$$= \frac{\gamma_d}{\gamma_w}\left(w + \frac{1}{G}\right) = \frac{\gamma_d}{\gamma_w}\left(\frac{wG+1}{G}\right)$$

$$\therefore \quad \gamma_d = \frac{(1-n_a)G\gamma_w}{1+wG} \quad \text{...(2.12)}$$

Example 2.1

A soil sample in its undisturbed state was found to have volume of 105 cm^3 and mass of 201g. After oven drying the mass got reduced to 168g. Compute (*i*) water content, (*ii*) void ratio, (*iii*) porosity (*iv*) degree of saturation and (*v*) air content. Take $G = 2.7$.

Solution:

Volume of soil mass, V = 105 cm^3

Mass of soil mass, M = 201 g

Mass of dry soil mass, M_d = 168 g

Specific gravity of soil particles, G = 2.7

(*i*) Water content, $w = \frac{M_w}{M_s} = \frac{M - M_d}{M_d} = \frac{201-168}{168} = 0.196 = 19.6\%$

(*ii*) Dry density, $\gamma_d = \frac{M_s}{V} = \frac{M_d}{V} = \frac{168}{105} = 1.6 g/cm^3$

Void ratio, $e = \frac{G\gamma_\omega}{\gamma_d} - 1 = \frac{2.7(1)}{1.6} - 1 = 0.69$

Example 2.2

For a soil sample the specific gravity of soil mass is 1.7 and specific gravity of soil particles is 2.7. Determine the void ratio (*i*) assuming the soil sample is dry and (*ii*) the sample has a water content of 12 percent.

Solution: $G_m = 1.7$ $\quad G = 2.7$

(*i*) For dry soil mass $\gamma = \gamma_d$

$$G_m = \frac{\gamma}{\gamma_w} = \frac{\gamma_d}{\gamma_w}$$

$$\gamma_d = G_m \gamma_w$$

Void ratio, $e = \frac{G\gamma_w}{\gamma_d} - 1 = \frac{G\gamma_w}{G_m\gamma_w} - 1 = \frac{G}{G_m} - 1$

$$= \frac{2.7}{1.7} - 1 = 0.59$$

(*ii*) When $w = 12\% = 0.12$

$$G_m = \frac{\gamma}{\gamma_w} \text{ or } \gamma = G_m\gamma_w = (1.7)(9.81) = 16.68 kN/m^3$$

$$\gamma_d = \frac{\gamma}{1+w} = \frac{16.68}{1+0.12} = 14.89 kN/m^3$$

$$e = \frac{G\gamma_w}{\gamma_d} - 1 = \frac{(2.7)(9.81)}{14.89} - 1 = 0.78$$

Example 2.3

Calculate the bulk unit weight of soil mass and specific gravity of soil particles for (*i*) a soil sample composed of only quartz and (*ii*) a soil sample composed of 65% quartz, 23% mica and 12% iron oxide if the average value of specific gravity of soil particles is 2.65 for quartz, 3.0 for mica and 3.8 for iron oxide. Assume that both soils are fully saturated and have void ratio of 0.6.

Solution: $S_r = 1 \quad e = 0.6$

For quartz $G_{qa} = 2.65$

For mica $G_{mi} = 3.0$

For iron oxide $G_{io} = 3.8$

(*a*) Soil sample composed of only quartz

For the soil sample, $G = G_{qa} = 2.65$

Bulk unit weight, $$\gamma = \gamma_{sat} = \frac{(G+e)\gamma_w}{1+e} = \frac{(2.65+0.6)(9.81)}{1+0.6} = 19.93\,kN/m^3$$

(*b*) Soil sample composed of 65%quartz, 23% mica and 12% iron oxide

For the soil sample, $G = \frac{\gamma_s}{\gamma_w} = \frac{W_s}{V_s\gamma_w}$

Weight of quartz particles, $W_{qa} = 0.65\,W_s$

Weight of mica particles, $W_{mi} = 0.23\,W_s$

Weight of iron oxide particles, $W_{io} = 0.12\,W_s$

Volume of quartz particles, $$V_{qa} = \frac{W_{qa}}{\gamma_{qa}} = \frac{0.65\,W_s}{(2.65)\gamma_w} = 0.245\frac{W_s}{\gamma_w}$$

Volume of mica particles, $$V_{mi} = \frac{W_{mi}}{\gamma_{mi}} = \frac{0.23W_s}{(3.0)\gamma_w} = 0.077\frac{W_s}{\gamma_w}$$

Volume of iron oxide particles, $$V_{io} = \frac{W_{io}}{\gamma_{io}} = \frac{0.12W_s}{(3.8)\gamma_w} = 0.031\frac{W_s}{\gamma_w}$$

$$V_s = V_{qa} + V_{mi} + V_{io} = (0.245 + 0.077 + 0.031)\frac{W_s}{\gamma_w} = 0.353\frac{W_s}{\gamma_w}$$

$$G = \frac{W_s}{V_s\gamma_w} = \frac{W_s}{0.353\frac{W_s}{\gamma_w}\gamma_w} = \frac{1}{0.353} = 2.83$$

$$\gamma = \gamma_{sat} = \frac{(G+e)\gamma_w}{1+e} = \frac{(2.83+0.6)(9.81)}{1+0.6} = 21.03\,kN/m^3$$

Example 2.4

A soil sample assumed to consist of spherical grains all of same diameter will have maximum void ratio when the grains are arranged in a cubical array. Find void ratio and dry unit weight. Take unit weight of grains as 20 kN/m³.

Solution: We consider a unit cube packed with the spherical grains of diameter d.

Number of spherical grains in the container $= \frac{1}{d} \times \frac{1}{d} \times \frac{1}{d} = \frac{1}{d^3}$

Volume of each spherical grain $= \frac{\pi d^3}{6}$

Volume of soil solids, $V_s = \frac{1}{d^3} \times \frac{\pi d^3}{6} = \frac{\pi}{6}$

Total volume of cube, $V = 1 \times 1 \times 1 = 1\ m^3$

Volume of voids, $V_v = V - V_s = 1 - \frac{\pi}{6} = \frac{6 - \pi}{6}$

Void ratio $e = \frac{V_v}{V_s} = \frac{(6-\pi)(6)}{6(\pi)} = \frac{6-\pi}{\pi} = 0.91$

Dry unit weight $\gamma_d = \frac{W_s}{V} = \frac{V_s \gamma_s}{V} = \frac{\pi}{6}(20) = 10.47\ kN/m^3$

Example 2.5

$1000\ m^3$ of earthfill is to be constructed. How many cubic metres of soil is to be excavated from borrow pit in which the void ratio is 0.95, if the void ratio of earthfill is to be 0.7?

Solution: Volume of earth fill, $V_1 = 1000\ m^3$

Void ratio of earth fill, $e_1 = 0.7$

Void ratio in borrow pit, $e_2 = 0.95$

Let volume of soil to be excavated from borrow pit $= V_2$

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

Adding 1 to both sides, $1 + e = \frac{V_v}{V_s} + 1 = \frac{V_v + V_s}{V_s} = \frac{V}{V_s}$

For soil in earth fill, $1 + e_1 = \frac{V_1}{V_s}$ ...(*i*)

For soil to be excavated from borrow pit $1 + e_2 = \frac{V_2}{V_s}$ ...(*ii*)

Dividing (*ii*) by (*i*), $\frac{V_2}{V_1} = \frac{1+e_2}{1+e_1}$ ($\because$ V_s is same for earthfill and soil excavated from borrow pit)

$$V_2 = \left(\frac{1+e_2}{1+e_1}\right)V_1 = \left(\frac{1+0.95}{1+0.7}\right)(1000) = 1147\ m^3$$

Example 2.6

A sample of clay with a weight of 6.7 N was coated with paraffin wax. The combined weight of clay and wax was found to be 6.78 N. The volume of the wax coated sample was found, by immersion in water, to be $350 \times 10^3\ mm^3$. The sample was then broken open and moisture content was found to be 17%. If the specific gravities of soil particles and wax are 2.67 and 0.89, determine the bulk unit weight, void ratio and degree of saturation of the soil sample.

Solution:

Weight of clay sample, $W = 6.7$ N

Weight of soil sample + wax, $W_1 = 6.78$ N

Volume of wax coated soil sample, $V_1 = 350 \times 10^3\ mm^3$

Water content of soil sample, $w = 17\%$

Specific gravity of soil solids, $G = 2.67$

Specific gravity of paraffin wax, $G_p = 0.89$

We have $$V_p = \frac{W_p}{\gamma_p} = \frac{W_p}{G_p \gamma_w} = \frac{6.78 - 6.7}{(0.89)(9.81 \times 10^{-6})} = 9.16 \times 10^3\ mm^3$$

Volume of soil sample, $$V = V_1 - V_p = (350 - 9.16) \times 10^3 = 340.84 \times 10^3\ mm^3$$

Bulk unit weight, $$\gamma = \frac{W}{V} = \frac{6.7}{340.84 \times 10^3} = 19.66 \times 10^{-6}\ N/mm^3$$

Dry unit weight $$\gamma_d = \frac{\gamma}{1+w} = \frac{19.66 \times 10^{-6}}{1+0.17} = 16.80 \times 10^{-6}\ N/mm^3$$

Void ratio, $$e = \frac{G\gamma_w}{\gamma_d} - 1 = \frac{2.67 \times 9.81 \times 10^{-6}}{16.8 \times 10^{-6}} - 1 = 0.56$$

Degree of saturation, $$S_r = \frac{wG}{e} = \frac{(0.17)(2.67)}{0.56} = 81.05\%$$

Example 2.7

In an earthen embankment under construction the bulk unit weight is 16.5 kN/m³ at water content of 11%. If the water content is to be raised to 15%, compute the quantity of water required to be added per cubic meter of soil? Assume no change in the void ratio.

Solution :

$$\gamma_1 = 16.5\ kN/m^3$$
$$w_1 = 11\%$$
$$w_2 = 15\%$$
$$V = 1 m^3$$

$$(\gamma_d)_1 = \frac{\gamma_1}{1+w_1} = \frac{16.5}{1+0.11} = 14.86\ kN/m^3$$

$$W_s = (\gamma_d)_1 . V = (14.86)(1) = 14.86\ kN$$

$$w_1 = \frac{Ww_1}{W_s}$$

$$Ww_1 = w_1 . W_s = (0.11)(14.86) = 1.635\ kN$$

$$Vw_1 = \frac{Ww_1}{\gamma_w} = \frac{1.635}{9.81} = 0.167\ m^3 = 167\ litres$$

Similarly,

$$Ww_2 = w_2 . W_s = (0.15)(14.86) = 2.229\ kN$$

$$Vw_2 = \frac{Ww_2}{\gamma_w} = \frac{2.229}{9.81} = 0.227\ m^3 = 227\ litres$$

Answer: Required quantity of water to be added per cubic meter of soil

$$= 227 - 167 = 60\ litres.$$

Example 3.1

An oven-dried soil sample having mass of 195 g was put inside a pycnometer which was then completely filled with distilled water. The mass of pycnometer with soil and water was found to be 1584 g. The mass of pycnometer filled with water alone was 1465 g. Calculate the specific gravity of soil solids.

Solution:

Mass of soil solids, $M_d = 195$ g

Mass of pycnometer + soil + water, $M_1 = 1584$ g

Mass of pycnometer + water, $M_2 = 1465$ g

We have

$$M_2 - \frac{M_d}{G} + M_d = M_1$$

$$\therefore \quad \frac{M_d}{G} = M_2 - M_1 + M_d = M_d - (M_1 - M_2)$$

$$\therefore \quad G = \frac{M_d}{M_d - (M_1 - M_2)} = \frac{195}{195 - (1584 - 1465)}$$

$$= 2.56$$

Example 3.2

The specific gravity of soil solids for a given soil sample was determined by density bottle method using kerosene. Following observations were recorded. Compute the specific gravity of soil solids at test temperature which was maintained at 27°*C*. Also report the value at 4°*C*. Take specific gravity of kerosene at 27°*C* as 0.773.

Mass of density bottle, $M_1 = 61.45$ g

Mass of bottle + soil, $M_2 = 82.24$ g

Mass of bottle + soil + kerosene, $M_3 = 261.12$ g

Mass of bottle + kerosene, $M_4 = 246.49$ g

Solution:

Mass of soil solids, $M_d = M_2 - M_1 = 82.24 - 61.45$

$= 20.79$ g

We have

$$M_4 - \frac{M_d}{G} + M_d = M_3$$

$$\therefore \quad G = \frac{M_d . G_k}{M_d - (M_3 - M_4)} = \frac{20.79 \times 0.773}{20.79 - (261.12 - 246.49)} = 2.61$$

$$G_{27°C} = 2.61$$

If the value of G has to be reported at 4°*C* we have

$$G_{4°C} = G_{27°C} \times \frac{\text{Sp. gr. of water at } 27°\text{ C}}{\text{Sp. gr. of water at } 4°\text{ C}}$$

$$= 2.61 \times \frac{0.9965}{1.0000} = 2.60$$

Example 3.3 If in problem of Ex. 3.1, while finding mass of pycnometer with soil and water, 2 cm^3 of air got entrapped, will the computed value of G be higher or lower than the correct value and what will be the percentage error?

Using the data given in Example 3.1,

$$G = \frac{M_d}{M_d - (M_1 - M_2)} = \frac{195}{195 - (1584 - 1465)} = 2.57$$

If some air got entrapped while finding M_1, then the value of M_1 will be less than that when water replaces the entrapped air. Since M_1 occurs with negative sign in the denominator, the denominator will increase and hence computed value of G will be less than the correct value.

Corrected value of G is obtained as

$$G = \frac{195}{195 - (1586 - 1465)} = 2.63$$

$$\text{Percentage error} = \frac{2.63 - 2.57}{2.63} \times 100 = 2.28\ \%$$

3.3 Water Content

The water content of a soil sample can be determined by the following methods:

(i) *Oven-drying method*

(ii) *Pycnometer method*

(iii) *Rapid methods*

(i) *Oven-drying method*

This is the most accurate method and is recommended as the standard method for determining water content in the laboratory. A cup with tight fitting lid, of non-corrodible material, is used. The mass, M_1, of cup with lid is found. Suitable quantity of wet soil sample whose water content is to be determined is put inside the cup and the lid replaced. The mass, M_2, of the cup with soil and lid is found. The lid is removed and the cup with soil is kept inside a thermostatically controlled oven and the soil is dried for 24 hours at 105 to 110° C. The cup is then taken out of the oven, the lid replaced and cooled. The mass, M_3, of the cup with dry soil and lid is found. The water content is calculated as shown below.

Mass of soil solids, $M_s = (M_3 - M_1)$

Mass of water, $M_w = (M_2 - M_3)$

Water content, $w = \frac{M_w}{M_s} = \frac{M_2 - M_3}{M_3 - M_1} \times 100\%.$

It may be noted that sandy soils require about 4 hours and clays about 15 hours of drying. However, to standardize the procedure 24 hours of drying is recommended. In most of the soils, there is chance of breaking the soil structure when heated beyond 110°C. Hence the temperature range of 105-110°C is recommended. But in the case of soils containing organic matter or calcareous compounds a lower temperature 60-80°C will have to be used and the soil dried for a longer period.

(ii) *Pycnometer method*

When the specific gravity of soil solids, G, is known this method can be used for quick determination of water content. The mass, M_1, of pycnometer with cone fitted to it is found. The cone is removed and suitable quantity of soil sample is put inside pycnometer. The cone is refitted and the mass, M_2, of the pycnometer with soil is found. Water is added to the soil inside the pycnometer until the excess water oozes out of the hole in the cone. The outer surface of the pycnometer is wiped dry and the mass, M_3, of pycnometer with soil and water is found. The pycnometer is emptied of its contents, cleaned and filled with water only. The outer surface is wiped dry and the mass, M_4, of pycnometer with water is found. In the last two steps care is taken to remove entrapped air from water inside the pycnometer. The water content is calculated as shown below.

If from mass M_4 we deduct mass of water whose volume is equivalent to volume of soil solids and add mass of soil solids, we get mass M_3.

Mass of water equivalent in volume to that of soil solids

$$= \left(\frac{M_s}{\gamma_s}\right)\gamma_w = \left(\frac{M_s}{G\gamma_w}\right)\gamma_w = \frac{M_s}{G}$$

$$\therefore \quad M_4 - \frac{M_s}{G} + M_s = M_3$$

$$M_s\left(1 - \frac{1}{G}\right) = M_3 - M_4$$

$$M_s\left(\frac{G-1}{G}\right) = M_3 - M_4$$

$$M_s = \frac{G}{G-1}(M_3 - M_4)$$

$$M_w = (M_2 - M_1) - M_s$$

Water Content,

$$w = \frac{M_w}{M_s} = \frac{(M_2 - M_1) - M_s}{M_s}$$

$$= \frac{(M_2 - M_1)}{M_s} - 1$$

$$w = \left[\frac{M_2 - M_1}{M_3 - M_4}\left(\frac{G-1}{G}\right) - 1\right] \times 100\%$$

This method is not convenient for use in the case of fine grained soils as it becomes difficult to find M_3 accurately.

(*iii*) *Rapid Methods*: Infra-red lamp and torsion balance method, calcium carbide method and Proctor needle method are used for rapid determination of water content. The student is advised to refer to a laboratory manual which gives full details about the principle, apparatus and procedure for these methods.

Example 3.4

Following observations were made while determining water content of a soil sample by pycnometer method.

Weight of wet soil sample, $W = 2.308$ N

Weight of pycnometer + soil + water, $W_1 = 30.930$ N

Weight of pycnometer + water, $W_2 = 29.661$ N

Calculate water content of soil sample, if $G = 2.69$.

Solution:

We have $W_2 - \frac{W_s}{G} + W_s = W_1$, where W_s = weight of soil solids

$$W_s\left(1 - \frac{1}{G}\right) = W_1 - W_2$$

$$W_s = (W_1 - W_2)\frac{G}{G-1}$$

$$= (30.930 - 29.661)\frac{2.69}{(2.69-1)}$$

$$= 2.02 \text{ N}$$

Weight of water present in soil sample,

$$W_w = W - W_s = 2.308 - 2.02 = 0.288 \text{ N}$$

$$\therefore \quad w = \frac{W_w}{W_s} = \frac{0.288}{2.02} = 0.1426$$

$$= 14.26\%$$

Example 3.5

In determining water content of a soil sample by pycnometer method, following observations were made

Mass of pycnometer, $M_1 = 803$ g

Mass of pycnometer + wet sample, $M_2 = 1165$ g

Mass of pycnometer + soil + water, $M_3 = 2008$ g

Mass of pycnometer + water, $M_4 = 1802$ g

Calculate water content of soil sample, if $G = 2.65$

We have $M_4 - \frac{M_s}{G} + M_s = M_3$ where M_s = mass of soil solids

$$M_s\left(1 - \frac{1}{G}\right) = M_3 - M_4$$

$$M_s = (M_3 - M_4)\left(\frac{G}{G-1}\right)$$

$$M_w = (M - M_s)$$

where total mass of soil sample, $M = M_2 - M_1$

$$w = \frac{M_w}{M_s} = \frac{(M_2 - M_1) - M_s}{M_s}$$

$$= \frac{(M_2 - M_1)}{M_s} - 1 = \left(\frac{M_2 - M_1}{M_3 - M_4}\right)\left(\frac{G-1}{G}\right) - 1$$

$$= \left(\frac{1165 - 803}{2008 - 1802}\right)\left(\frac{1.65}{2.65}\right) - 1 = 9.41\%$$

3.4 Particle Size Distribution

The particle size distribution for a given soil sample is quantitatively expressed by giving the percentage by mass of different soil components such as silt, clay etc. based on a particle size classification chart. To enable the student to understand the discussion that follows, the I.S. particle size classification chart is given in the following page.

Also, we can write

$$SR = \frac{\frac{V_1 - V_d}{V_d} \times 100}{w_1 - w_s} = \frac{VS}{w_1 - w_s}$$

$$\therefore \quad VS = SR\,(w_1 - w_s) \qquad 3.5(vi)$$

Example 3.8

The mass and volume of a saturated clay specimen were 29.8g and 17.7cm^3 respectively. On oven drying the mass got reduced to 19g and the volume to 8.9cm^3. Calculate shrinkage limit, shrinkage ratio and volumetric shrinkage. Also compute G of soil.

Solution:

Mass of wet soil specimen, $M = 29.8$ g
Volume of wet soil specimen, $V = 17.7$ cm^3
Mass of dry soil specimen, $M_d = 19.0$ g
Volume of dry soil specimen, $V_d = 8.9$ cm^3

Shrinkage limit, $$w_s = \frac{\text{Mass of water at shrinkage limit}}{\text{Mass of soil solids}}$$

$$= \frac{(M - M_d) - (V - V_d)\gamma_w}{M_d}$$

$$= \frac{(29.8-19.0)-(17.7-8.9)(1)}{19.0} = 0.1053$$

$$= 10.53\%$$

Shrinkage ratio, $$SR = \frac{M_d}{V_d \cdot \gamma_w} = \frac{19.0}{8.9(1)} = 2.13$$

Volumetric shrinkage, $$V_s = \frac{V - V_d}{V_d} \times 100\%$$

$$= \frac{17.7 - 8.9}{8.9} = 98.8\%$$

We have $$w_s = \frac{V_d}{M_d}\gamma_w - \frac{1}{G}$$

$$\frac{1}{G} = \frac{V_d}{M_d}\gamma_w - w_s = \frac{8.9}{19.0}(1) - 0.1053$$

$$= 0.3631$$

$$G = \frac{1}{0.3631} = 2.75$$

Example 3.9

A fully saturated sample of clay was found to have mass specific gravity of 1.91 and water content of 29%. The soil sample was oven-dried and its mass specific gravity was found to reduce to 1.83. Calculate the shrinkage limit of soil.

Solution

For saturated soil sample,

$$e = wG = 0.29\,G$$

$$G_m = \frac{\gamma}{\gamma_w} = \left[\frac{(G+e)\gamma_w}{1+e}\right]\frac{1}{\gamma_w}$$

$$1.91 = \frac{G + 0.29G}{1 + 0.29G}$$

$$1.91 + 0.554\,G = G + 0.29G = 1.29\,G$$

$$G = \frac{1.91}{0.736} = 2.59$$

Shrinkage limit,

$$w_s = \frac{V_d}{W_d}\gamma_w - \frac{1}{G}$$

$$= \frac{\gamma_w}{(\gamma)_{dry\ state}} - \frac{1}{G}$$

$$= \frac{1}{(G_m)_{dry\ state}} - \frac{1}{G} = \frac{1}{1.83} - \frac{1}{2.59} = 16\%$$

Example 3.10

The liquid limit and shrinkage limit of a soil sample are 49% and 16% respectively. If the volume of a specimen of this soil decreases, on drying, from 37.2 cm³ at liquid limit to 22.4 cm³ at shrinkage limit, compute the specific gravity of soil particles.

Solution

Liquid limit, $w_L = 49\%$

Shrinkage limit, $w_s = 16\%$

Volume of soil specimen at liquid limit, $V_L = 37.2\ \text{cm}^3$

Volume of soil specimen at shrinkage limit, $V_d = 22.4\ \text{cm}^3$

we have

Shrinkage ratio,

$$SR = \frac{\left(\frac{V_L - V_d}{V_d}\right)\times 100}{w_L - w_s} = \frac{\left(\frac{37.2 - 22.4}{22.4}\right)\times 100}{49 - 16}$$

$$= 2$$

Also

$$SR = \frac{W_d}{V_d\gamma_w}$$

∴

$$\frac{W_d}{V_d} = (SR)\gamma_w = 2\gamma_w$$

$$w_s = \frac{V_d}{W_d}\gamma_w - \frac{1}{G} = \frac{\gamma_w}{2\gamma_w} - \frac{1}{G}$$

$$0.16 = \frac{1}{2} - \frac{1}{G}$$

$$\frac{1}{G} = \frac{1}{2} - 0.16 = 0.34$$

$$G = \frac{1}{0.34} = 2.94$$

Example 3.11

The liquid limit and plastic limit of a soil are 34% and 26% respectively. When the soil is dried from its state at liquid limit to dry state the reduction in volume was found to be 35% of its volume at liquid limit. The corresponding volume reduction from the state of plastic limit to dry state was 25% of its volume at plastic limit. Calculate (*i*) shrinkage limit and (*ii*) shrinkage ratio

Solution: $w_L = 34\ \%\ \ w_p = 26\ \%$

(*i*) Let volume at liquid limit be denoted by V_L and that at plastic limit by V_p.

Then $V_d = V_L - 0.35\ V_L = 0.65\ V_L$

Also $V_d = V_p - 0.25\ V_p = 0.75\ V_p$

$$\therefore \quad V_p = \frac{0.65}{0.75} V_L = 0.87 V_L$$

Referring to Fig.3.6, $w_S = w_L - AB$

From similar triangles, ABE and CDE,

$$\frac{AB}{CD} = \frac{BE}{DE}$$

$$\therefore \quad AB = \frac{BE}{DE} . CD$$

$$= \frac{0.35 V_L}{0.13 V_L} \times 0.08 = 0.215$$

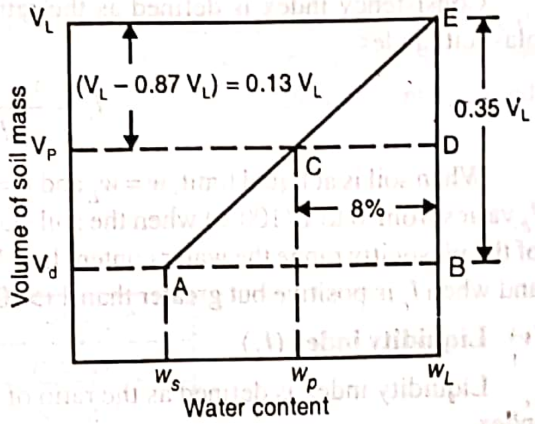

Fig. 3.6. For Example 3.11

$$\therefore \quad w_s = 0.340 - 0.215 = 12.5\%$$

(*ii*) Shrinkage ratio,

$$SR = \frac{\left(\dfrac{V_L - V_P}{V_d}\right) \times 100}{w_L - w_p} = \frac{(V_L - 0.87 V_L) \times 100}{0.65 V_L (34 - 26)}$$

$$= \frac{0.13 \times 100}{0.65 \times 8} = 2.5$$

3.5.6 Atterberg Indices

Following is the list of Atterberg indices:

1. Plasticity index
2. Flow index
3. Toughness index
4. Consistency index
5. Liquidity index

(*i*) Plasticity index

Plasticity index is defined as liquid limit minus plastic limit.

$$I_p = w_L - w_p \qquad 3.5(vii)$$