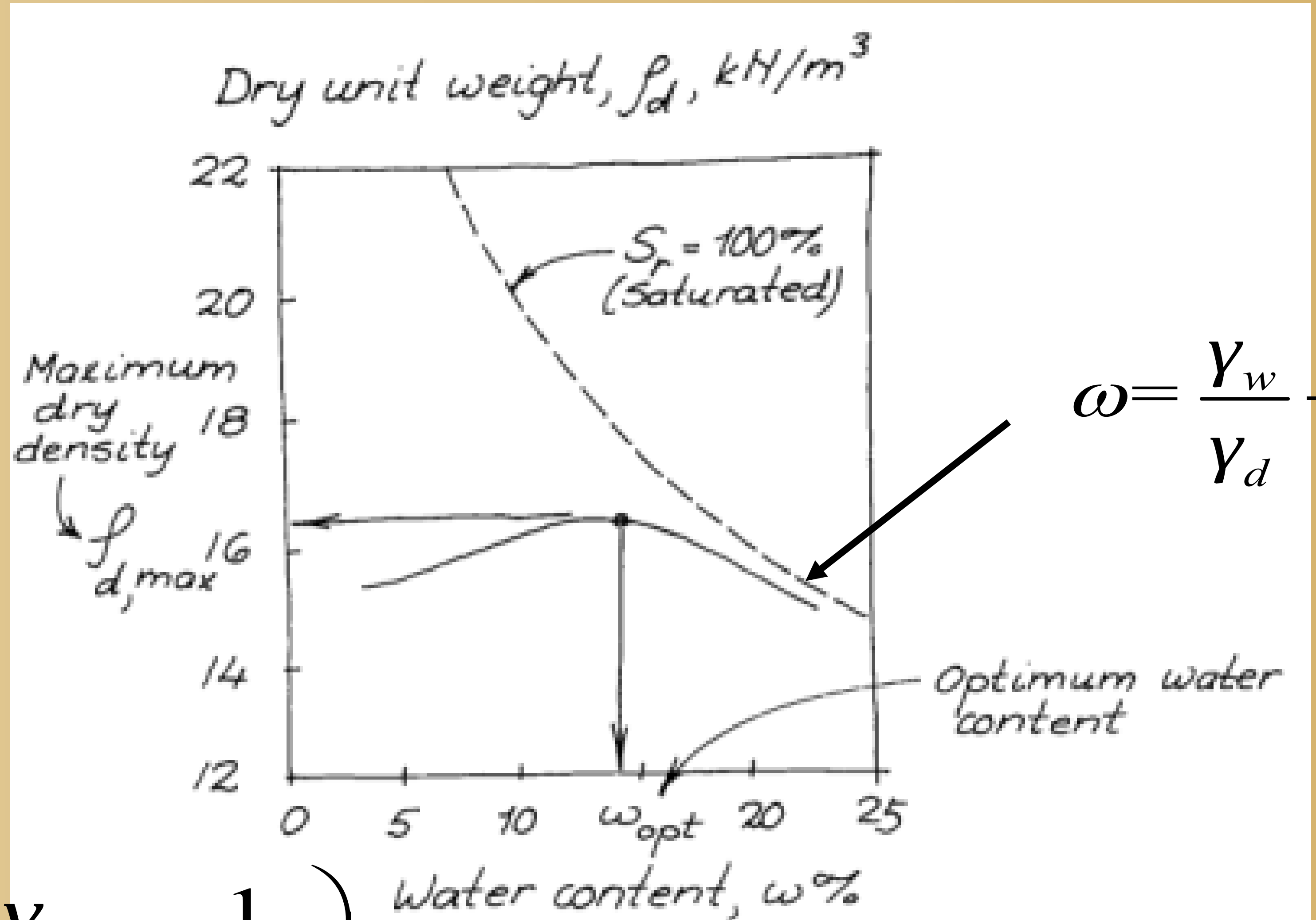
Results

- All quantities obtained for each specimen
    - Weight of mould plus wet soil
    - Inside volume of compaction mould
    - Weight of water content specimen plus tare before and after oven drying
    - Wet and dry unit weight and water content determined for each specimen in same way as with standard water content test

Trimming of Sample

Removal of Soil for Moisture Content Testing

Graphing the Results



$$\omega = \frac{\gamma_w}{\gamma_d} - \frac{1}{G_s}$$

$$\omega = S\left(\frac{\gamma_w}{\gamma_d} - \frac{1}{G_s}\right)$$

Compaction Example

- Given
  - Compaction Tests with results as shown below
  - Compaction mould mass = 2.031 kg
  - Volume of mould = 9.44×10^{-4} m^3
- Find
  - Water content and dry unit weight for each point and plot the results
  - Draw the compaction curve and determine the maximum dry density and corresponding water content

Data Point	1	2	3	4	5
Mass of Compacted Soil and Mould, kg	3.7620	3.9210	4.0340	4.0910	4.0400
Mass of Can, g	20.11	21.24	19.81	20.30	20.99
Mass of Can and Wet Soil, g	240.85	227.03	263.45	267.01	240.29
Mass of Can and Dry Soil, g	231.32	212.65	241.14	238.81	209.33

Note: Lower three lines are results of water content test

Compaction Example

- Example Calculations for Point 1
  - Wet unit weight of soil in mould = (3.762 kg-2.031 kg)(9.81 m/sec^2)/9.44 x 10-4 m^3 = 17,990 N/m^3 = 17.98 kN/m^3
  - Water content = (240.85 g – 231.32 g)/(231.32 g – 20.11 g) = 0.045 = 4.51%
  - Dry unit weight of soil in mould = 17.99/(1 + 0.045) = 17.21 kN/m^3

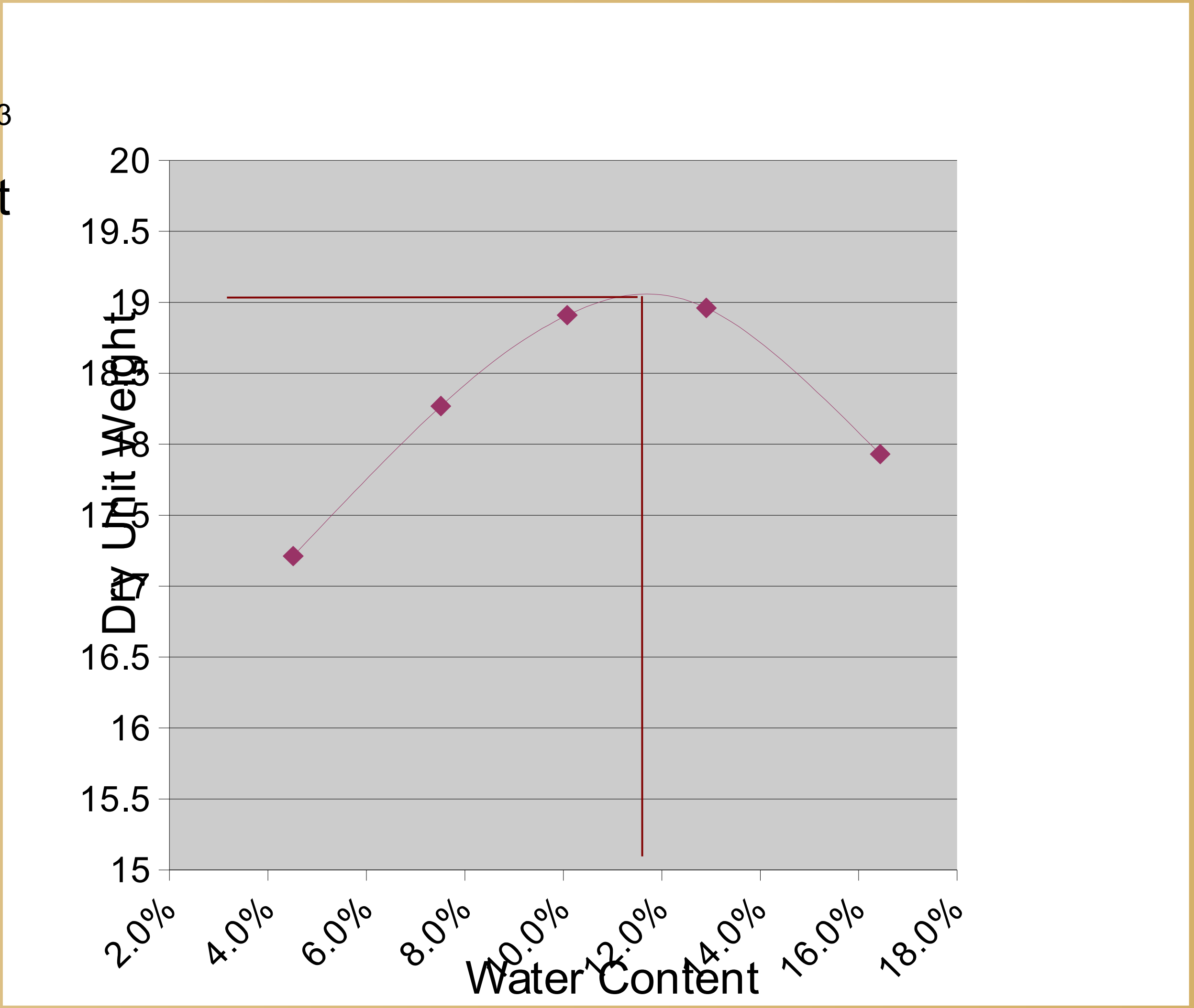
Compaction Example

- Results for all Data Points

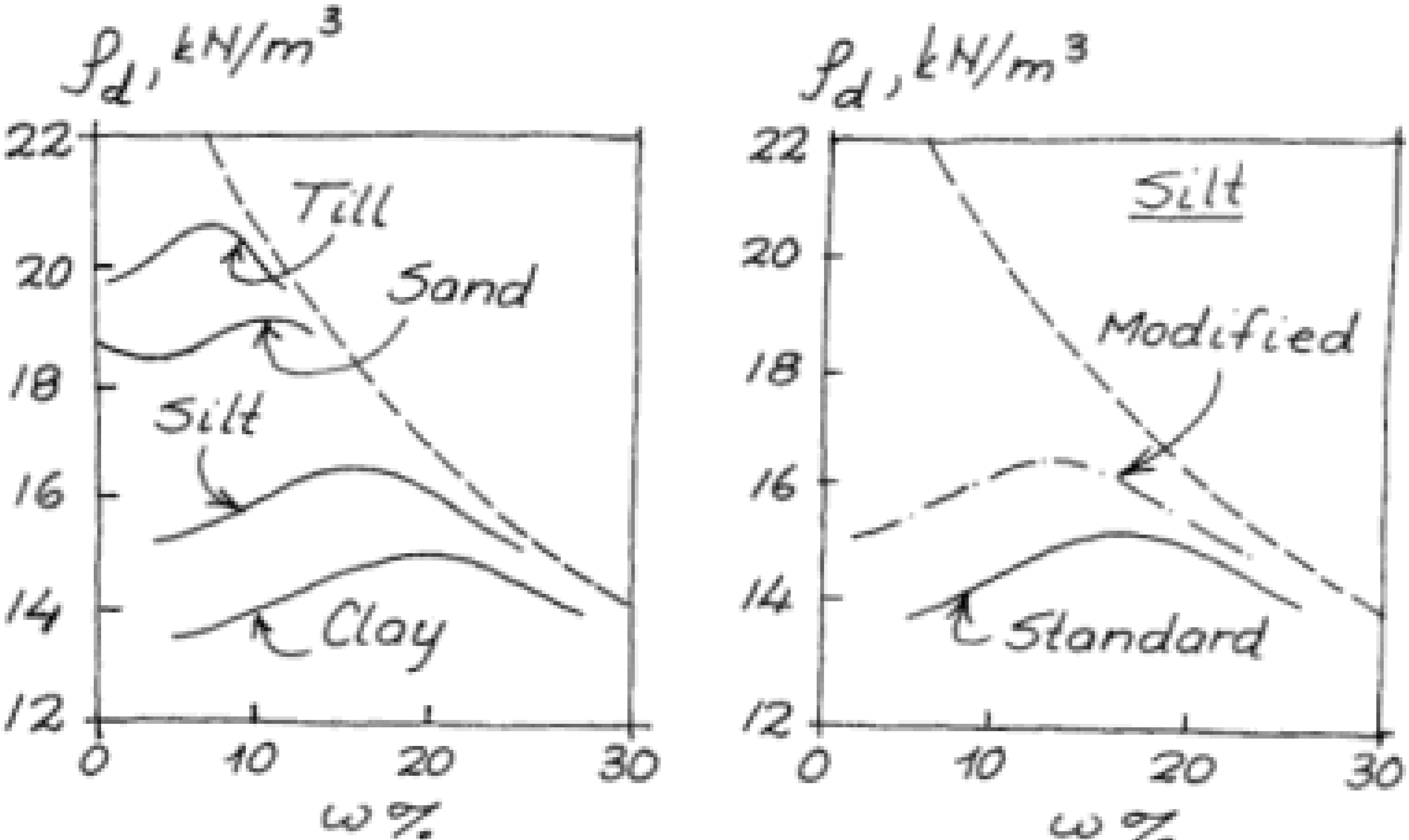
Data Point	1	2	3	4	5
Mass of Compacted Soil and Mould, kg	3.7620	3.9210	4.0340	4.0910	4.0400
Mass of Can, g	20.11	21.24	19.81	20.30	20.99
Mass of Can and Wet Soil, g	240.85	227.03	263.45	267.01	240.29
Mass of Can and Dry Soil, g	231.32	212.65	241.14	238.81	209.33
Wet Unit Weight, kN/cu. m.	17.99	19.64	20.82	21.41	20.88
Water Content	4.51%	7.51%	10.08%	12.91%	16.44%
Dry Unit Weight, kN/cu. m.	17.21	18.27	18.91	18.96	17.93

Compaction Example

- Plot of Results
  - Maximum Dry Density = 19 kN/m^3
  - Moisture content at maximum dry density = 11.8%

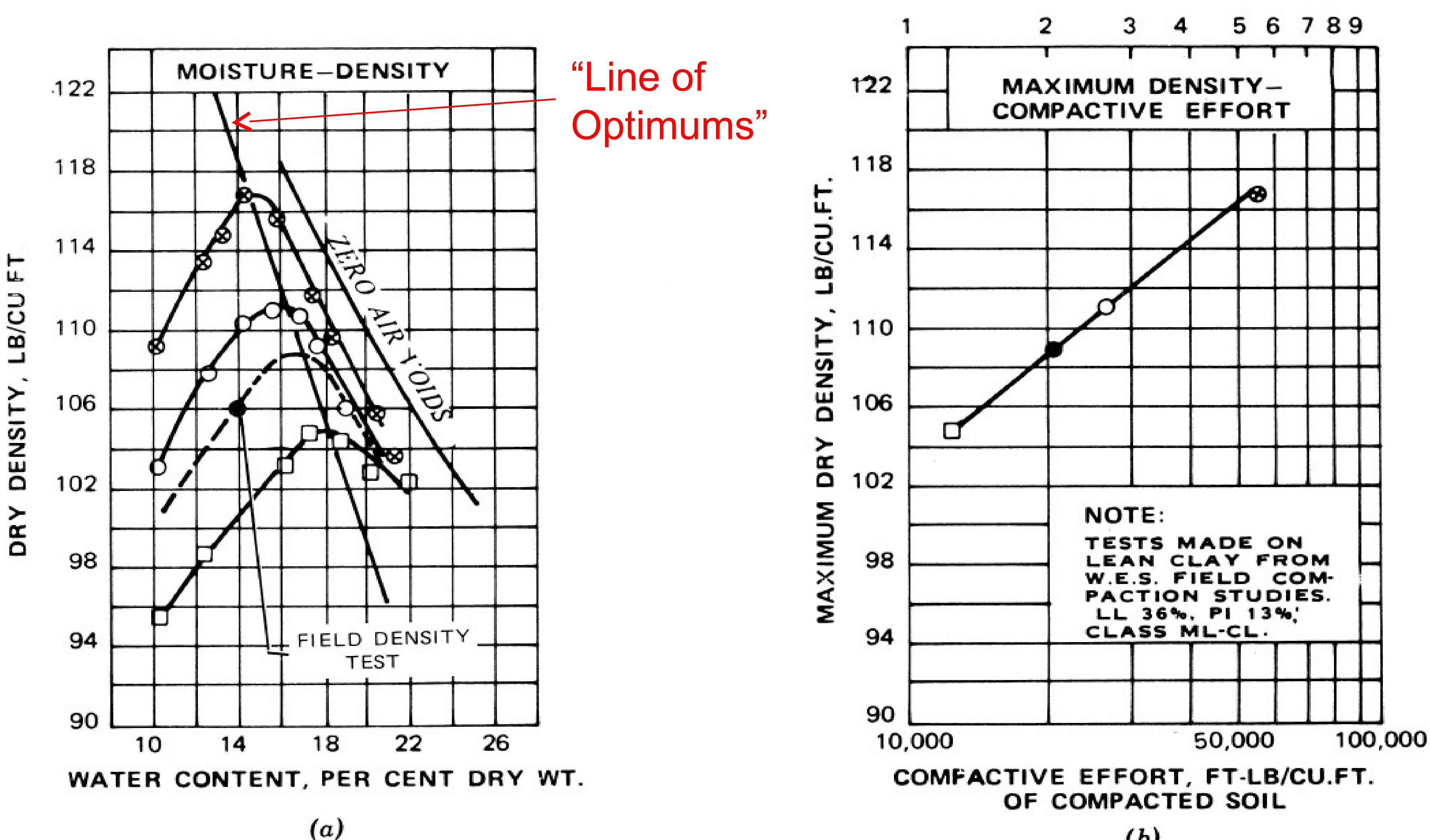


Soil Type and Compaction Effort Effects



Changes in Compactive Energy to Alter a Field Compaction Procedure

	LAYERS	BLOWS PER LAYER	WT. OF HAMMER	DROP IN INCHES	COMPACTIVE EFFORT FT-LB/CU FT
⊗	5	55	10 LB	18	56,250 ASTM D1557
○	5	26	10 LB	18	26,400
□	5	12	10 LB	18	12,375 ASTM D698



Effect of Changing the Lift Thickness

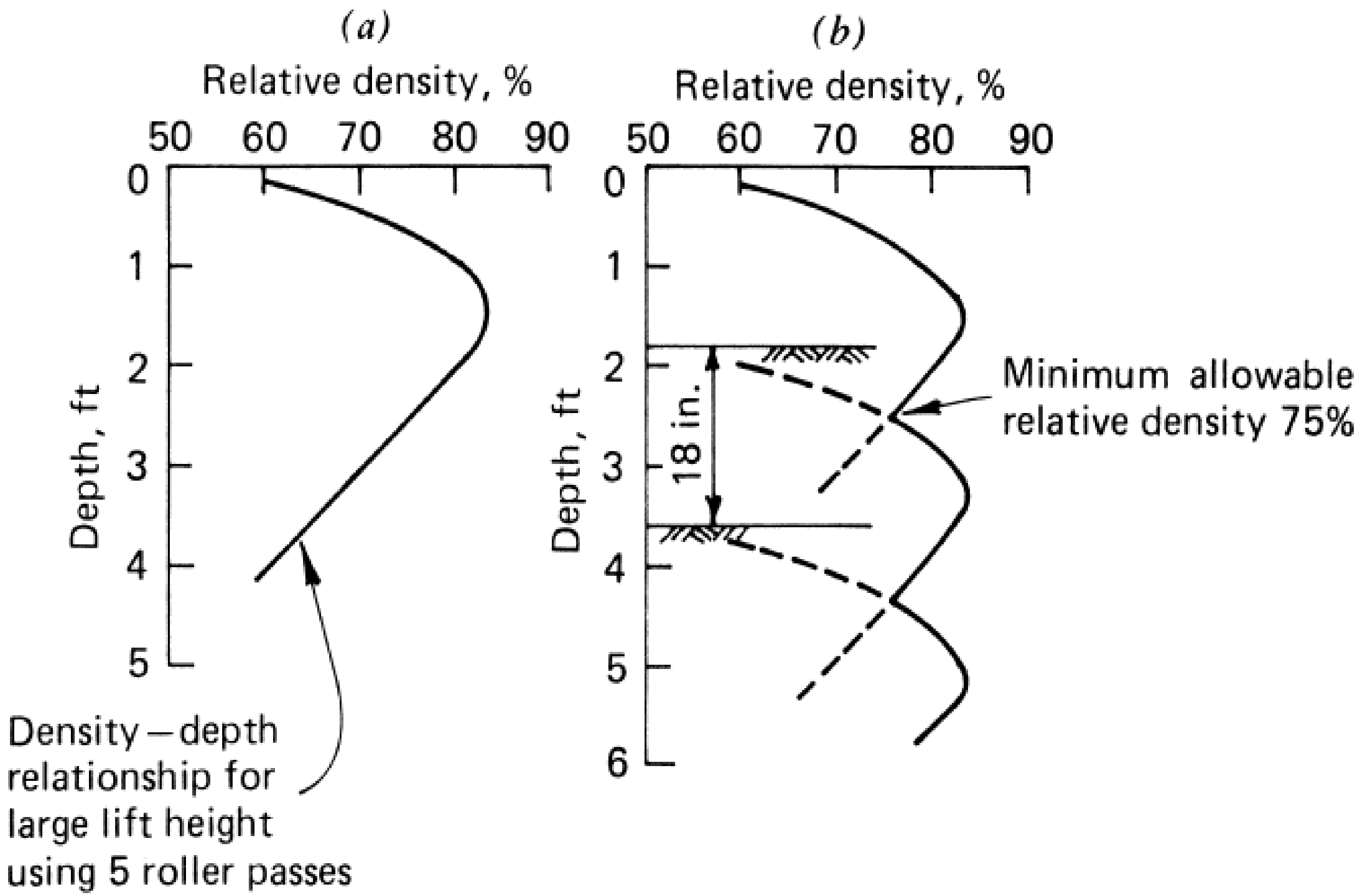


Figure 8.23 Depth–density relationships for compaction of a granular soil by vibratory roller. (After D'Appolonia, Whitman, and D'Appolonia, 1969.) (*a*) Single pass. (*b*) Multiple lifts.

Properties of Compacted Soils

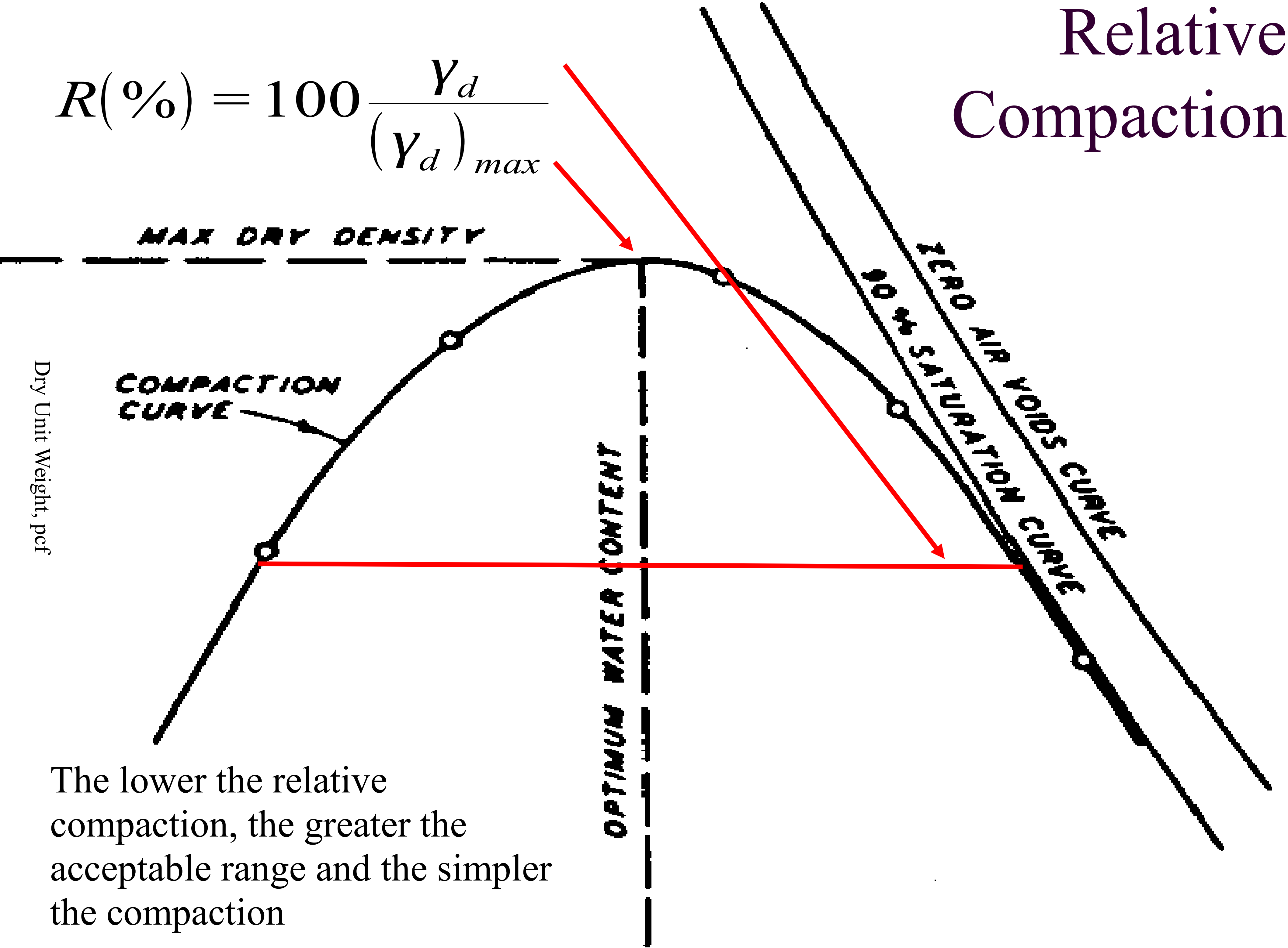
Table 5-15
Average engineering properties of compacted inorganic soils (after USBR, 1960)

USCS	Standard Proctor Compaction (ASTM D 698/AASHTO T 99): Maximum Dry Density, pcf (kN/m^3)	Standard Proctor Compaction (ASTM D 698/AASHTO T 99): Optimum Moisture Content (%)	As Compacted Cohesion, c' psi (kPa)	Saturated Cohesion, c'_{sat} psi (kPa)	Friction Angle, ϕ' (deg)	Void Ratio, e [Permeability, k (ft/yr)]
GW	>119 (>18.7)	<13.3	*	*	>38	* [27,000±13,000]
GP	>110 (>17.3)	<12.4	*	*	>37	* [64,000±34,000]
GM	>114 (>17.9)	<14.5	*	*	>34	* [>0.3]
GC	>115 (>18.1)	<14.7	*	*	>31	* [>0.3]
SW	119±5 (18.7±0.8)	13.3±2.5	5.7±0.6 (39±4)	*	38±1	0.37±* [*]
SP	110±2 (17.3±0.3)	12.4±1.0	3.3±0.9 (23±6)	*	37±1	0.50±0.03 [>15.0]
SM	114±1 (17.9±0.2)	14.5±0.4	7.4±0.9 (51±6)	2.9±1.0 (20±7)	34±1	0.48±0.02 [7.5±4.8]
SM-SC	119±1 (18.7±0.2)	12.8±0.5	7.3±3.1 (50±21)	2.1±0.8 (14±6)	33±4	0.41±0.02 [0.8±0.6]
SC	115±1 (18.1±0.2)	14.7±0.4	10.9±2.2 (75±15)	1.6±0.9 (11±6)	31±4	0.48±0.01 [0.3±0.2]
ML	103±1 (16.2±0.2)	19.2±0.7	9.7±1.5 (67±10)	1.3±* (9±*)	32±2	0.63±0.02 [0.59±0.23]
ML-CL	109±2 (17.1±0.3)	16.8±0.7	9.2±2.4 (63±17)	3.2±* (22±*)	32±3	0.54±0.03 [0.13±0.07]
CL	108±1 (17.0±0.2)	17.3±0.3	12.6±1.5 (87±10)	1.9±0.3 (13±2)	28±2	0.56±0.01 [0.08±0.03]
MH	82±4 (12.9±0.6)	36.3±3.2	10.5±4.3 (72±30)	2.9±1.3 (20±9)	25±3	1.15±0.12 [0.16±0.10]
CH	94±2 (14.8±0.3)	25.5±1.2	14.9±4.9 (103±34)	1.6±0.86 (11±6)	19±5	0.80±0.04 [0.05±0.05]

Notes:
1. The entry ± indicates 90 percent confidence limits of the average value; * denotes insufficient data.
2. For permeability, 1 ft/yr ≈ 10^{-6} cm/sec.
3. All shear strengths, void ratios and permeabilities were determined on samples prepared at Standard Proctor maximum dry density and optimum moisture content.
4. The values of cohesion, c', and friction angle, ϕ', are based on a straight-line Mohr strength envelope on an effective stress basis. The value c'_{sat}, was obtained by saturating the sample and shearing it to failure. Consolidated-undrained (CU) triaxial tests were used to determine all the shear strengths.
5. Since all laboratory tests, except large-sized permeability tests, were performed on the minus No. 4 (4.75 mm) fraction of soil, data on average values for gravels are not available for most properties. However, an indication as to whether these average values will be greater than or less than the average values for the corresponding sand group are given in the table (note entries with > or < symbol).
6. Void ratio was derived from the maximum dry density and specific gravity of the soil.
7. In USCS, there are no upper boundaries of liquid limit of MH and CH soils. The maximum limits for MH and CH soils tested by USBR (1960) were 81% and 88%, respectively. Soils with higher liquid limits than these will have inferior engineering properties.

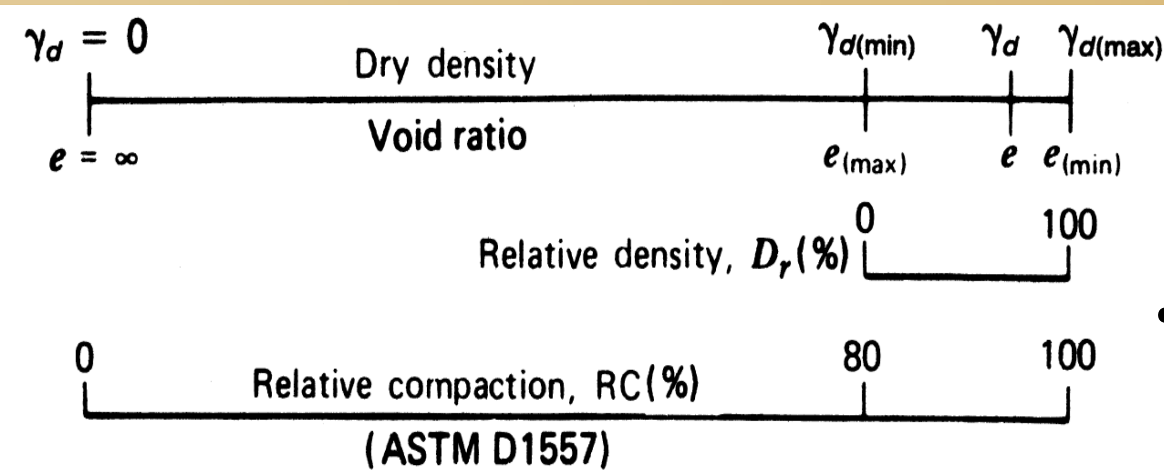
Relative Compaction

$$R(\%) = 100 \frac{\gamma_d}{(\gamma_d)_{max}}$$



The lower the relative compaction, the greater the acceptable range and the simpler the compaction

Relative Compaction and Relative Density



$$D_r = \left[\frac{e_{(max)} - e}{e_{(max)} - e_{(min)}}\right] 100 = \frac{\gamma_{d\,(max)}}{\gamma_d}\left[\frac{\gamma_d - \gamma_{d\,(min)}}{\gamma_{d\,(max)} - \gamma_{d\,(min)}}\right] 100$$

$$RC = \frac{\gamma_d}{\gamma_{d\,(max)}} \times 100$$

- The ratio of the dry unit weight achieved in the field to the maximum dry unit weight achieved in the Proctor (Standard or Modified) test
- Can be used with virtually any type of soil, but really only useful with soils where relative density is relevant
  - Relative Density is generally only used with fines (passing #200 sieve) less than 12%

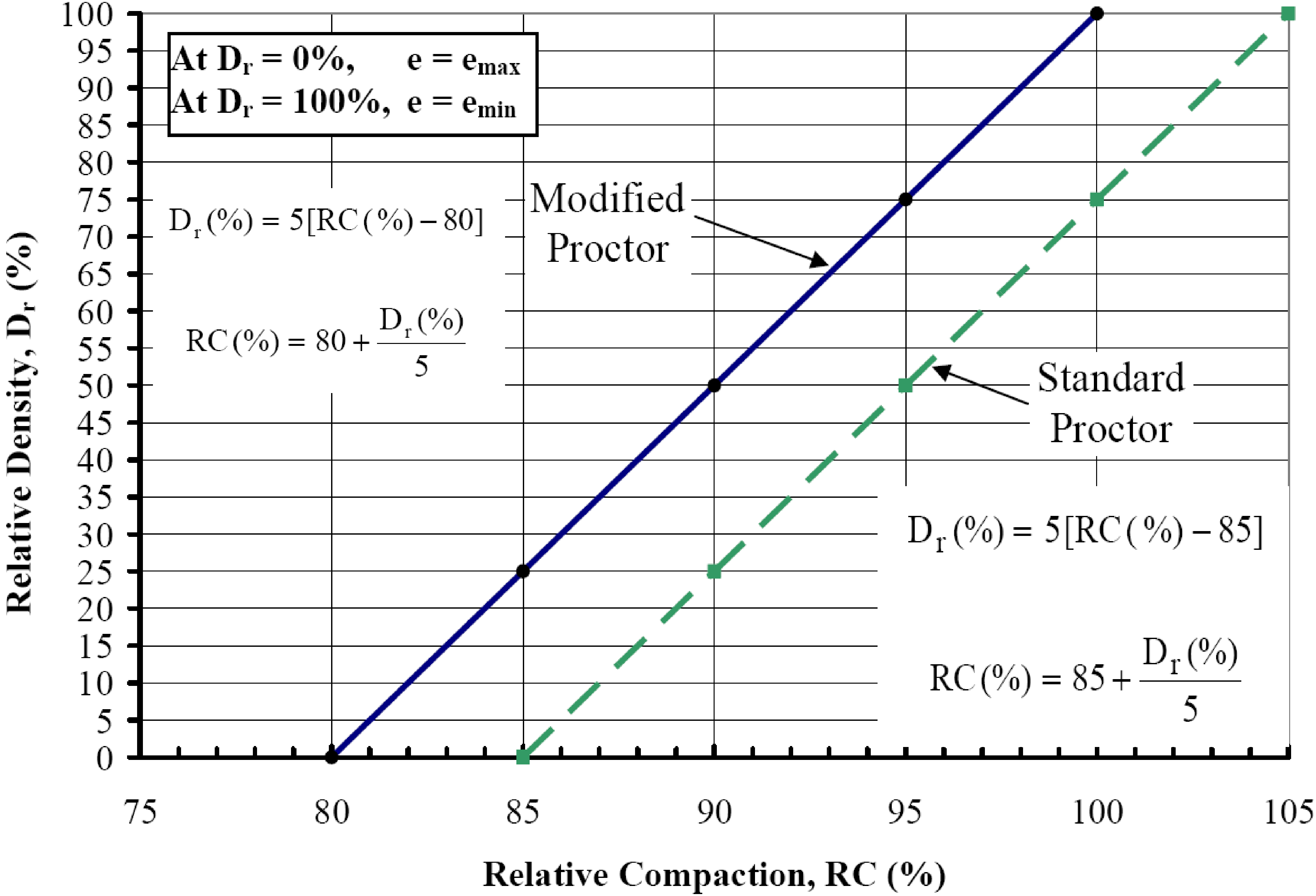
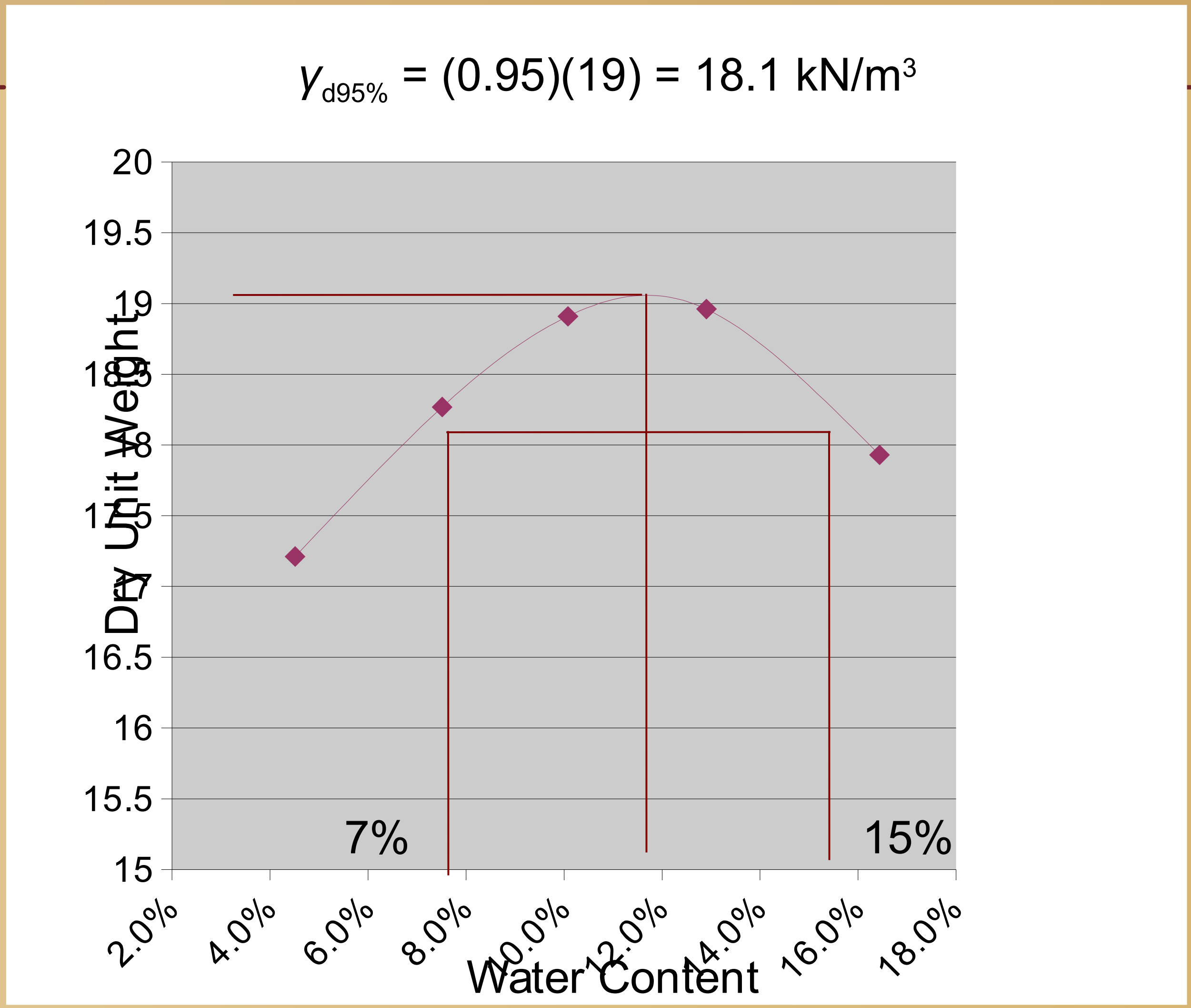


Figure 5-33. Relative density, relative compaction and void ratio concepts.

Relative Compaction Example

- Given
  - Results from Previous Problem
    - Maximum Dry Density = 19 kN/m^3
    - Moisture content at maximum dry density = 11.8%
  - Relative Compaction Requirement = 95%
- Find
  - Maximum Dry Density Requirement at Relative Compaction Requirements
  - Upper and lower bounds of water content
  - “Equivalent” Relative Density using Standard Proctor Test
- Solution
  - $\gamma_{d95\%}$ = (0.95)(19) = 18.1 kN/m^3

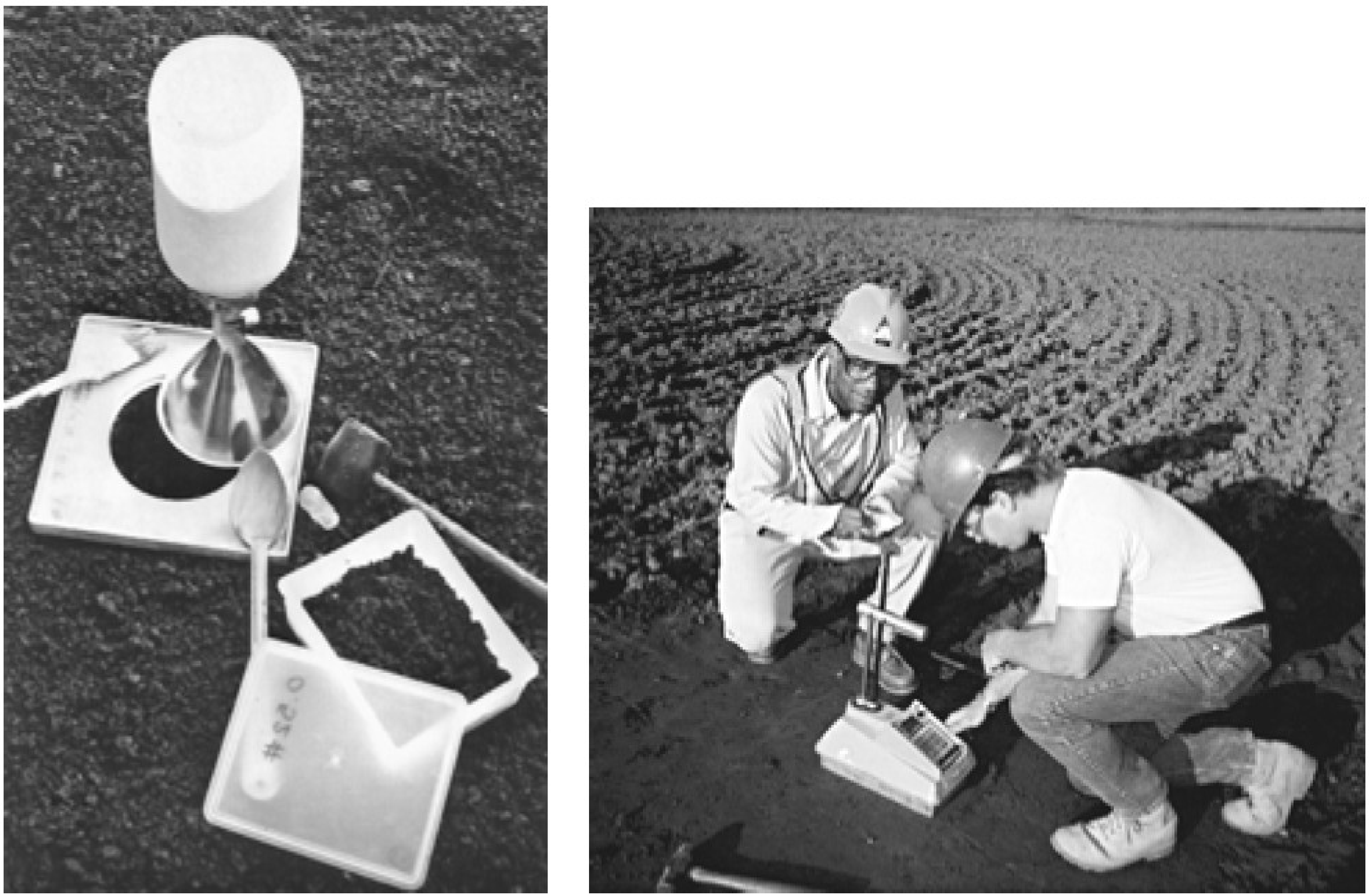
Relative Compaction Example



$$D_r = 5[RC - 85]$$

$$D_r = 5[95 - 85] = 50$$

Field Verification Methods



(a) (b)

Figure 8.19 Common methods of field density testing. (*a*) The sand cone test. (*b*) Nuclear density testing.

Sand Cone Typical Results

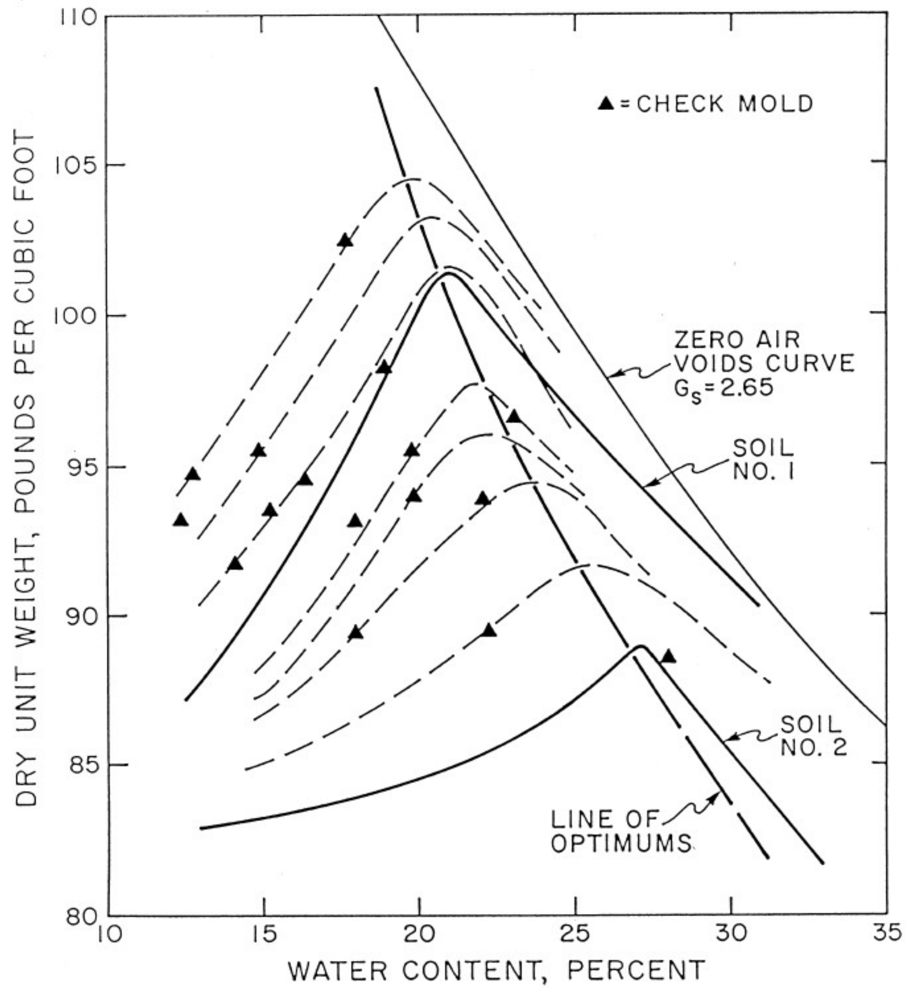


Figure 8.20 Use of check mold points to estimate maximum dry density and optimum water content.

FIELD DENSITY – SAND CONE METHOD

TEST FOR *Site Fill - Test 3*

TEST BY *TKN* DATE *6 JUNE 1994*

SOIL DESCRIPTION *gravelly sand*

TEST LOCATION *see sketch*

FIELD DENSITY		CYLINDER	
1. Wt. Sand + Jar	11.90	1. ASTM Designation	D 1557
2. Wt. Residue + Jar	5.78	2. Wt. Soil + Mold	9.63
3. Wt. Sand Used (1) - (2)	6.12	3. Wt. Mold	9.36
4. Wt. Sand in Cone & Plate	3.41	4. Wt. Soil	4.74
5. Wt. Sand in Hole (3) - (4)	2.71	5. Wet Density, pcf (4) ÷ Vol. Mold	142.2
6. Density of Sand	89.5	6. Moisture Content	6.76
7. Wt. Container + Soil	4.57	7. Dry Density, pcf (5) ÷ [1 + (6)]	133.2
8. Tare Wt. Container	0.16		
9. Wt. Soil (7) - (8)	4.41		
10. Vol. of Hole (5) ÷ (6)	0.0303		
11. Wet Density, pcf (9) ÷ (10)	145.54		
12. Moisture Content, %	6.56		
13. Dry Density, pcf (11) ÷ [1 + (12)]	136.58		
Representative Curve No.	2		
14. Optimum Moisture, %	7.0		
15. Maximum Dry Density, pcf	133.3		
16. Relative Compaction, % (13) ÷ (15)	102.0		

MOISTURE CONTENT

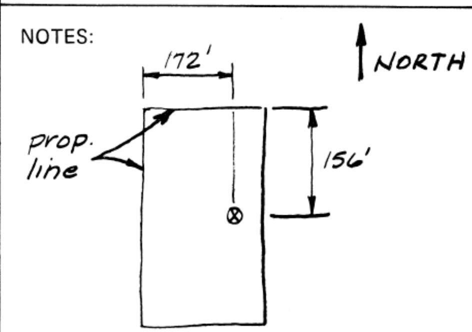
		PAN NO.	110
WW	127.25	DW	121.30
DW	121.30	TW	33.25
WATER	5.95	SOIL	88.05
	PER CENT MOISTURE		6.76

FIELD MOISTURE DETERMINATION

Method *oven*

Percent Moisture *6.56*

NOTES:



Test @ EL. 26.6
depth in fill = 18"

Figure 8.18 Field density test results using the sand cone method.

Vibroflotation

- Special type of vibratory probe
  - Mounts the rotating eccentric weight in a round probe which then penetrates the soil
  - Probe includes both the vibrator mechanism and water jets
  - Probe is lowered into the ground using a crane
  - Vibratory eccentric force induces compaction and water jets assist in insertion and extraction
- Vibratory probe compaction is effective if silt content < 12-15% and clay < 3%
- Probes inserted in grid pattern with 1.5 – 4 m spacings

Dynamic Compaction

- Uses a special crane to lift 4-27 Mg (5-30 tons) weight (pounder) to heights of 12-30 m (40-100') then drop these weights onto the ground
- Although crude, it can be a cost-effective method of densifying loose sandy and silty soils up to 5-10 m (15-30') deep

Depth of Effectiveness of Dynamic Compaction

- Formula:

$$D = \frac{\sqrt{Wh}}{2}$$

  - D = depth of compaction, meters
  - W = dropped weight/mass, metric tons (1000 kg)
  - h = height of drop, meters

Questions?