Chapter 4: Plasticity of Fine-Grained Soils

4.1 Introduction

The physical and mechanical behavior of fine-grained soils is linked to four distinct states: solid, semisolid, plastic and liquid in; order of increasing water content. If a soil initially is in a liquid state, it locates at point A in Figure (4.1). As the soil dries, its water content reduces and consequently, its volume.

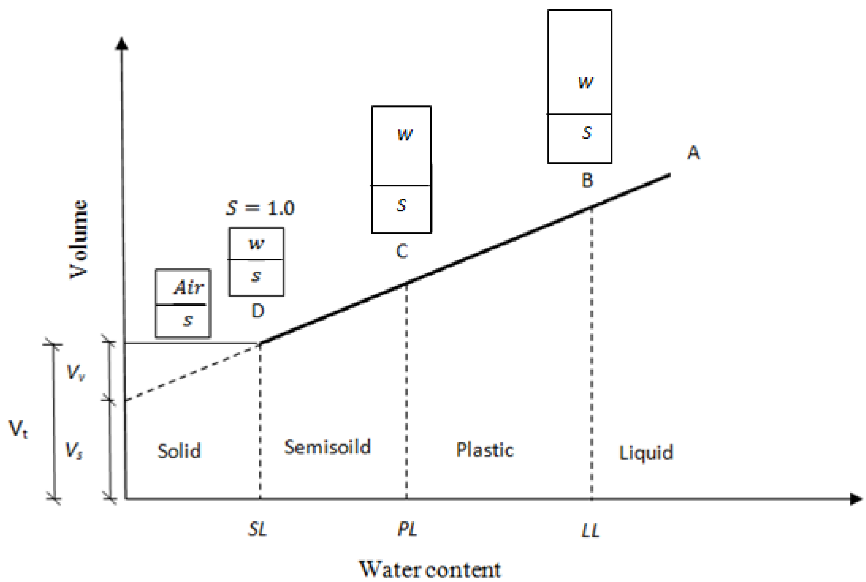


Figure (4.1) Change in soil states as a function of water content

At point B, the soil becomes so stiff that it can no longer be flow as a liquid. The boundary water content at point B is called the liquid limit (LL). As the soil continues to dry, there is a range of water content at which the soil can be molded into any desired shape without rupture. The soil at this state is said to exhibit plastic behaviour-the ability to deform continuously without rupture. But if drying is continued beyond the range of water content for plastic behavior, the soil becomes a semisolid. The soil cannot be molded now without visible cracks appearing. The water content at which the soil changes from a plastic to a semisolid is known as the plastic limit (PL). The rang of water contents over which the soil deforms plastically is known as the plasticity index, (PI);

$$PI = LL - PL \tag{4.1}$$

As the soil continues to dry, it comes to a final state called the solid state. At this state, no further volune change occurs since nearly all the water in the soil has been removed. The water content at which the soil changes from a semisolid to a solid state is called the shrinkage limit (SL). The shrinkage limit is useful for the determination of the swelling and shrinkage potential of soils. The liquid and plastic limits are called the Atterberg limits named after their originator, Swedish soil scientist, Atterberg (1911).

Since engineers are interested in the strength and deformation of materials, we can associate specific strength characteristic to each of the soil states. At one extreme, the liquid state, the soil has the lowest strength and the largest deformation. At the other extreme, the solid state, the soil has the largest strength and the lowest deformation. A measure of soil strength using the Atterberg limits is known as the liquidity index (LI) and is expressed as:

$$LI = \frac{w - PL}{PI} \tag{4.2}$$

The liquidity index is the ratio of the difference in water content between the natural or in-situ water content of a soil and its plastic limit to its plasticity index. Table below shows a description of soil strength based on the values of (LI).

Values of LI	Description of soil strength
LI < 0	Semisolid state – high strength , brittle , (sudden) fracture is expected
0 < LI < 1	Plastic state – intermediate strength, soil deforms like a plastic material
LI > 1	Liquid state – low strength , soil deforms like a viscous fluid

4.2 Liquid Limit (*LL*)

The liquid limit is determined from an apparatus Figure (4.2) that consists of a semispherical brass cup that is repeatedly dropped onto a hard rubber base from a height of 10 mm by a cam-operated mechanism. The apparatus was developed by A. Casagrande (1932) and the procedure for the test is called the Casagrande cup method.

A dry powder of the soil is mixed with distilled water into a paste and placed in the cup to a thickness of about 12.5 mm. The soil surface is smoothed and a groove is cut into the soil using a standard grooving tool. The crank operating the cam is turned at a rate of 2 revolutions per second and the number of blows required to close the groove over a length of 12.5 mm is counted and recorded. A specimen of soil within the closed portion is extracted for detemination of the water content. The liquid limit is defined as the water content at which the groove cut into the soil will close over a distance of 12.5 mm following 25 blowes. This is difficult to achieve in a single test.

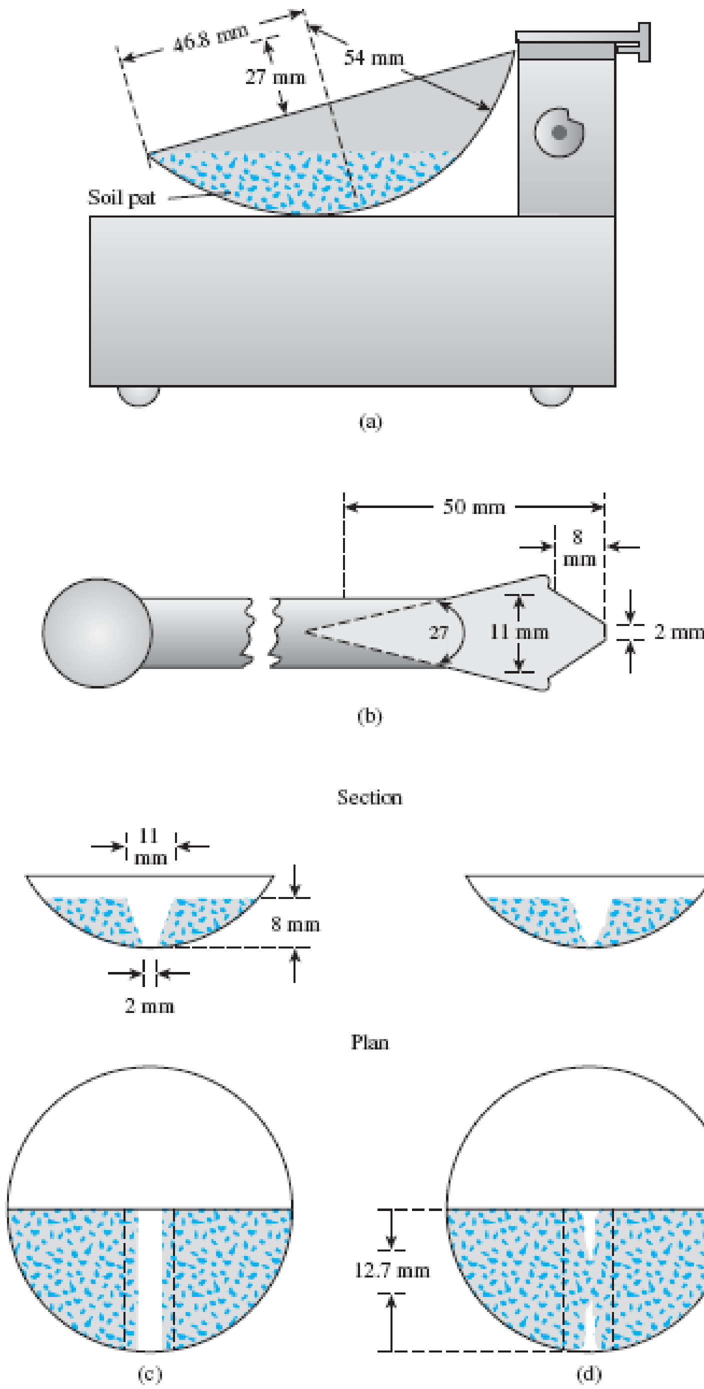


Figure (4.2) Liquid limit test: (a) Liquid limit device; (b) grooving tool; (c) soil pat befor test; (d) soil after test

Four or more tests at different water contents are usually required for terminal blows (number of blows to close the groove over a distance of 12.5 mm) ranging from 10 to 40. The results are presented in a plot of water content (ordinate, arithmetic scale) versus terminal blows (abscissa, logarithm scale) as shown in Figure (4.3).

The best-fit straight line to the data points, usually called the flow line, is drown. The liquid limit is read from the graph as the water content on the liquid state line corresponding to 25 blows.

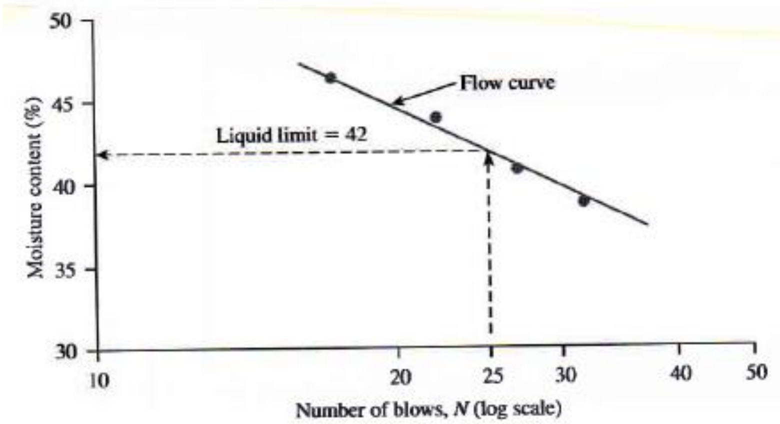


Figure (4.3) Flow curve for liquid limit determination of a clayey silt

4.3 Plastic Limit (*PL*)

The plastic limit is determined by rolling a small clay sample [Figure (4.4)] into threads and finding the water content at which threads approximately 3 mm in diameter will just start to crumble. Two or more determinations are made and the average water content is reported as the plastic limit.

Figure (4.4) Rolling of soil mass on ground glass plate to determine plastic limit

4.4 Shrinkage Limit (SL)

The shrinkage limit is determined as follows. A mass of wet soil, m_1, is placed in a porcelain dish 44.5 mm in a diameter and 12.5 mm high and then oven-dried. The volume of oven-dried soil is determined by using mercury to occupy the vacant spaces caused by shrinkage. The mass of the mercury is determined and the volume decrease casued by shrinkage can be calculated from the known density of mercury. The shrinkage limit is calculated from

$$SL = \left(\frac{m_1 - m_2}{m_2} - \frac{V_1 - V_2}{m_2}\frac{\gamma_w}{g}\right) \times 100 \qquad (4.3)$$

Where m_1 is the mass of the wet soil, m_2 is the mass of the oven-dried soil, V_1 is the volume of wet soil, V_2 is the volume of the oven-dried soil, and g is the acceleration due to gravity (9.8 m/s^2). The range of water content from the plastic to the shrinkage limits is called the shrinkage index (SI).

$$SI = PL - SL \qquad (4.4)$$

4.5 Plasticity Chart

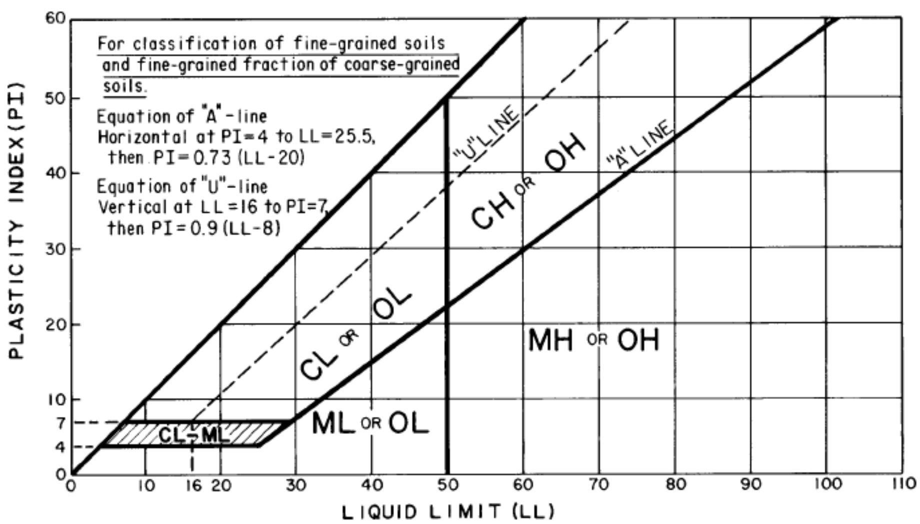
Experimaental results from soils tested from different parts of the world were plotted on a graph of plasticity index (ordinate) versus liquid limit (abscissa). It was found that clay, silt, and organic soils lie in distinct regions of the graph. A line defined by the equation:

$$PI = 0.73(LL - 20)\%$$

called the "A-line", delineates the boundaries between clays (above the line) and silts and organic soils (below the line). A second line, the U-line expresses as:

$$PI = 0.9(LL - 8)$$

defines the upper limit of the correlation between plasticity index and liquid limit. It the results of your soil tests fall above the U-line, you should be suspicious of your results and repeat your tests.



Plasticity chart for fine-grained soils

Example 4.1

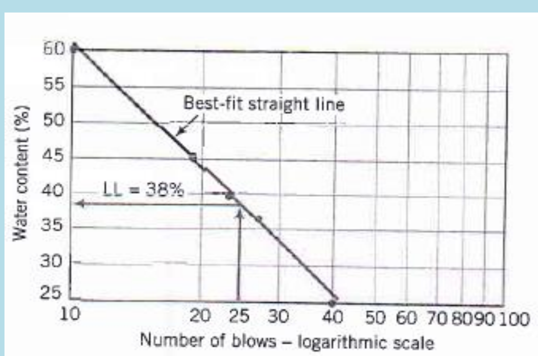
A liquid limit test conducted on a soil sample in the cup device gave the following results:

Number of blows	10	19	23	27	40
Water content (%)	60	45.2	39.8	36.5	25.2

Two determinations for the plastic limit gave water contents of 20.3 % and 20.8 %. Determine (a) the liquide limit and plastic limit, (b) the plasticity index, (c) the liquidity index if the natural water content is 27.4%, and (d) the void ratio at the liquid limit, if G_s = 2.7. if the soil were to be loaded to failure, would you expect a brittle failure?

Solution:

(a) Plot the data



Plot of the flow curve by the Casagrande cup method

The water content on the liquid state line corresponding to a terminal blow of 25 gives the liquid limit,

$$LL = 38\ \%$$

The plastic limit is

$$PL = \frac{20.3 + 20.8}{2} = 20.6\ \%$$

(b) Calculate *PI*

$$PI = LL - PL = 38 - 20.6 = 17.4\%$$

(c) Calculate *LI*

$$LI = \frac{(w - PL)}{PI} = \frac{27.4 - 20.6}{17.4} = 0.39$$

(d) Calculate the void ratio

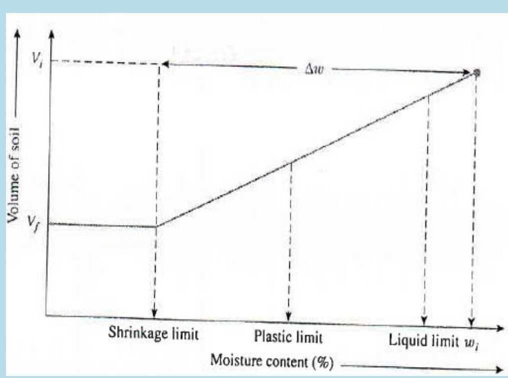
Assume the soil is saturated at the liquid limit. For a saturated soil, $e = wG_s$. Thus,

$$e_{LL} = LLG_s = 0.38 \times 2.7 = 1.03$$

Brittle failure is not expected as the soil is in a plastic state ($0 < LI < 1$).

Example 4.2

A saturated soil has the following characteristics: initial volume ($V_i = V_1$) = 19.65 cm^3. Final volume ($V_f = V_2$) = 13.5 cm^3, mass of wet soil (m_1) = 36g, and mass of dry soil (m_2) = 25g. Determine the shrinkage limit.



Solution:

$$SL = \left(\frac{m_1 - m_2}{m_2} - \frac{V_1 - V_2}{m_2}\rho_w\right) \times 100$$

$$= (\frac{36-25}{25} - \frac{19.65-13.5}{25} \times 1) \times 100$$

= 19.4 %

Example 4.3

A sample of saturated clay has a volume of 97 cm^3 and a mass of (0.202 kg). When completely dried out, the volume reduces to (87 cm^3) and its mass (0.167kg). Find:

a- Initial water content
b- Shrinkage limit
c- Specific gravity

Solution:

At fully saturated state;

$$\rho = \frac{M}{V} = \frac{202}{97} = 2.08\ gm/cm^3$$

$$\gamma_{sat} = \rho g = \left(\frac{G_s + e}{1+e}\right)\gamma_w \quad \Rightarrow \quad \rho = (\frac{G_s+e}{1+e})\rho_w$$

$$2.08 = \frac{G_s + e}{1+e}\left(1\,\frac{gm}{cm^3}\right) \qquad \dots\dots\dots\dots\dots\dots\dots (1)$$

$$w = \frac{M_w}{M_s} = \frac{202-167}{167} = 0.21 = 21\%$$

$$Se = G_s w \ \Rightarrow 1 \times e = G_s \times 0.21 \qquad \dots\dots\dots\dots\dots\dots (2)$$

Solve (1) and (2) yields;

G_s = 2.69 , e = 0.565

At dry state,

$$\rho_d = \frac{M_s}{V} = \frac{167}{87} = 1.92\ gm/cm^3$$

$$\gamma_d = \frac{G_s}{1+e}\gamma_w \qquad or \qquad \rho_d = \frac{G_s}{1+e}\rho_w$$

$$\Rightarrow 1.92 = \frac{2.69}{1+e}(1) \quad \Rightarrow \quad e_{dry} = 0.4$$

$$e_{SL} = e_{dry} = 0.4$$

$$Se = G_s w \qquad (w=SL)$$

$$1 \times 0.4 = 2.69 \times SL \quad \Rightarrow \quad SL = 0.15 = 15\%$$

Example 4.4 (H.W)

A dry sample of soil has the following properties:

LL= 52%, PL = 30%, G_s = 2.7, e = 0.53. Find:

Shrinkage limit, dry density and dry unit weight.

Ans:

SL = 19.6%

ρ_d = 1.764 gm/cm^3

γ_d = 17.3 kN/m^3

Problems

4.1 Following are the results from the liquid and plastic limit tests for a soil.
Liquid limit test:

Number of blows, *N*	Moisture content (%)
16	36.5
20	34.1
28	27.0

Plastic limit test: PL= 12.2%

a- Draw the flow curve and obtain the liquid limit.
b- What is the plasticity index of the soil?
Ans: (b) *PI* = 16.3 %

4.2 Determine the liquidity index of the soil described in Problem 4.1, if $w_{\text{in situ}}$ = 31%.
Ans: *LI* = 1.15

4.3 Following are the results from the liquid and plastic limit tests for a soil.
Liquid limit test:

Number of blows, *N*	Moisture content (%)
15	42
20	40.8
28	39.1

Plastic limit test: PL= 12.2%

a- Draw the flow curve and obtain the liquid limit.
b- What is the plasticity index of the soil?
Ans: (b) *PI* = 21 %

4.4 Refer to Problem 4.3. Determine the liquidity index of the soil when the *in situ* moisture content is 26%.

Ans: *LI* = 0.35

4.5 A saturated soil has the following characteristics: initial volume (V_i) = 24.6 cm^3, final volume (V_f) = 15.9 cm^3, mass of wet soil (M_l) = 44 g, and mass of dry soil (M_2) = 30.1 g. Determine the shrinkage limit.

Ans: *SL* =17.3%