# Soil Compaction I

Chapter 4
Dr. Talat A Bader

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## Compaction

- **Soil is used as a basic material for construction**
  - *Retaining walls,*
  - *Highways, Embankments, Ramps*
  - *Airports,*
  - *Dams, Dikes, etc.*
- **The advantages of using soil are:**
  1. *Is generally available everywhere*
  2. *Is durable - it will last for a long time*
  3. *Has a comparatively low cost*

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## What is Compaction?

- **In most instances in civil engineering and/or construction practice, whenever soils are imported or excavated and re-applied, they are *compacted*.**
- **The terms compaction and consolidation may sound as though they describe the same thing, but in reality they do not.**

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## What is Consolidation

- When a Static loads are applied to saturated soils, and over a period of time the increased stresses are transferred to the soil skeleton, leading to a reduction in void ratio.
- Depending on the permeability of the soil and the magnitude of the drainage distance, this can be a very time-consuming process.
- Typically applies to existing, undisturbed soil deposits that has appreciable amount of clay.

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## Compaction - Consolidation

- **Compaction means the removal of air-filled porosity.**
- **Consolidation means the removal of water-filled porosity.**

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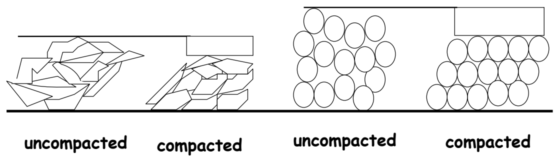
## Principles of Compaction

Compaction of soils is achieved by reducing the volume of voids. It is assumed that the compaction process does not decrease the volume of the solids or soil grains.

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## Principles of Compaction

- **The degree of compaction of a soil is measured by the dry unit weight of the skeleton.**
- **The dry unit weight correlates with the degree of packing of the soil grains.**

**Recall that $\gamma_d = G_s\gamma_w/(1+e)$ .**

- **The more compacted a soil is:**
  - ✓ **the smaller its void ratio (e) will be.**
  - ✓ **the higher its dry unit weight ($\gamma_d$) will be**

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## What Does Compaction Do?

- **1) Increased Shear Strength**
  - **This means that larger loads can be applied to compacted soils since they are typically stronger.**
- **2) Reduced Permeability**
  - **This inhibits soils' ability to absorb water, and therefore reduces the tendency to expand/shrink and potentially liquefy**
- **3) Reduced Compressibility**
  - **This also means that larger loads can be applied to compacted soils since they will produce smaller settlements.**
- **4) Control Swelling & Shrinking**
- **5) Reduce Liquefaction Potential**

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# Various Types of compaction test

| Type of Test | Mould | Hammer mass (kg) | Drop (mm) | No of layers | Blows per layer |
|---|---|---|---|---|---|
| BS "Light" | One Liter | 2.5 | 300 | 3 | 27 |
| | CBR | 2.5 | 300 | 3 | 62 |
| ASTM (5.5lb) | 4 in | 2.49 | 305 | 3 | 25 |
| | 6 in | 2.49 | 305 | 3 | 56 |
| BS "Heavy" | One Liter | 4.5 | 450 | 5 | 27 |
| | CBR | 4.5 | 450 | 5 | 62 |
| ASTM (10lb) | 4 in | 4.54 | 457 | 5 | 25 |
| | 6 in | 4.54 | 457 | 5 | 56 |
| BS Vibration hammer | CBR | 32 to 41 | Vibration | 3 | 1 minute |



(Holtz and Kovacs, 1981; Head, 1992)

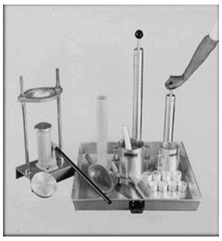
# General Compaction Methods

| | Coarse-grained soils | Fine-grained soils |
|---|---|---|
| Laboratory | •Vibrating hammer (BS) | •Falling weight and hammers<br>•Kneading compactors<br>•Static loading and press |
| Field | •Hand-operated vibration plates<br>•Motorized vibratory rollers<br>•Rubber-tired equipment<br>•Free-falling weight; dynamic compaction (low frequency vibration, 4~10 Hz) | •Hand-operated tampers<br>•Sheepsfoot rollers<br>•Rubber-tired rollers |
| | Vibration | Kneading |



# The Standard Proctor Test

- **R.R. Proctor in the early 1930's was building dams for the old Bureau of Waterworks and Supply in Los Angeles, and he developed the principles of compaction in a series of articles in Engineering News-Record.**



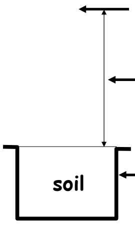


# Variables of Compaction

Proctor established that compaction is a function of four variables:

- Dry density ($\rho_d$) or dry unit weight $\gamma_d$.
- Water content w
- Compactive effort (energy E)
- Soil type (gradation, presence of clay minerals, etc.)

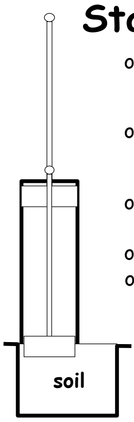
# The Standard Proctor Test Equipments



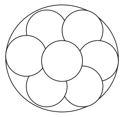

Volume 1/30 $ft^3$ or 944 $cm^3$
Diameter 4 in or 10.16 cm
Height 4.584 in or11.643cm



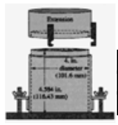
# Standard Proctor Test




- The soil is mixed with varying amounts of water to achieve different water contents.
- For each water content,the soil is compacted by dropping a hammer 25 times onto the confined soil
- The soil is in mold will be divided into three lifts
- Each Lift is compacted 25 times
- This is don 4-6 times from dry-wet



25 Blows/Layer



| |
|---|
| Layer or lift # 3 |
| Layer or lift # 2 |
| Layer or lift # 1 |

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# Standard Energy

- Compactive (E) applied to soil per unit volume:

$$E = \frac{(\#\text{ blows/layer}) * (\#\text{ of layers}) * (\text{hammer weight}) * (\text{height of drop})}{\text{Volume of mold}}$$

$$E_{SP} = \frac{(25\text{blows/layer}) * (3\text{ of layers}) * (5.5\text{ lbs}) * (1.0\text{ ft})}{(1/30)ft^3} = 12{,}375\ ft-lb/ft^3$$

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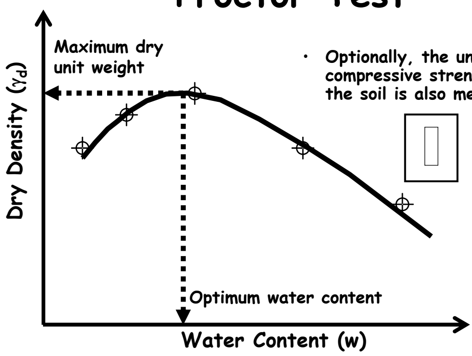
# Results from Standard Proctor Test




- Optionally, the unconfined compressive strength of the soil is also measured

A sample from the mold

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# Dry Unit Weight

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- The compacted soil is removed from the mold and its dry density (or dry unit weight) is measured.

$$\gamma_d = \frac{\gamma_m}{1+\omega}$$ Where $$\gamma_m = \frac{Mg}{V}$$

- $\gamma_d$ =Dry Unit weight
- $\gamma_m$ =Bulk Density
- $\omega$ =Water Content
- $V$ =Total Soil Volume
- $M$ =Total Wet Soil Mass
- $g$ =Gravitational Acceleration

# Water Role in Compaction Process

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- Water lubricates the soil grains so that they slide more easily over each other and can thus achieve a more densely packed arrangement.
  - A little bit of water facilitates compaction
  - too much water inhibits compaction.

# Dry Unit Weight

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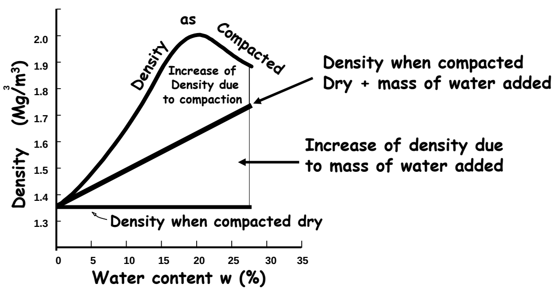


# Modified Proctor Test

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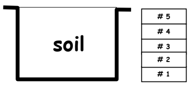
- Was developed during World War II
- By the U.S. Army Corps of Engineering
  - For a better representation of the compaction required for airfield to support heavy aircraft.

# Modified Proctor Test

- Same as the Standard Proctor Test with the following exceptions:
  - The soil is compacted in five layers
  - Hammer weight is 10 Lbs or 4.54 Kg
  - Drop height h is 18 inches or 45.72cm
  - Then the amount of Energy is calculated
  - Remember Standard Proctor Energy $E_{SP} = 12{,}375\ ft - lb/ft^3$



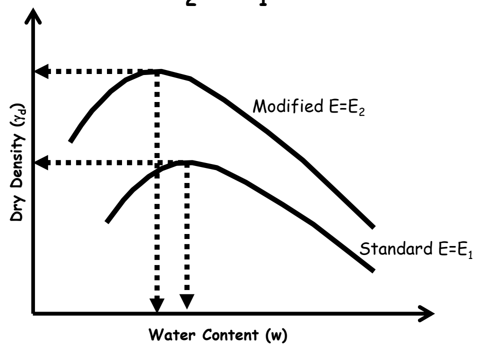

$$E_{MP} = \frac{(25\text{blows/layer}) * (5\text{ of layers}) * (10\text{ lbs}) * (1.0\text{ ft})}{(1/30)\text{ft}^3}$$

$$E_{MP} = 56{,}250\ ft - lb/ft^3$$

$$\frac{E_{MP}}{E_{SP}} = \frac{56{,}250\ ft - lb/ft^3}{12{,}375\ ft - lb/ft^3} = 4.55$$



# Effect of Energy on Compaction $E_2 > E_1$

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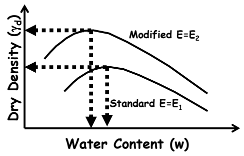
# Comparison-Summary

| Standard Proctor Test | Modified Proctor Test |
|---|---|
| Mold size: 1/30 $ft^3$ | Mold size: 1/30 $ft^3$ |
| 12 in height of drop | 18 in height of drop |
| 5.5 lb hammer | 10 lb hammer |
| 3 layers | 5 layers |
| 25 blows/layer | 25 blows/layer |
| Energy 12,375 ft·lb/$ft^3$ | Energy 56,250 ft·lb/$ft^3$ |

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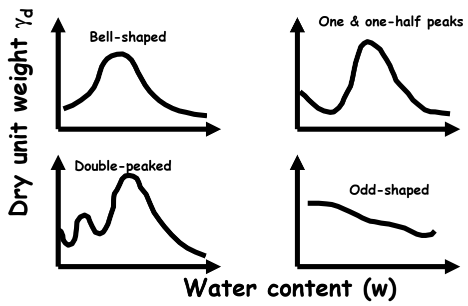
# Common Compaction Curves Encountered in Practice

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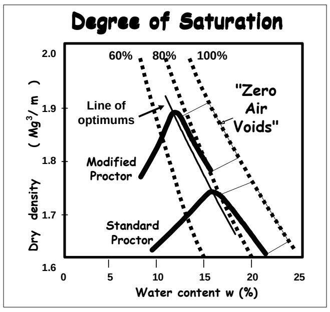
Holtz and Kovacs, 1981

# Zero-Air-Void




Points from the ZAV curve can be calculated from:

$$\gamma_{dry} = G_s\gamma_\omega / 1+e$$

ZAV: The curve represents the fully saturated condition (S=100%).

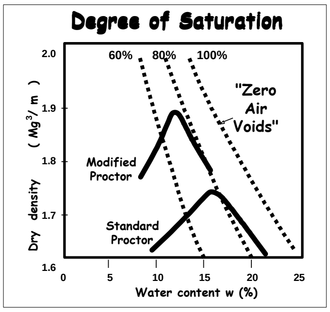
ZAV cannot be reached by compaction.

Line of Optimum: A line drawn through the peak points of several compaction curves at different compactive efforts for the same soil will be almost parallel to a 100 % S curve

Entrapped Air: is the distance between the wet side of the compaction curve and the line of 100% saturation.



# Zero-Air-Void




The Equation for the ZAV curves with different degree of saturation is :

$$\rho_d = \frac{\rho_w S}{w + \frac{\rho_w}{\rho_s} S} = \frac{\rho_w S}{w + \frac{S}{G_s}}$$

You can derive the equation by yourself, Hint

$$\rho_d = \frac{\rho_s}{1+e}$$

$$Se = wG_s$$

Back

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Holtz and Kovacs, 1981

# Results-Explanation

**Below $w_{omc}$**

**Dry of Optimum**

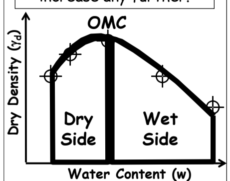
•As the water content increases, the particles develop larger and larger water films around them, which tend to "lubricate" the particles and make them easier to be moved about and reoriented into a denser configuration.

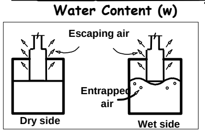
**Hammer Impact**

•Air expelled from the soil upon impact in quantities larger than the volume of water added.

**At $w_{omc}$**

The density is at the maximum, and it does not increase any further.




**Above $w_{omc}$**

**Wet of Optimum**

Water starts to replace soil particles in the mold, and since $\rho_w << \rho_s$ the dry density starts to decrease.

**Hammer Impact**

Moisture cannot escape under impact of the hammer. Instead, the entrapped air is energized and lifts the soil in the region around the hammer.

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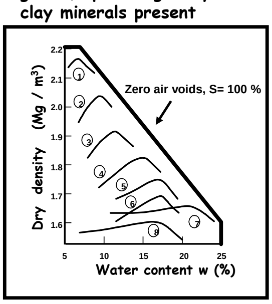
Holtz and Kovacs, 1981; Das, 1998

# Effects of Soil Types on Compaction

**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**




Soil texture and Plasticity data

| NO | Description | Sand | Silt | Clay | LL | PI |
|---|---|---|---|---|---|---|
| 1 | Well graded loamy sand | 88 | 10 | 2 | 16 | NP |
| 2 | Well graded sandy loam | 72 | 15 | 13 | 16 | NP |
| 3 | Med graded sandy loam | 73 | 9 | 18 | 22 | 4 |
| 4 | Lean sandy silty clay | 32 | 33 | 35 | 28 | 9 |
| 5 | Lean silty clay | 5 | 64 | 31 | 36 | 15 |
| 6 | Loessial silt | 5 | 85 | 10 | 26 | 2 |
| 7 | Heavy clay | 6 | 22 | 72 | 67 | 40 |
| 8 | Poorly graded sand | 94 | 6 | 0 | NP | NP |

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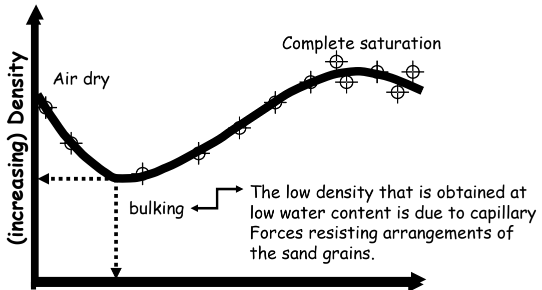
## Typical Compaction Curve for Cohesionless Sands & Sandy Gravel






## Water & Compaction

Remember what is the Affect

- **Increasing the water content at which soil is compacted:**
  - ❖ **Increases the likelihood of obtaining dispersed soil structure with reduced shear strengths.**
  - ❖ **Increases the pore pressure in the soil, decreasing the short term shear strength.**



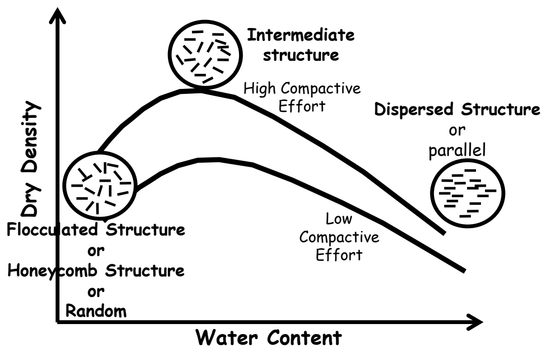
## Water Role in Compaction Process

- **Water lubricates the soil grains so that they slide more easily over each other and can thus achieve a more densely packed arrangement.**
  - **A little bit of water facilitates compaction**
  - **too much water inhibits compaction.**



Lambe and Whitman, 1979

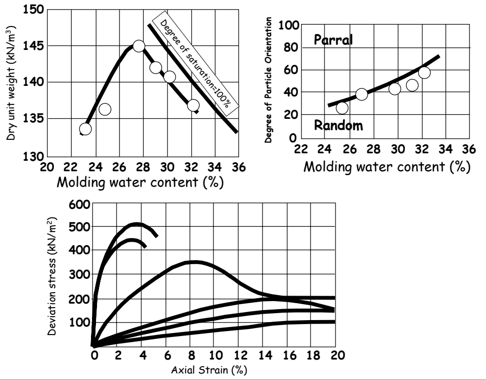
## Structure of Compacted Clay



From Lambe and Whitman, 1979

# Effect of Strength

**Samples (Kaolinite) compacted dry of optimum tend to be more rigid and stronger than samples compacted wet of optimum**

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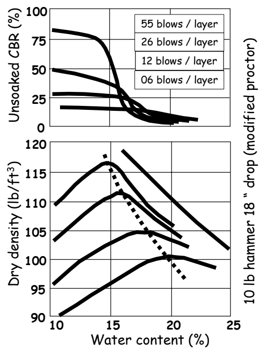
Holtz and Kovacs, 1981

# Effect of Strength (con)




The CBR (California bearing ratio)

CBR= resistance required to penetrate a 3-in$^2$ piston into the compacted specimen/ resistance required to penetrate the same depth into a standard sample of crushed stone.

A greater compactive effort produces a greater CBR for the dry of optimum. However, the CBR is actually less for the wet of optimum for the higher compaction energies (overcompaction).

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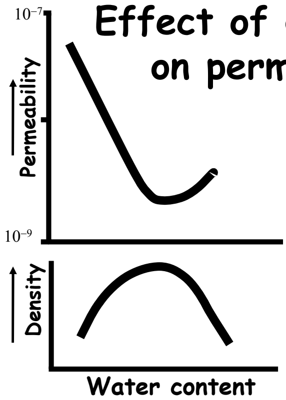
From Lambe and Whitman, 1979;
Holtz and Kovacs, 1981

# Effect of Compaction on permeability




Permeability at constant compactive effort decreases with increasing water content and reaches a minimum at about the optimum.

If compactive effort is increased, the permeability decreases because the void ratio decreases.

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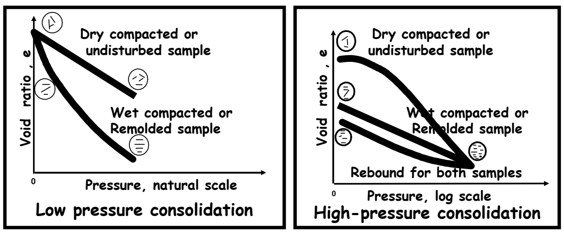
From Lambe and Whitman, 1979;
Holtz and Kovacs, 1981

# Effect of Compressibility




**Compressibility of compacted clays is function of stress level.**

**Low stress level: Clay compacted wet of optimum are more compressible.**

**High stress level: The opposite is true**

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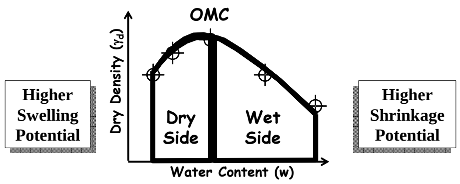
Holtz and Kovacs, 1981

# Effect of Swelling

- **Swelling of compacted clays is greater for those compacted dry of optimum. They have a relatively greater deficiency of water and therefore have a greater tendency to adsorb water and thus swell more.**

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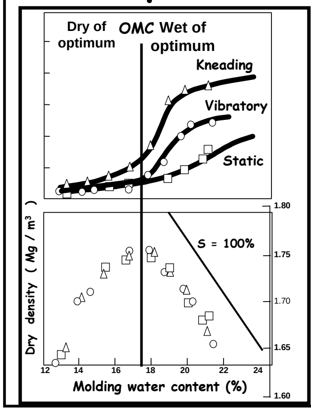
# Compaction and Shrinkage




- **samples compacted wet of optimum have the highest shrinkage**

**Legend**
- △ Kneading compaction
- ○ Vibratory compaction
- □ Static compaction

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# Engineering Properties Summary

| Properties | Dry side | Wet side |
|---|---|---|
| Structure | More random | More oriented (parallel) |
| Permeability | More permeable | |
| Compressibility | More compressible in *high* pressure range | More compressible in *low* pressure range |
| Swelling | Swell more, higher water deficiency | *Shrinkage more |
| Strength | Higher | |

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