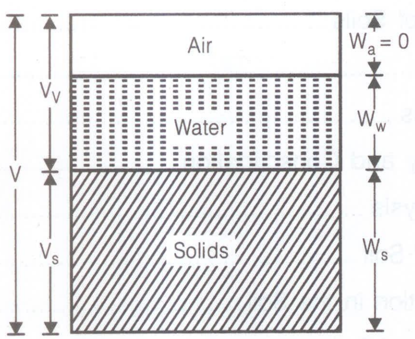
1. PROPERTIES OF SOILS

PHASE DIAGRAM

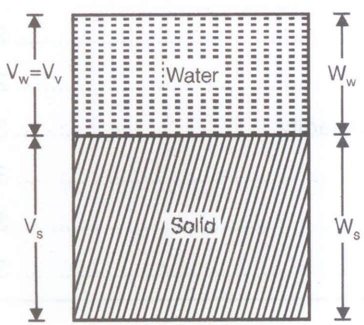
Soil mass is in general a three phase system composed of solid, liquid and gaseous matter.

The diagrammatic representation of the different phases in a soil mass is called the “phase diagram”.

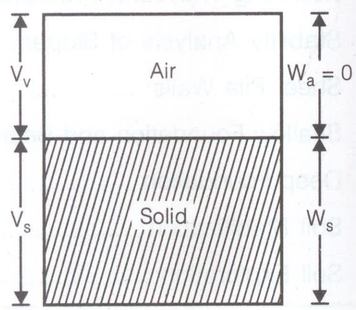
Soil
- 3 Phase
  - Partially saturated
    $0 < S < 1$
    → Solids
    → Water
    → Air
- 2 Phase
  - Oven dried
    $S = 0$
    → Solid
    → Air
  - Fully saturated
    $S = 1$
    → Solid
    → Water



3-Phase: (Partially Saturated)



2-Phase (Saturated)



2-Phase (Dry)

WATER CONTENT

$$w = \frac{W_w}{W_s} \times 100$$

where, W_w = Weight of water
W_s = Weight of solids

There can be no upper limit to water content, i.e., $w \geq 0$

> **NOTE** Water content in soil represents gravity water + Capilary water + Hygroscopic water which can be removed on ovendrying.

VOID RATIO

$$e = \frac{V_v}{V_s}$$

where, V_v = Volume of voids
V_s = Volume of solids.

Void ratio of fine grained soils are generally higher than those of coarse grained soils.

In general $e > 0$ i.e., no upper limit for void ratio.

POROSITY

$$n = \frac{V_v}{V} \times 100$$

where, V_v = Volume of voids
V = Total volume of soil

Porosity cannot exceed 100% i.e.,
$0 < n < 100$

> **NOTE** In comparison to porosity, void ratio is more frequently used because volume of solids remains same, whereas total volume changes.

DEGREE OF SATURATION

$$S = \frac{V_w}{V_v} \times 100$$

where, V_w = volume of water
V_v = Volume of voids

$0 \leq S \leq 100$

for perfectly dry soil : S = O

for Fully saturated soil : S = 100%

AIR CONTENT

$$a_c = \frac{V_a}{V_v} = 1 - S$$

V_a = Volume of air

% AIR VOID

$$\%n_a = \frac{\text{Volume of air}}{\text{Total volume}} \times 100 = \boxed{\frac{V_a}{V} \times 100} \quad \boxed{n_a = n.a_c}$$

UNIT WEIGHT

(a) **Bulk unit weight**

$$\boxed{\gamma = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_w + V_a}}$$

Thus Bulk unit weight is total weight per unit volume.

(b) **Dry Unit Weight** is the weight of soil solids per unit volume.

$$\boxed{\gamma_d = \frac{W_s}{V}}$$

- Dry unit weight is used as a measure of denseness of soil. More dry unit weight means more compacted soil.

(c) **Saturated unit weight:** It is the ratio of total weight of fully saturated soil sample to its total volume.

$$\boxed{\gamma_{sat} = \frac{W_{sat}}{V}}$$

(d) **Submerged unit weight or Buoyant unit weight (γ'):** It is the submerged weight of soil solids per unit volume.

$$\boxed{\gamma' = \gamma_{sat} - \gamma_w}$$

γ_{sat} = unit wt. of saturated soil
γ_w = unit wt. of water

- γ is roughly 1/2 of saturated unit weight.

SPECIFIC GRAVITY

- Specific gravity of soil solids (G) is the ratio of the weight of a given volume of solids to the weight of an equivalent volume of water at 4°C.

$$\boxed{G = \frac{W_s}{V_s \cdot \gamma_w} = \frac{\gamma_s}{\gamma_w}}$$

G = 2.6 to 2.75 or inorganic solids
= 1.2 to 1.4 for organic solids

- **Apparent or mass specific gravity (G_m):** Mass specific gravity is the specific gravity of the soil mass and is defined as the ratio of the total weight of a given mass of soil to the weight of an equivalent volume of water.

$$\boxed{G_m = \frac{W}{V.\gamma_w} = \frac{\gamma}{\gamma_w}}$$

where, γ is bulk unit wt. of soil
$\gamma = \gamma_{sat}$ for saturated soil mass
$\gamma = \gamma_d$ = for dry soil mass

$$\boxed{G_m < G}$$

RELATIVE DENSITY (I_D)

$$\boxed{\%I_D = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100} \quad \boxed{\%I_D = \frac{\frac{1}{\gamma_{min}} - \frac{1}{\gamma}}{\frac{1}{\gamma_{min}} - \frac{1}{\gamma_{max}}} \times 100}$$

$\%I_D$	Discription
0 – 15	Very loose soil
15 – 30	Loose soil
30 – 65	Medium soil
65 – 85	Dense soil
85 – 100	Very dence soil

NOTE: For uniformly graded coarse soil having perfectly spherical grain of same size.

(a) When particles are arranged in cubical array
e_{max} = 91%, n_{max} = 47.6%

(b) When particles are arranged in prismoidal array
e_{min} = 35%, n_{min} = 25.9%

SOME IMPORTANT RELATIONSHIPS

(i) Relation between γ_s, γ

$$\boxed{\gamma_s = \frac{\gamma}{1 + w}}$$

(ii) Relation between e and n

$$\boxed{n = \frac{e}{1 + e}} \text{ or } \boxed{e = \frac{n}{1 - n}}$$

(iii) Relation between e, w, G and S :

$$\boxed{Se = w.G}$$

(iv) Bulk unit weight (γ) in terms of G, e, w and γ_w

$$\gamma = \frac{G\gamma_w(1+w)}{(1+e)}$$

(v) Saturated unit weight (γ sat.) in terms of G, e & γ_w

$$\gamma_{sat} = \left[\frac{G+e}{1+e}\right]\cdot\gamma_w$$

(vi) Dry unit weight (γ_d) in terms of G, e and γ_w

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

(vii) Submerged unit weight (γ') in terms of G,e and γ_w

$$\gamma' = \left(\frac{G-1}{1+e}\right)\cdot\gamma_w$$

(ix) Relation between degree of saturation (s) w and G

$$S = \frac{w}{\frac{\gamma_w}{\gamma}(1+w) - \frac{1}{G}}$$

NOTE: Index properties used for identification and classification of soils, ex. water content, consistency limits, insitu density, partical size distribution, sensitivity, activity.

METHODS FOR DETERMINATION OF WATER CONTENT

(i) Oven Drying Method

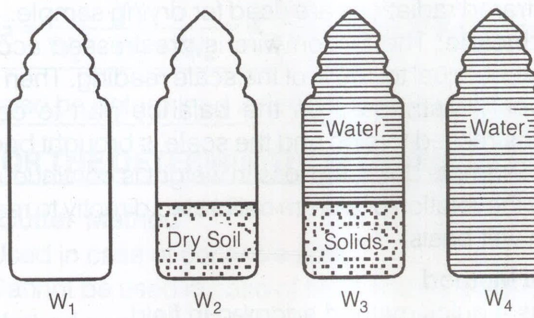
- Simplest and most accurate method
- Soil sample is dried in a controlled temperature (105-110°C)
- For organic soils, temperature is about 60°C.
- Sample is dried for 24 hrs.
- For sandy soils, complete drying can be achieved in 4 to 6 hrs.
- Water content is calculated as:

$$w = \frac{W_2 - W_3}{W_3 - W_1} \times 100\%$$

where, W_1 = weight of container
W_2 = weight of container + moist sample
W_3 = weight of container + dried sample
Weight of water = $W_2 - W_3$
Weight of solids = $W_3 - W_1$

(ii) Pycnometer Method

- quick method
- capacity of pycnometer = 900 m*l*.
- this method is more suitable for cohesionless soils.
- used when specific gravity of soil solids is known
- Let W_1 = Wt. of empty dried pycnometer bottle
  W_2 = Wt. of pycnometer + Soil
  W_3 = Wt. of pycnometer + Soil + Water
  W_4 = Wt. of pycnometer + Water.



$$w = \left[\frac{(W_2-W_1)}{(W_3-W_4)}\cdot\left(\frac{G-1}{G}\right)-1\right]\times 100\%$$

(W_1, W_2, W_3 and W_4 are in anticlockwise order)

(iii) Calcium Carbide Method/Rapid Moisture Meter Method

- Quick method (requires 5 to 7 minutes) ; but may not give accurate results.
- The reaction involved is
  $CaC_2 + 2H_2O \rightarrow C_2H_2\uparrow + Ca(OH)_2$
- Soil sample weights 4-6 gms.
- The gauge reads water content with respect to wet soil. i.e.,

$$w_r = \frac{W_w}{(W_s)_{wet}}$$

- Actual water content $w = \frac{w_r}{1-w_r} \times 100\%$

w_r is moisture content recorded, expressed as fraction of moist wt. of solid.
w is actual water content.

(iv) **Sand Bath Method**
- quick, field method
- used when electric oven is not available.
- soil sample is put in a container & dried by placing it in a sand bath, which is heated on kerosene store.
- water content is determined by using same formula as in oven drying method.

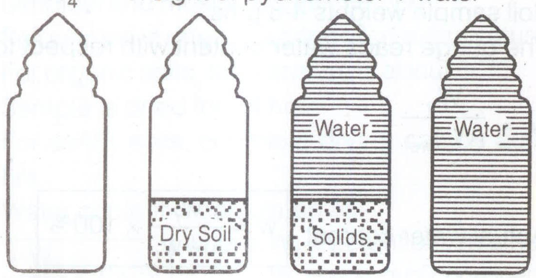
(v) Torsion Balance Moisture Meter Method
- quick method for use in laboratory.
- Infrared radiations are used for drying sample.
- **Principle:** The torsion wire is prestressed accurately to an extent equal to 100% of the scale reading. Then the sample is evenly distributed on the balance pan to counteract the prestressed torsion and the scale is brought back to zero. As the sample dries, the loss in weight is continuously balanced by the rotation of a drum calibrated directly to read moisture% on wet basis.

(vi) Alcohol Method
- It is a quick method adopted in field.
- Should not be used for organic soil and soils containing calcium compound.

DETERMINATION OF SPECIFIC GRAVITY OF SOIL SOLIDS

- Pycnometer method is used.
- Instead of pycnometer, Density bottle (50 ml) OR Flask (500 ml) can also be used.

Let, W_1 = Weight of empty pycnometer
W_2 = Weight of pycnometer + soil sample (oven dried)
W_3 = Weight of pycnometer + soil solids + water
W_4 = Weight of pycnometer + water



W_1 W_2 W_3 W_4

$$G = \frac{W_2 - W_1}{(W_4 - W_1) - (W_3 - W_2)} \Rightarrow G = \frac{W_s}{W_s - W_3 + W_4}$$

NOTE

1. Specific gravity values are generally reported at 27°C (in India)
2. If T°C is the test temperature then Sp.Gr. at 27°C is given by,

$$G_{27°C} = G_{T°C} \times \frac{\text{unit wt. of water at T°C}}{\text{unit wt. of water at 27°C}}$$

3. If kerosene (better wetting agent) is used instead of water then,

$$G = \frac{W_s}{W_s - W_3 + W_4} \times K \quad [K = \text{Sp. gr. of Kerosene}]$$

4. G can also be determined indirectly by using shrinkage limit.

METHODS FOR THE DETERMINATION OF INSITU UNIT WEIGHT

(a) Core-Cutter Method
- Used in case of cohesive soils.
- Cannot be used in case of hard and gravelly soils.
- Method consists of driving a core-cutter (Volume = 1000 cc) into the soil and removing it, the cutter filled with soil is weighed. Volume of cutter is known from its dimensions and in situ unit weight is obtained by dividing soil weight by volume of cutter.

$$\gamma = \frac{W}{V}$$

- If water content is known in laboratory, the dry unit weight can also be computed.

$$\gamma_d = \frac{\gamma}{1 + w}$$

(b) Sand Replacement Method
- Used in case of hard and gravelly soils.
- A hole in ground is made. The excavated soil is weighed. The volume of hole is determined by replacing it with sand. Insitu unit weight is obtained by dividing weight of excavated soil with volume of hole.

(c) Water Displacement Method
- Suitable for cohesive soils only, where it is possible to have a lump sample.
- A regular shape, well trimmed sample is weighed. (W_1). It is coated with paraffin wax & again weighed (W_2). The sample is

now placed in a metal container filled with water upto the brim. Let the volume of displaced water be V_w. Then volume of uncoated specimen is calculated as,

$$V = V_w - \left(\frac{W_2 - W_1}{\gamma_p}\right)$$

where, γ_p = unit wt. of paraffin wax

Thus, bulk unit wt. of soil $\gamma = \frac{W_1}{V}$

GRAIN SIZE DISTRIBUTION

Partical Size Analysis

- Sieve analysis [For coarse soils (gravels and sands)]
  - Coarse seiving (gravels)
  - Fine seiving (for sands)
    - Dry (when fines are less)
    - Wet (when fines are more)
- Sedimentation analysis [For fine soils (silts and clays)]
  - Pipette method
  - Hydrometer

- **Sieve Analysis : (For Coarse Grained Soils)**

  The fraction retained on 4.75 mm sieve is called the gravel fraction which is subjected to coarse sieve analysis.

  The material passing 4.75 mm sieve is further subjected to fine sieve analysis if it is sand or to a combined sieve and sedimentation analysis if silt and clay sizes are also present.

- **Concept of "Percentage finer"**

  % retained on a particular sieve

$$= \frac{\text{Weight of soil retained on that sieve}}{\text{Total weight of soil taken}} \times 100$$

  Cumulative % retained = sum of % retained on all sieves of larger sizes and the % retained on that particular sieve.

  "Percentage finer" than the sieve under reference = 100% - Cumulative % retained.

- **Sedimentation Analysis**

  According to stokes law, the terminal velocity is given by,

$$V = \frac{g}{18} \cdot \frac{\rho_s - \rho_w}{\mu} \cdot D^2$$

ρ_s = density of grains (g/cm³)
ρ_s = density of water (g/cm³)
μ = viscosity of water
g = acceleration due to gravity (cm/s²)
D = Diameter of grain (cm)

If 'h' the height through which particle falls in time 't', then

$$\frac{h}{t} = k.D^2 \quad \therefore \quad \frac{D_1}{D_2} = \sqrt{\frac{h_1}{h_2} \cdot \frac{t_2}{t_1}}$$

NOTE

- Stokes law is applicable for spheres of diameter between 0.2 mm and 0.0002 mm.
- Spheres of diameter larger than 0.2 mm falling through water cause turbulence, whereas, for spheres with diameter less than 0.0002 mm, Brownian motion takes place and the velocity of settlement is too small for accurate measurement.

- **Pipette Method**

  In this method, the weight of solids per cc of suspension is determined directly by collecting 10 cc of soil suspension from a specified sampling depth.

  If m_d = dry mass (obtained after drying the sample) then, mass present in unit vol. of pipette

$$\frac{m_d}{\text{Vol.of pipette } (V_p)} = \frac{m_d}{10 \text{ ml. } (V_p)}$$

  If M_d = total mass of soil dissolved in total volume of water (V)

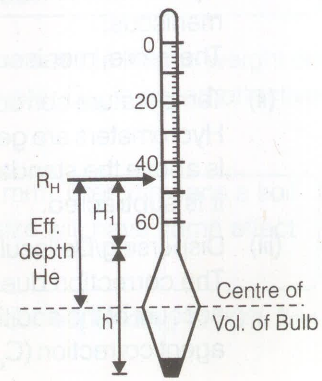
  then mass/unit volume = $\frac{M_d}{V}$

  Therefore, % finer is given by = %

$$N = \frac{m_d/V_p}{M_d/V}$$

  If m is the mass of dispersing agent dissolved in the total volume V, then actual % finer,

$$\%N = \frac{\frac{m_d}{V_p} - \frac{m}{V}}{\frac{M_d}{V}} \times 100$$



- **Hydrometer Method**

  In this method the weight of solids present at any time is calculated indirectly by reading the density of soil suspension.

- **Calibration of Hydrometer**

  Establishing a relation between the hydrometer reading R_H and effective depth (H_e).

  The effective depth is the distance from the surface of the soil suspension to the level at which the density of soil suspension is being measured. Effective depth is calculated as

$$H_e = H_1 + \frac{1}{2}\left(h - \frac{V_H}{A_j}\right)$$

where, H_1 = distance (cm) between any hydrometer reading and neck.
h = length of hydrometer bulb
V_H = volume of hydrometer bulb
A_J = area of the cross section of the Jar.

Reading of Hydrometer is related to sp. gr. or density of soil suspension as :

$$G_{SS} = 1 + \frac{R_H}{1000}$$

Thus a reading of R_H = 25 means, G_{ss} = 1.025 and a reading of R_H = –25 means, G_{ss} = 0.975

% finer is given as :

$$N = \frac{G}{G-1} \cdot \gamma_w \cdot \frac{V}{W} \cdot \frac{R_H}{10} \%$$

where, G = sp. gr. of soil solids
R_H = final corrected value of hydrometer
V = Total volume of soil suspension
W = weight of soil mass dissolved.

- **Corrections to Hydrometer Reading**

  (i) Meniscus correction : (C_m)
  Hydrometer reading is always corresponding to the upper level of meniscus.
  Therefore, meniscus correction is always positive ($+C_m$).

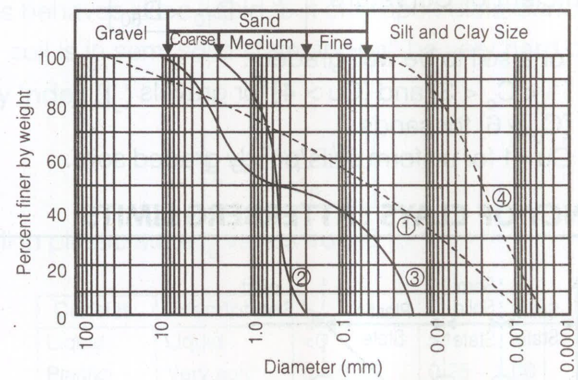
  (ii) Temperature correction : (C_t)
  Hydrometers are generally calibrated at 27°C. If the test temperature is above the standard (27°C) the correction is added and, if below, it is subtracted.

  (iii) Dispersing/Deflocculating agent correction: (C_d)
  The correction due to rise in specific gravity of the suspension on account of the addition of the deflocculating agent is called Dispersing agent correction (C_d).

  C_d is always negative.
  The corrected hydrometer reading is given by

$$(R_H) = R_H + C_m \pm C_t - C_d$$

- **Grain Size Distribution Curves**



Curve-1: Well graded soil : good representation of grain sizes over a wide range and its gradation curve is smooth.

Curve-2: Poorly graded soil / Uniform gradation:
It is either an excess or a deficiency of certain particle sizes or has most of the particles about the same size.

Curve-3: Gap graded soil : In this case some of the particle sizes are missing.

Curve-4: Predominantly coarse soil.

Curve-5: Predominantly fine soil.

> NOTE
> If slope of the curve is steep, soil is poorly graded.
> If slope is inclined, soil is well graded.

The diameter D_{10} corresponds to 10% of the sample finer in weight on the Grain size distribution curve. This diameter D_{10} is called effective size.

> NOTE
> For a soil mass if effectgive size is X mm. Then it means a soil having spherical particles of X mm size will have same effect as the above soil with D_{10} = X mm

Similarly, D_{30} and D_{60} are grain dia. (mm) corresponding to 30% fine and 60% finer.

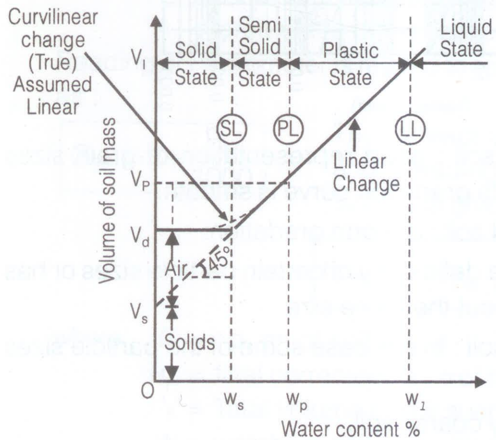
The shape parameters related to these are :

(a) Coefficient of Uniformity $C_u = \dfrac{D_{60}}{D_{10}}$

(b) Coefficient of Curvature $C_c = \dfrac{D_{30}^2}{D_{10} \times D_{60}}$

- for a soil to be well graded :
  [$1 < C_c < 3$] and [$Cu > 4$] for gravels ;
  [$C_u > 6$] for sands.
- $Cu \approx 1$ for uniform soils/poorly graded soils.

CONSISTENCY OF CLAYS : ATTERBERG LIMITS



LL = w_l = liquid limit
PL = w_p = Plastic limit
SL = w_s = Shrinkage limit
V_1 = Volume of soil mass at LL
V_P = Volume of soil mass at PL
V_d = Volume of soil mass at SL
V_S = Volume of solids

- **Plasticity Index (I_p)**: It is the range of moisture content over which a soil exhibits plasticity.

$I_p = w_L - w_p$

w_L = water content at LL
w_p = water content at PL

If PL ≥ LL, I_p is reported as zero.

Soil classification related to plasticity Index:

I_p(%)	Soil description
0	Non plastic
1 to 5	Slight Plastic
5 to 10	Low Plastic
10 to 20	Medium Plastic
20 to 40	Highly plastic
> 40	Very Highly plastic

- **Relative Consistency or Consistency-index (I_c)**

$I_C = \dfrac{w_L - w_N}{I_p}$ ∴ For $w_N = w_L \Rightarrow I_C = 0$; For $w_N = w_P \Rightarrow I_C = 1$

If $I_C < 0$, the natural water content of soil (w_N) is greater than w_L and the soil mass behaves like a liquid, but only upon disturbance.

If $I_C > 1$, soil is in semi solid state and will be very hard or stiff.

- **Liquidity Index (I_L)**

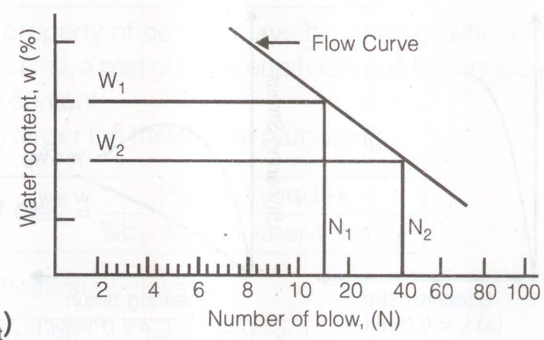
$I_L = \dfrac{w_N - w_P}{I_P}$

For a soil in plastic state I_L varies from 0 to 1.

Consist.	Description	I_C	I_L
Liquid	Liquid	<0	>1
Plastic	Very soft	0 – 0.25	0.75 – 1.00
	Soft	0.25 – 0.5	0.50 – 0.75
	Medium stiff	0.50 – 0.75	0.25 – 0.50
	Stiff	0.75–1.00	0.0 – 0.25
Semi-solid	Very stiff OR Hard	> 1	< 0
Solid	Hard OR Very Hard	> 1	< 0

- **Flow Index (I_f)**

$I_f = \dfrac{w_1 - w_2}{\log_{10}(N_2/N_1)}$



- **Toughness Index (I_t)**

$I_T = \dfrac{I_P}{I_F}$ For most of the soils : $0 < I_T < 3$

When $I_T < 1$, the soil is friable (easily crushed) at the plastic limit.

- **Shrinkage Ratio (SR)**

$$SR = \frac{\frac{V_1 - V_2}{V_d} \times 100}{w_1 - w_2}$$

where, V_1 = volume of soil mass at water content w_1%.

V_2 = volume of soil mass at water content w_2%.

V_d = volume of dry soil mass

Now, at SL, $w_2 = w_s$ and $V_2 = V_d$

$$\therefore \quad SR = \frac{\left(\frac{V_1 - V_d}{V_d} \times 100\right)}{(w_1 - w_s)}$$

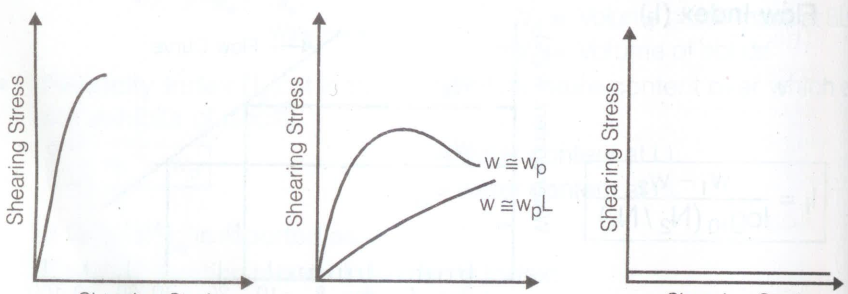
If w_1 & w_2 are expressed as ratio,

$$SR = \frac{(V_1 - V_2)/V_d}{w_1 - w_2}$$

But, $w_1 - w_2 = \frac{(V_1 - V_2)/\gamma_w}{W_s}$

$$\therefore \quad SR = \frac{W_s}{V_d} \cdot \frac{1}{\gamma_w} = \frac{\gamma_d}{\gamma_w}$$

STRESS-STRAIN CURVE FOR DIFFERENT CONSISTENCY STATES



(a) $I_L < 0$ (brittle) (b) $0 < I_L < 1$ (Plastic) (c) $I_L > 1$ (Liquid)

- **Unconfined Compressive Strength (q_u)**
Defined as the load per unit area at which an unconfined prismatic or cylindrical specimen of standard dimensions of a soil fails in a simple compression test.
q_u = 2 × shear strength of a clay soil (under undrained condition).

q_u is related to consistency of clays as :

Consistency	q_u (KN/m^2)	(Kg/cm^2)
very soft	< 25	< 0.25
soft	25-50	0.25-0.50
Medium	50-100	0.50-1.0
Stiff	100-200	1.0-2.0
Very stiff	200-400	2.0-4.0
Hard	> 400	> 4.0

- **Sensitivity (S_t):** It is defined as the ratio of the unconfined compressive strength of an undisturbed specimen of the soil to the unconfined compressive strength of a specimen of the same soil after remolding at unaltered water content.

$$S_t = \frac{(q_u)\text{undisturbed}}{(q_u)\text{remoulded}}$$

Soil classification based on sensitivity :

Sensitivity	Classification
1	No loss in strength on remoulding.
2-4	Soil is normal sensitive
4-8	Sensitive
8-15	Extra-Sensitive
>15	Quick

- **Thixotropy:** It is the property of certain clays by virtue of which they regain, if left alone for a time, a part of the strength lost due to remoulding, at unaltered moisture content.
Higher the sensitivity, larger the thixotropic hardening.

- **Activity** $\text{Activity of clay} = \frac{\text{Plasticity index}}{\text{\%by weight finer than } 2\mu}$

Activity based classification of clays

Activity	Classification
< 0.75	Inactive
0.75-1.25	Normal
>1.25	Active

Note: Black cotton soil is very active.

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