1.1 INTRODUCTION

Soil Mechanics is defined as the branch of engineering science which enable an engineer to know theoretically or experimentally the behavior of soil under the action of loads (static or dynamic) and gravitational forces as well as under the influence of water and temperature. Simply speaking it is the knowledge of engineering science. which deals with properties, behavior and performance of soil as a construction material or foundation support. Terzaghi, a famous scientist defines soil mechanics as follows:

Soil Mechanics is the application of laws of hydraulics and mechanics to engineering problem dealing with sediments and other unconsolidated accumulations of solid particles produced by the mechanical and chemical disintegration of rocks.

With the recent advances in the science of Engineering, the design and execution of large projects, which at times were considered beyond imagination and control, have now become quite common. Sky scrapers, subways, maritime and off shore structures, dams and bridges spanning the sea are some examples of large projects.

For the design and construction of almost all such projects the engineers have to deal with both soil and rock either, as construction material or as a foundation support. Further, it is known that physical and engineering properties of soil and rock are very much dependent of the geological processes of formation. Few decades back, it was therefore considered more logical to use a more descriptive term of geotechnical engineering instead of Soil Mechanics. Thus Soil Mechanics, now-a-days is considered as a section of geotechnical engineering.

1.2 OBJECTIVES OF SOIL MECHANICS

Various objectives of soil mechanics are

1. To perform engineering soil surveys.
2. To develop suitable soil sampling devices and soil sampiing methods.

3. To develop suitable soil testing devices and testing methods.
4. To collect information about soil and their physical properties in the light of fundamental knowledge of soil mechanics, earth work and foundation engineering.
5. To determine physical properties of soil.
6. To evaluate and interpret test results and their application to the use of soil as foundation support, construction material or under the action of gravitational forces.
7. To try to understand the physical process which actually take place in soils when subjected to various factors, such as static and dynamic loads, water, temperature and environmental effects.
8. To select and adopt suitable soil conservation techniques.
9. To select and adopt the most suitable and economical methods to control sedimentation of dam reservoirs.
10. To select suitable sites for disposal of solid waste (i.e., land fills) and to deal with their design, operation and post completion problems.

1.3 SOIL

The term soil according to engineering point of view is defined as the material, by means of which and upon which engineer build their structures. The term soil includes entire thickness of earth's crust (from ground surface to bed-rock) which is accessible and feasible for practical utilization as a foundation support or construction material. It is composed of loosely bound mineral grains of various sizes and shapes formed due to weathering of rocks. It also has organic matter, water and air in it. The behavior of soil as a foundation support or construction material is greatly influenced by the presence of moisture in it, the fluctuation of ground water table, freezing and thawing phenomena, history of the formation/deposit and seismicity of the area. The binding power of soil grains is very low as compared to the binding power of rocks. The type of soil may vary from clay to gravel. The top soil which usually extends to a depth of about two feet contains organic matter and is generally considered unsuitable for Civil Engineering use.

1.4 FORMATION OF SOIL

Soil is generally formed by the disintegration and decomposition of rock and minerals at or near the earth's surface through the action of many natural, physical, mechanical and chemical agents, which break them into smaller and smaller particles (Fig: P-4).

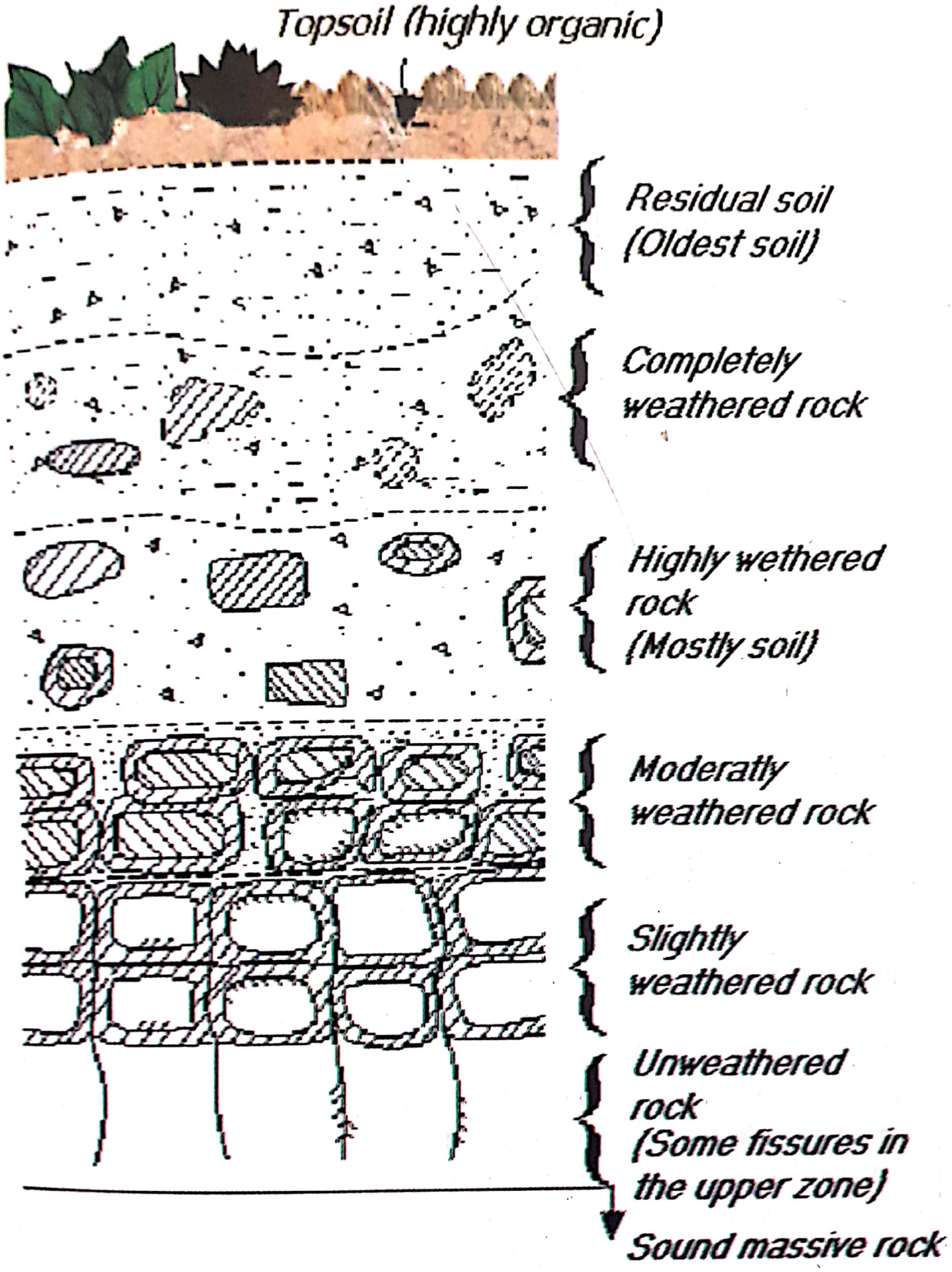


Fig: P-4. Different stages of weathering of rocks and formation of soil.

The weathering of rocks disintegrates them into the soil. Gravity, wind, snow and water help in the transportation of disintegrated material from the parent rock and deposit at various places. Soil deposits found on the earth are the result of this ages-old action. As this process has been going on and still continuous, layers of different soil deposits exist on earth's surface.

1.5 TYPES OF SOIL

a. Geological Consideration:

The properties of soil highly depend on the geological agent/process through which the soil deposits have been developed.

Following are the types of soil based on the geological agents/processes of formation of soil.

1. Glacial soil: This type of soil is developed, transported and deposited by the action of glaciers. These deposits consist of rock fragment, boulder, gravel, sand, silt and clay in various proportions (a heterogeneous mixture of all sizes of particles).

2. Residual soil: This type of soil is found on nearly flat rock surfaces where the weathering action has produced a soil with a little or no tendency to move. Residual soil also occurs when the rate of weathering is higher than the rate of removal. The surface soil formed due to weathering of upper rock layers; conceal the parent intact rock below ground surface.

3. Alluvial soil: The soil transported and deposited by water is called alluvial soil. As flowing water (stream or river) loses velocity, it tends to deposit some of the particles that it was carrying in suspension or by rolling, sliding or skipping along the river bottom. Coarser of heavier particles are dropped first. Hence on the higher reaches of a river, gravel and sand are found. However on the lower parts, silt and clay dominate, where the flow velocity is almost zero or very small, i.e., when the river enters the sea or a lake. Thus river deposits are segregated according to size.

4. Wind blown soil or Aeolian soil: The soil transported by wind and subsequently deposited is known as wind blown soil or Aeolian deposits. Wind can move small particles by rolling or carrying them. Wind born soil has two main types namely Dune and Loess.

i- *Dune or Dune Sand:* In arid parts of the world, wind is continually forming sand deposits in the form of the dunes characterized by low hill and ridge formation. They generally occur in deserts and comprise of sand particles which are fairly rounded and uniform in size. Dune material is generally a good source of sand for construction purposes.

ii- *Loess:* Accumulations of wind blown dust (mainly siliceous silt or silty-clay) laid down in a loose condition is known as loess. The dust is originally derived from desert areas or from vegetation free areas around the ice sheets. Silt soil in arid regions have no moisture to bond the particles together and are very susceptible to the effects wind and therefore can be carried great distances by wind storms. An important engineering property of loess is its low density and high permeability. In saturated condition its strength falls significantly, such that its structures collapses and it consolidates under its own weight. Saturated loess is very weak and always causes foundation problems e.g., liquefaction

b. Engineering Consideration:

The types of soil are based solely on the particle size. Since the engineering properties of soil markedly change with the change of particle size, different names are assigned to particular ranges of particle sizes.

1. Clay: It is composed of very fine particles less than .002 mm in size. They are flaky in shape and therefore have considerable surface area. These surfaces carry electrical charge, which helps in understanding the engineering properties of clay soils. In a moist condition, clay becomes very sticky and can be rolled into threads. Due to electrical charge, clay shows high inter-particle attraction and thus exhibits sufficient cohesion. It has a high dry strength, low erosion, good

workability under moist condition, and compacts readily. It has no inter-particle friction and is, therefore, subjected to slides at high moisture contents. It also is susceptible to shrinkage and swelling. It has very low permeability.

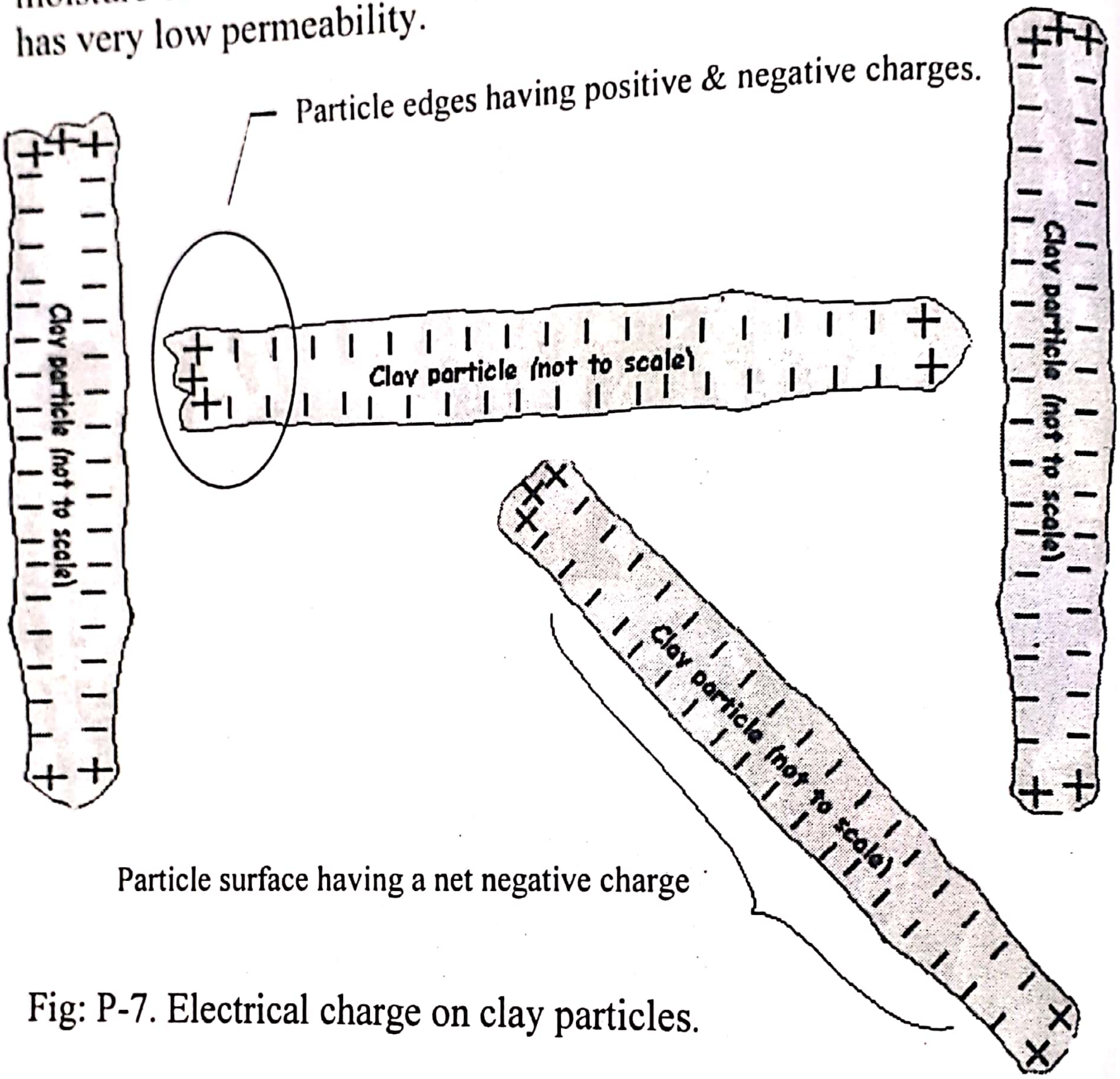


Fig: P-7. Electrical charge on clay particles.

2. Silt: It is composed of particle between .002 and .06 mm in size. It ha high capillarity, no plasticity and has very little dry strength.
3. Sand: It consists of particles ranging in size from .06 mm to 2 mm. These particles may be round to angular in shape. It has no plasticity, high strength in a confined state and possesses considerable frictional resistance. It has high permeability and low capillarity.
4. Gravel: It consists of particle varying in size from 2 mm to 60 m. It is a good foundation material. When sand and silt are mixed with gravel its bearing capacity in further increased.
5. Cobbles or Boulders: Particles larger than gravel are commonly known as cobbles or boulders. Cobbles generally very in size from

60mm to 200mm. The material larger than 200mm are designated as boulders.

6. Organic Matter: The main source of organic matter is the plants or animal remains that are added to the soil when these organism die. Plants decompose at a slower rate than the animal remains. Commonly about 12" of the soil from top surface has a major concentration of organic matter. Organic matter has open spongy structure and is mechanically weak. It undergoes large volume changes under loads and contains high natural moisture content. The strength of soil is very much reduced when the concentration of organic matter is more than 2% and the soil is considered unsuitable for foundation support.

1.6: PHYSICAL PROPERTIES OF SOIL

The fundamental physical properties of soil are colour, structure, particle size and shape, specific gravity, unit weight, porosity, void ratio, soil phases, moisture content, and consistency.

1. Colour:

It is the most common property of soil. Soil exist in nature in a wide variety of colours depending upon the particular type of soil mineral matter, organic contents, the amount of colouring oxides and the degree of oxidation. Black colour of soil is due to the presence of manganese compounds, green or blue colour due to ferrous compound, red, brown or yellow due to iron, and grey due to organic matter.

Soil Structure:

Arrangement or grouping of soil particles depending upon their size and shape in various patterns of structural framework is called soil structure. This arrangement is usually developed during the process of sedimentation or rock weathering.

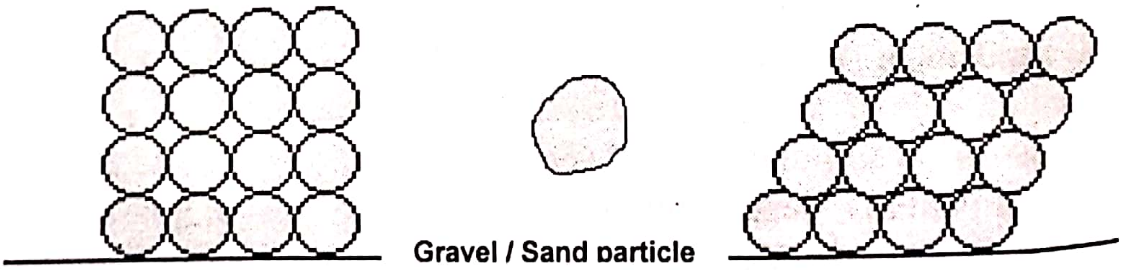
Soil deposits at the face of earth, are made by many natural processes of accumulations of soil particles over historical period of time. During the process of accumulation soil particles arrange/group themselves in different patterns, depending upon their size and shape (mass to surface area ratio). For coarse grained or cohesion-less soil, mass to surface area ratio, is relatively higher. Therefore, the effect of gravity has major influence over the arrangement of particles of these soils, and the effect of electrical charge on the particle surface is negligible. The fine-grained soil (mainly clay) because of their low mass to surface area ratio is more affected by the electrical forces acting on their surfaces compared with gravity forces.

Terzaghi grouped the most common patterns of soil structure into the following three principal groups.

i. Granular or Single-grained structure
ii. Flocculent Structure
iii. Dispersed structure

i. Granular or single-grained structure:

Cohesion-less soils (coarse-grained soils and silts> .01mm) tend to form a single-grained structure which may be loose or dense (Fig: P-9). In Single grained structure, each grain is in contact with several of its neighbors in such a way that the aggregate is stable even if there are no forces of adhesion at the point of contact between the grains. Single-grained soil structures are formed when soil grains independently settle slowly in quiet water. However experience indicates that it is possible for sands or silts to develop an unusual loose or honeycomb structure (Fig: P-10). Honeycomb structure may develop due to settlement of grains in soil-water suspension, or from a loosely dumped moist soil, where grains develop a particle-to-particle contact that bridge over relatively large void spaces and can resist the overburden pressure. Such deposits in coarse-grained soil may be unstable when subjected to shock or vibrations, resulting in quick volume reduction and loss of strength.



(a) Loose (a) Dense

Fig: P-9. Granular soil structure.

The risk of instability or loss of strength is reasonably reduced if some cementing at points of particle contacts exist. The cementation over, geologic time period may occur as percolating water precipitates various carbonates and other materials.

ii. Flocculent Structure:

The clay minerals are extremely flaky in shape and have a large surface area-to-mass ratio. The clay particles carry a negative electrical charge on their surfaces. The affect of electrical forces is more than the gravity forces. Clay deposits developed from particles settling out of soil-water suspension (either in fresh-water or salt-water) tend to form a flocculent structure. A flocculated structure is developed when the edge of one clay particle is attracted to the flat face of another (i.e., edge-to-face contact) (Fig: P-9). The structure of clay soil settling out in marine environment (salt-water, which acts as an electrolyte) is more flocculent than clay in fresh water.

Clay deposits with flocculent structure have high void ratio, low-density high water content and high permeability. The structure however is quite stable and resistant to external forces that can be maintained as long as the electrical charges on the edges of the particles remain opposite in sign to those on the faces. However, due to change of environment surrounding the clays such as the salts being leached from the deposit the inter-particle attraction and hence the strength is drastically reduced.

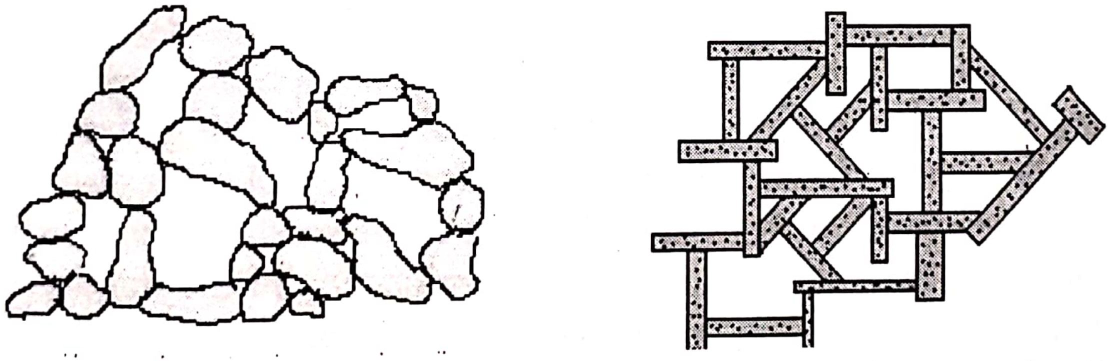
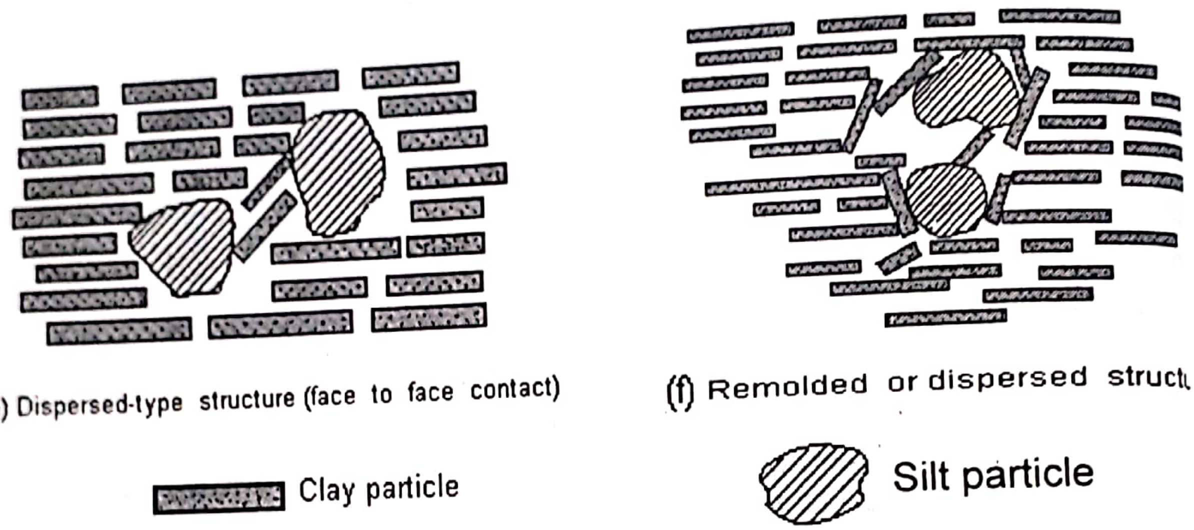

(c) Honeycomb structure in a granular soil **Flocculated-type structure (edge to face cor**

Fig: P-10. Honeycomb and flocculent structure.

iii Dispersed Structure:

The dispersed structure is developed when the edges and faces of the clay particles have similar electrical charge. The particles repel each other and the orientation is nearly parallel (Fig: P-11). The dispersed structure also develops as a result of remolding by the transportation process (man-made earth fills). The particle arrangement that develops from remolding has a more parallel orientation of particles. A flocculated structure with the addition of moisture content and application of compaction energy is changed to a dispersed or oriented structure.


(e) Dispersed-type structure (face to face contact)

(f) Remolded or dispersed structu

Fig: P-11. Dispersed structure.

3. Particle Shape and Size:

Particle size and shape very much influence the engineering properties of soil. Particles of coarse-grained soil (sand, gravel, boulder etc.) are generally bulky in shape, i.e., the length, width and thickness are approximately equal. Different shapes are commonly termed as angular, sub-angular, sub-rounded and rounded (Fig: P-12). The shapes of the particles however depend on the rock type, their age, weathering and transportation processes. The newer particles are generally angular, and rough surfaced. With time and as a result of weathering and transportation processes, the edges are broken and they change finally to rounded shape. Sub-angular and sub-rounded are the transition stages. The angular and rough surfaced particles possess better engineering properties compared with those of rounded and smooth particles. Some of the rocks, upon weathering produce flake-shaped particles. The presence of flaky particles in a granular soil mass has significant effect on the engineering properties (e.g., void ratio, density and compressibility). The flaky particles bridge over open spaces, which can resist overburden pressure and so develop relatively large void ratios (Fig: P-13). The flakes, however, are incapable of resisting the applied loading. They bend or break and allow rearrangement of particles under applied loading, which some times produce undesirable deformations.

Angular Sub-Angular Sub-Rounded

Fig: P-12.1. Particle shapes.

The silt particles although classified as fines are still bulky in shape and have the same mineralogical composition as the coarse grained soil.

The clay particles are very flaky (flat plate-like shape), where the length and width is many-many times the thickness. The clay particles originate from crystalline minerals and due to their distinct mineralogical composition, exhibit inter-particle attraction and bonding

Rounded Elongated Flaky

Fig: P-12.2. Particle shapes.

with water molecules. As a result the behavior of clay soil drastically changes with change of moisture content. At different moisture contents, but with same void ratio, a clay soil may behave as a liquid, plastic or a solid mass.

Individual clay particle seldom exists. Due to cohesive forces, they group together, to form a cluster. The clay particles are very small in size (less than .002mm or 2μ). However it must be kept in mind that the properties of clay (cohesion and plasticity) are due to the type of the mineral (i.e., clay mineral) and not due to its small size. The particles of non-clay minerals although smaller than .002mm, do not exhibit the clay properties (i.e., cohesion and plasticity).

Actual soil deposits consist of soil particles having variation in particle sizes. The variation of particle sizes may be small to large. An ideal particle size distribution (well graded) produces an optimum particle arrangement or packing. While a mass of soil having particles of nearly the same sizes (uniformly or poorly graded), produces a loose packing due to absence of small particles to fill the voids between bigger particles.

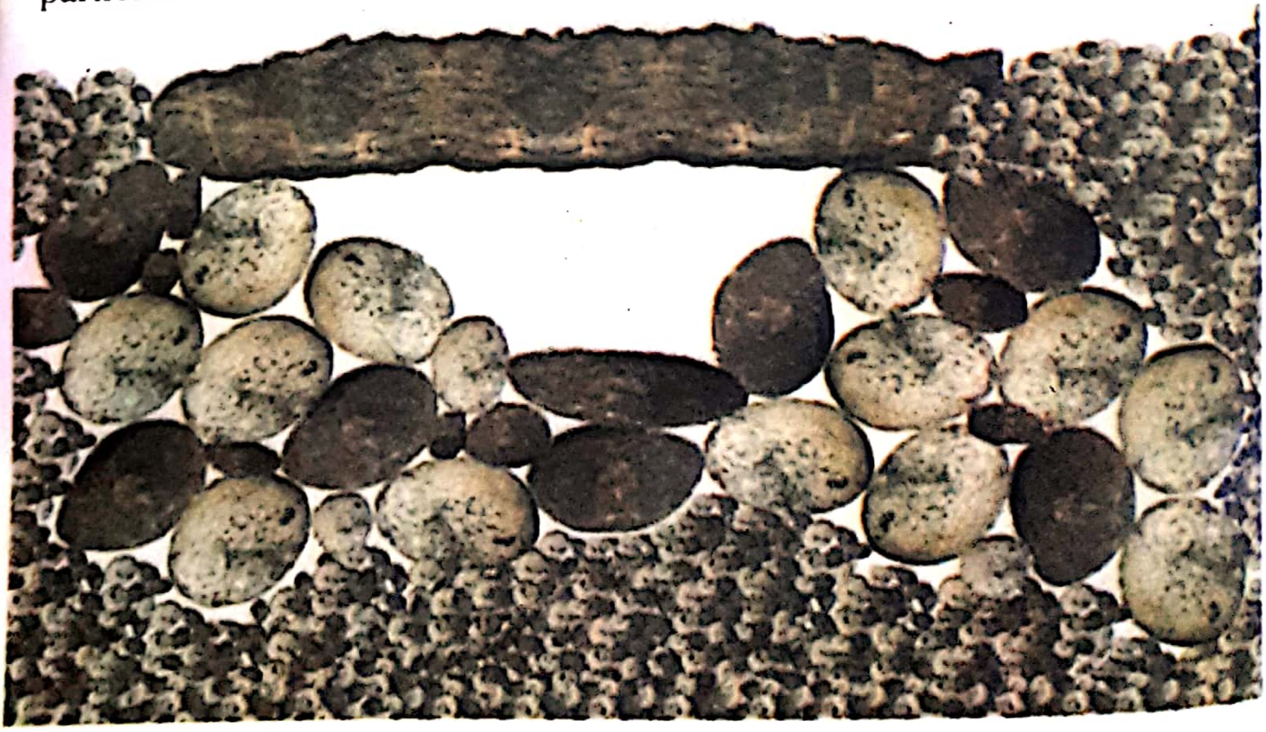


Fig: P-13. Elongated particles bridging the gap

4. Specific Gravity:

The specific gravity of any substance is defined as the ratio of the unit weight of that substance, to the unit weight of water at 4°C.

The above definition simply means that how many times a substance (or material) is heavier than water. For example the specific gravity of mercury of 13.6 means that if equal volumes of mercury and water are taken than mercury will be 13.6 times heavier than water. Similarly specific gravity of gold is 19.3 or one can say that gold is 19.3 times heavier than water. A geo-technical engineer is commonly interested in the specific gravity of the soil grains (or solids), which is defined as the ratio of unit weight of soil grains, to the unit weight of water. It is denoted by Gs and expressed as:

$$G_s = \frac{\gamma_s}{\gamma_w} = \frac{W_s}{V_s \gamma_w} \tag{1.1}$$

Where, γ_s = unit weight of the soil solids (no pores)

$$\gamma_s = W_s/V_s \tag{1.2}$$

Where W_s is the weight of soil solids, which is equal to the dry weight. And V_s is the volume of soil solids (no pores).
The term bulk specific gravity or mass specific gravity is also used and it is expressed as

$$G = \gamma_b/\gamma_w \tag{1.3}$$

Where γ_b = bulk density of soil.

Average values of G_s for soil solids range from 2.50 to 2.70, and it depends on the mineral making the soil particles. If the mineral composing the soil is heavier the specific will be greater. A soil mass may be composed of a single mineral or have been developed by a mixture of various minerals. Any mineral soil has a unique v specific gravity, which is independent of state of soil depos moisture content, compaction etc.).

The bulk specific gravity however depends on the state of soil deposit. It is variable i.e., lower for loose soil and higher for dense soil but can never be more than the specific gravity of soil solids.

The specific gravity is a very important soil property and is extensively used for the determination and calculation of many other soil properties, some of them are listed below.

i) Particle size analysis by hydrometer test.
ii) Porosity and void ratio
iii) Unit weight
iv) Critical hydraulic gradient in studying the quick condition especially to check piping failure hydraulic structures, or heaving of soil while excavating below water table.
v) Degree of saturation or zero air void in the compaction theory of soil.

It is therefore very important to pay serious attention and care to the determination of specific gravity of soil.

Specific gravity of some common soil minerals and various soils are given in the table below.

Table: P-15. Specific Gravity of some Minerals and Soil types.

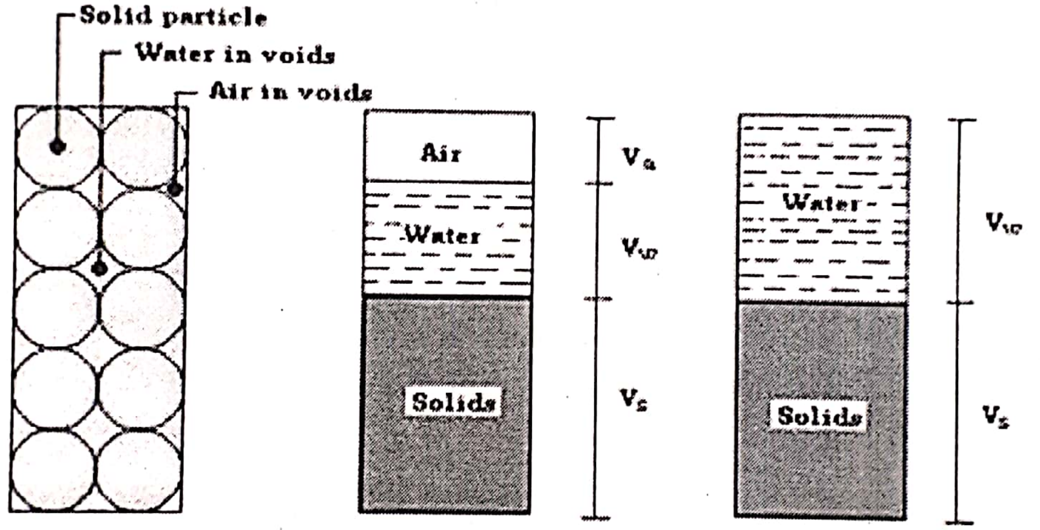
Minerals	Specific Gravity	Soil-type	Specific Gravity
Dolomite	2.8-2.9	Bentonite clay	2.13-2.18
Feldspar	2.5-2.6	Chalk	2.63-2.73
Gypsum	2.2-2.4	Clay	2.45-2.90
Illite	2.60	Humus	1.37
Quartz	2.60-2.65	Loess	2.65-2.75
Talc	2.7-2.8	Peat	1.26-1.8
Kaolinite	2.6-2.63	Silt	2.68-2.72
Magnetite	5.17-5.18	Quartz sand	2.60-2.65
Calcite	2.8-2.9	Lime	2.7

5. Soil Phases:

A soil mass is an assemblage or collection of solid particles of different sizes and shapes, which form a porous medium. Depending upon the circumstances these pores may be filled with air or water or both. The phase of a soil means any homogeneous part of a soil mass different from other parts in the mass and clearly separated from them.

Since soil is a porous medium consisting of three different homogenous parts, (e.g., solid particles, water and air) a given volume of soil mass may be regarded as a mass consisting of three fundamental phases, namely.

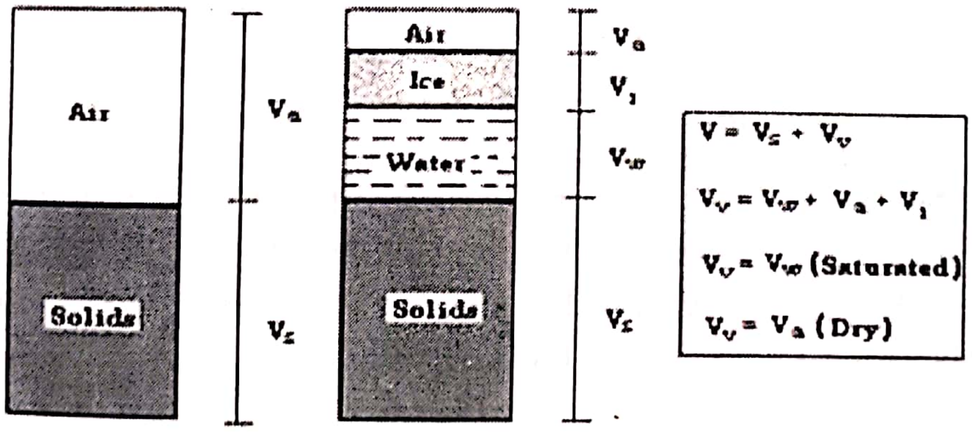
Solid phase
Liquid phase
Gaseous or vapour phase



Volume of
soil mass-V

Partially Saturated
3-phase soil mass

Fully Saturated
2-phase soil mass



Fully dried
2-phase soil mass

Frozen soil
4-phase soil mass

Fig: P-16. Schematic diagram indicating different soil phases

In cold regions, the pore water in the upper soil layers freezes due to accumulation of snow on the ground surface.

In the studies of these soils, four phases can be defined as under.

1- Solid phase
2- Liquid phase
3- Gaseous phase
4- Ice phase.

The volumetric proportion of different phases can be studied by phase diagram. It must be kept in mind that there is no real means of separating the soil phases and shown.

6. Porosity

A soil mass is a porous medium consisting of solid particle, and the pores or voids. The total volume of soil mass is the summation of volume of solid particles and the volume of pores or voids. The volume of the pores or voids depends on the degree of soil density or packing and is reduced considerably by compaction.

$$V = V_s + V_v \tag{1.4}$$

V = Total volume of soil mass
V_s = Volume of solid particles of soil.
V_v = Volume of voids, which may be filled with air or water or both

The ratio of volume of all the voids "V_v" to the total volume of the soil mass "V" is known as the porosity. It is denoted by 'n' and expressed in percentage.

$$n = \frac{V_v}{V} \times 100 \tag{1.5}$$

In the above basic formula, it is difficult to determine the term "V_v" by any simple means. The porosity "n" may be expressed in terms of other physical properties of soil and then it will be easily determined. The relationships can be developed as follows.

$$n = \frac{V_v}{V} = \frac{V - V_s}{V}$$

$$n = 1 - \frac{V_s}{V} \tag{1.6}$$

The specific gravity, $G = \frac{\gamma_s}{\gamma_w}$

$$G = \frac{W_s}{V_s \gamma_w} \qquad while \ \gamma_s = \frac{W_s}{V_s}$$

$$V_s = \frac{W_s}{G\gamma_w} \qquad \text{while } W_s = \text{dry weight of soil}$$

Putting the value of V_s in --*Eq*-(1.6)

$$n = 1 - \frac{W_s}{G\gamma_w V} \tag{1.7}$$

All the terms on the right hand side of Eq-3 can be easily determined and hence "n" can be calculated. Porosity falls in the range of

$$0 < n < 100$$

Since it is practically impossible to eliminate all the voids therefore porosity can never be zero. The increase in the volume of voids increases the total volume by the same amount therefore porosity can never be 100 percent.

Porosity helps in the studies of seepage through soil.

7. Void Ratio

It is defined as the ratio of volume of voids present in the soil to the volume of solid particles in a soil mass. It is denoted by "e".

$$e = \frac{volume\ of\ voids\ in\ soil}{volume\ of\ slids\ in\ soil} = \frac{V_v}{V_s} \tag{1.8}$$

Relationship with other soil properties.

$$e = \frac{V_v}{V_s} = \frac{V - V_s}{V_s} = \frac{V}{V_s} - 1 \tag{1.9}$$

$$e = \frac{VG\gamma_w}{W_s} - 1 \ \ while \ \ V_s = \frac{W_s}{G_s \gamma_w} \tag{1.10}$$

The values on the right hand side of the equation can be determined easily and hence "e" can be calculated.

Again from Eq-(1.9)

$$1 + e = \frac{V}{V_s}$$

$$\frac{1}{1+e} = \frac{V_s}{V} = \frac{V - V_v}{V}$$

$$\frac{1}{1+e} = 1 - \frac{V_v}{V} = 1 - n$$

$$n = 1 - \frac{1}{1+e}$$

$$n = \frac{1+e-1}{1+e} = \frac{e}{1+e} \qquad (1.11$$

Similarly it can be derived that

$$e = \frac{n}{1-n} \qquad (1.12$$

The void ratio is expressed as a number and the limiting values can be within the range.

$$0 < e << \infty$$

The common values however may range from 0.5 to 1.3. The values a lower for sand and higher for clay, but also depend upon the compacti The void ratio is extensively used in calculating the following importa soil parameters

i – unit weight $$\gamma_b = \frac{(es + G)}{1+e}\gamma_w \qquad (1.13)$$

$$\gamma_{sat} = \frac{(e+G)\gamma w}{1+e} \qquad (1.14)$$

$$\gamma_d = \frac{G\gamma\ w}{1+e} \tag{1.15}$$

$$\gamma_{sub} = \frac{(G-1)\gamma\ w}{1+e} \tag{1.16}$$

$$ii - Critical\ hydraulic\ gradient, i_c = \frac{G-1}{1+e} \tag{1.17}$$

$$iii - \text{Re}lative\ density.\ D = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \tag{1.18}$$

$$iv - Modulus\ of\ compressibility\ , m_v = \frac{e_1 - e_2}{(p_2 - p_1)(1 + e_1)} \tag{1.19}$$

$$v - Theoratical\ maximum\ dry\ density, \gamma_{d_{\max}} = \frac{G\gamma_w}{1+e} \tag{1.20}$$

$$vi - Final\ settlement, \Delta\ H = (\frac{\Delta_e}{1+e_1})\ H \tag{1.21}$$

Void ratio further plays an important role to understand the process of consolidation of soil and in the settlement analysis of structures. Practically, void ratio “e” cannot be reduced to zero but it can be more than one.

8. Soil Moisture Content:

The amount of water present in the voids of a soil in its natural state is termed as the moisture content of the soil. It is denoted by “m” and expressed as percentage. It is numerically expressed as under

$$m = \frac{weight\ \ of\ \ water}{weight\ \ of\ dry\ \ soil} \times 100 \tag{1.22}$$

It is a very important physical property since the behavior of soil is very much influenced by changes of moisture content. At large changes of moisture content the behavior of soil is entirely changed e.g., a soil which behaves as a solid at low moisture contents is changed to liquid state at high moisture content and the shear strength is practically is reduced to zero. Increase in soil moisture always increases the unit weight of a dry soil.

The moisture/water in the voids of a soil mass can occur in a variety of forms. Depending upon the form of occurrence they are given different names e.g.,

a- *Hygroscopic Moisture-*It is also known as adsorbed moisture, contact moisture or surface bound moisture. This form of soil moisture exists as a very thin film of moisture surrounding the surfaces of individual soil particles and is held by the force of adhesion. Practically the moisture present in an air dried soil sample may be termed as Hygroscopic moisture. The value of hygroscopic moisture content however depends on the atmospheric temperature, relative humidity and the type of soil. In fine grained soil such as clays, due to large specific surface, hygroscopic moisture is high (upto 20% or more) while in coarse grained soil (sand) it is relatively low due to limited amount of specific surface.

The approximate values of hygroscopic moisture for various soils is as under

1-	Sand	1-2 percent
2-	Silt	7-9 percent
3-	Clay	17-20 percent

The values are just approximate and vary with humidity and temperature etc.

Hygroscopic moisture is not affected by gravitational forces, capillary forces and air drying at ordinary temperature. Hygroscopic moisture film is bound so rigidly to the particle surfaces that it can not be removed even by centrifugation. It does not exert any hydrostatic pressure.

The difference between the weight of an air-dried sample to its weight after oven drying at + 105°C gives the amount of hygroscopic moisture present in the soil.

b- *Film Moisture:* The thickness of the moisture film around the soil particles varies depending upon the conditions such as weather etc. The moisture film attached to the soil particles, upon the layer of hygroscopic moisture film, is known is film moisture. It is held by the molecular forces and is not affected by gravity. It can move from points of higher potentials (heat or electric) to lower ones or from points of thicker to thinner films. The amount of film moisture depends on the specific surface i.e., higher the specific surface higher will be the film moisture and vice-versa.

c- *Capillary Moisture:* It is defined as the moisture content which in held within the voids of capillary size of soil. The capillary moisture is continuously connected to the ground water table. It rises above the water table and is held by the surface tension force of the menisci when the interconnected voids act as capillary tubes. The voids are completely filled with water and the soil is fully saturated. The height/thickness of capillary saturated zone above the ground water table depends on the fineness of the soil particles.

Capillary water can be removed from the soil by drainage only when, the quantity of water present within the voids is in excess of that retained by surface tension forces.

d- *Chemically Bound Moisture:* It is the moisture contained chemically within the mineral particles and can be removed only by chemical processes of the substance when the crystalline structure of the mineral breaks. The chemically bound water does not influence the physical or chemical properties of soil and therefore is not determined for soil engineering problems.

The moisture content determined through over drying method (or any other method) by Eq-(1.22) includes adsorbed moisture, film moisture and only that portion of capillary moisture, which is held within the voids by surface tension forces. All other forms of water (not discussed here) will be drained out by gravity as the soil sample is extracted from the soil mass (from surface or sub-surface layers). Chemically bound moisture is not important for common soil engineering problems and therefore is not determined.

The range of water content is

$$0 \leq m << \infty$$

It is not unusual for some soils (marine or organic lake soil) to have moisture content up to 300-400 percent. The common range of moisture content for most soil is under 50-60 percent. Oven dried soil has zero percent moisture and the soils which appear dry often have 2 to 4 percent moisture content.

9. Degree of Saturation:

The moisture content in a soil mass is variable. It continues changing depending upon the climatic conditions. In rainy season it is high while in dry weather it is low. The condition when voids are partially filled with water is expressed by the degree of saturation or relative moisture content. It is the ratio of actual volume of water in voids "V_w" to the total volume of voids "V_v".

It is denoted by "S" and is expressed by the following relationship.

$$S = \frac{V_w}{V_v} = \frac{W_w}{W_v} = \frac{m}{m_{sat}} \qquad (1.23)$$

W_w – is the weight of water actually present in the voids.
W_v – is wt of water that can fill all the voids.
m – actual moisture content.

m_{sat} – moisture content when all voids are totally filled with water.

The range of "S" is expressed as follows.

$$0 \leq S \leq 100$$

For an over dried soil, S = 0, which means that all the voids are filled with air i.e., $V_w = 0$. For fully saturated soil, S = 1, which means that all the voids are filled with water i.e., $V_w = V_v$. Remember! For air dried soil the value of 'S' is seldom equal to zero but is always more than zero, the value however depends on the type of soil, atmosphere temp and humidity etc.

10. Air Void Ratio or Air Content

In fully dried or partially saturated soil the voids are fully or partially filled with air. When the soil is considered for engineering purposes the volume of air should be reduced as much as possible. Since it contributes nothing to the strength when the soil is subjected to loading (e.g., highway embankment or foundation support etc.,) and obstruct the seepage flow when the soil is being used as a permeable medium (e.g., filters etc.,)

The air void ratio or air content is defined as the ratio of the volume of air present in the voids to the total volume of a soil mass.

$$A_v \text{ or } A = \frac{V_a}{V} = \frac{V_v - V_w}{V_v + V_s} \tag{1.24}$$

$$A = \frac{V_v - SV_v}{V_s\,(1 + \frac{V_v}{V_s})} \qquad \textit{while } V_w = SV_v$$

$$A = \frac{V_v\,(1 - S)}{V_s(1 + e)} \tag{1.25}$$

$$A = \frac{e\,(1 - s\,)}{1 + e} \tag{1.26}$$

$$A = n(1 - S) \qquad while \quad n = \frac{e}{1+e} \tag{1.27}$$

A study of Eq- (1.27), indicates that for fully saturated soil, the air content will be zero and for fully dried soil the air content will be equal to porosity. Air content fall within the range of

$$0 \le A < 100 \quad - percent.$$

11. Atterberg or Consistency Limits.

The term consistency is related to fine-grained soils (i.e., clay). In clay soil the shape of the particles has greater influence on engineering properties rather than the size. The flaky shape of the clay particles, with changes of moisture content results in a material, the properties of which are inherently variable. It is daily life experience of a common man that the strength of clay varies widely with changes of moisture content. It is very hard in dry state and behaves as a viscous fluid (almost zero shear strength) at high moisture content. The consistency of a soil is its physical state, at specific moisture content

Four consistency states are commonly defined for clays (cohesive soils)

1- Solid state
2- Semi solid state
3- Plastic state
4- Liquid state.

Atterberg, a swedish soil scientist defined the boundaries of four states in terms limits as follows.

1- Shrinkage Limit: It is the moisture content at which soil changes from solid to semi-solid state.

2- Plastic Limit: It is the moisture content at which soil passes from semi-solid to plastic state.

3- Liquid Limit: It is the moisture content at which the soil passes from plastic to liquid state.

The transition from one state to the next however is gradual, and according to above definitions it is quite difficult to know the value of moisture content at which the change of state occurs. The definition that clearly states the moisture content at which the change of state occurs will be given later.

The most important of these limits are the liquid and the plastic limits, which indicate the range of plastic state. The range of plastic state means, the upper and lower bounds of moisture content within which the soil behaves similar to a plastic material. It is the numerical difference between the liquid and plastic limits and is known as plasticity index.

Due to this plastic behavior of fine-grained soils, these limits relate to the plasticity characteristic of soil. Plasticity is a major characteristic of fine-grained (clay) soils. It is defined as the property that enables a material to undergo large irrecoverable deformations without cracking or crumbling. Since the plasticity, greatly influence the engineering properties, such as shear strength and compressibility, it is therefore used as a basis for the classification of fined grained soils.

As discussed earlier the plasticity does not depend on the size of the particles. Rock flour, for example, practically exhibits no plasticity, where as clay having the same size will exhibit a marked plasticity. Bentonite and kaolinite clays having almost similar particle sizes have different plasticity values. Actually many factors, such as, the size, shape, nature of the clay mineral and the nature of the adsorbed layer, control the plasticity. Where the average specific surface is high (more fine and flaky e.g; Montmorillonite clay having approximate size, length=0.1-0.5, & thickness=0.001-0.01.µm), the plasticity may be extremely high and the soil extremely compressible.

11-a. ShrinkageLimit:

It is defined as that moisture content at which a reduction in moisture will not cause a decrease in the total volume of soil mass, but an increase in moisture, will result in an increase in volume of soil mass.

This happens due to the fact, that at a certain point during the drying process, air begins to enter the soil mass and the volume decrease becomes appreciably less than the volume of water lost. The process of drying can be better explained by the following diagram:-

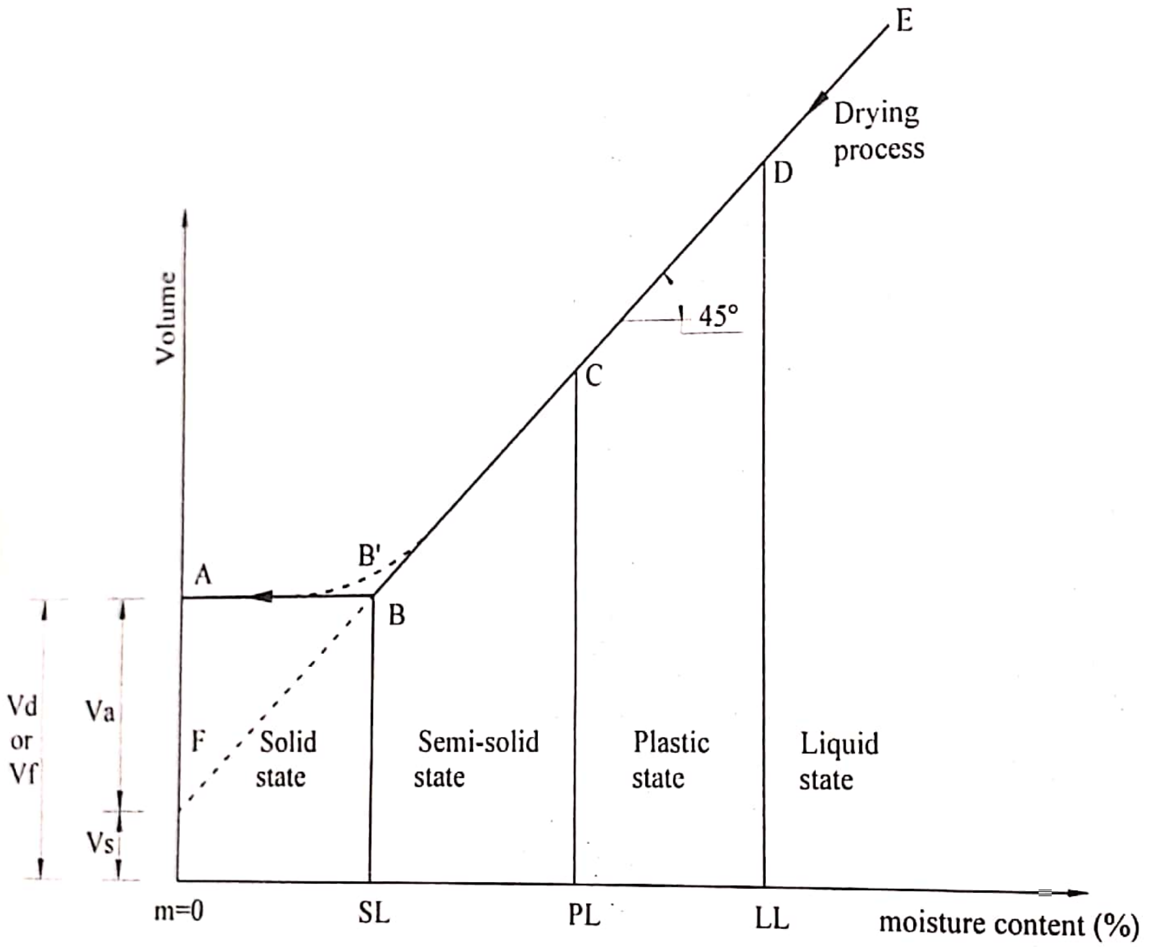


Fig:P-27. Relationship between volume of soil its and moisture conten

During drying process from point ‘E’ to point ‘B’ the reduction in total volume of soil mass is equal to the volume of moisture lost and the soil shrinks. As the drying continues from point ‘B’ to point ‘A’ i.e. up to zero % moisture content, no appreciable volume change observed, and the soil ceases to shrink. At this point the soil changes it color from dark to light. It should be kept in mind that at shrinkage limit the degree of saturation is 100 percent.

The shrinkage limit is not given very much importance and not commonly determined, since it is not used for classification of soil, as do liquid and plastic limits. The shrinkage limit however gives some idea about the soil structure e.g., a dispersed structure will generally produce a low shrinkage limit while a flocculated structure show a high shrinkage limit. It is also of much importance for certain soil types, which exhibit considerable volume change with changes in moisture content. It should be noted that, the smaller the shrinkage limit the more susceptible is the soil to change in volume. For example if the shrinkage limit of a soil is 10-percent, then according to Fig-P-27 when the moisture content exceeds this value the soil will begin to expand. And then in the drying cycle will start shrinking until the moisture content reduces back to 10-percent (i.e. shrinkage limit).

The concept of shrinkage limit of cohesive soil is helpful in studying the behavior of slopes of dams, highway embankments and cuts, especially to check the possibility of development of shrinkage cracks. In rainy seasons these cracks get filled with water, which increase the weight of earth mass due to saturation and exert hydrostatic pressure and eventually may cause a land slide to occur. Higher the liquid limit of a soil, higher is the shrinkage potential.

With the increase of moisture in a soil mass the thickness of moisture film around the clay particle increases, until at certain state the cohesion is reduced to such a low level that the soil behaves as a liquid. At this stage the soil particles are separated by water so widely that the shear strength of the soil mass is almost lost and the particles tend to flow under the influence of gravity. When this soil is subjected to drying, it looses its moisture and the particles which were separated by water get closer due to decrease in thickness of moisture film and the soil shrinks. During drying process the surface tension forces of the pore water, compress the particles together into a compact mass and the volume/void ratio of soil decreases. The loss of moisture accompanied by the decrease in volume of the soil mass continues down to the shrinkage limit moisture content. When this moisture content is attained, no further decrease in volume or shrinkage takes place. At this stage the menisci of the moisture tear off (Fig P-29) and air begins to enter the voids and further drying causes no volume change

It is worth bearing in mind that very high compressive stresses are developed during drying due to large number of soil pores simultaneously being subjected to water surface tension. Due to these shrinkage stresses the soil is densified to such a degree as if it has been subjected to overburden pressures of the order of 200 to 800 kpa.(Tschebotarioff,1936).

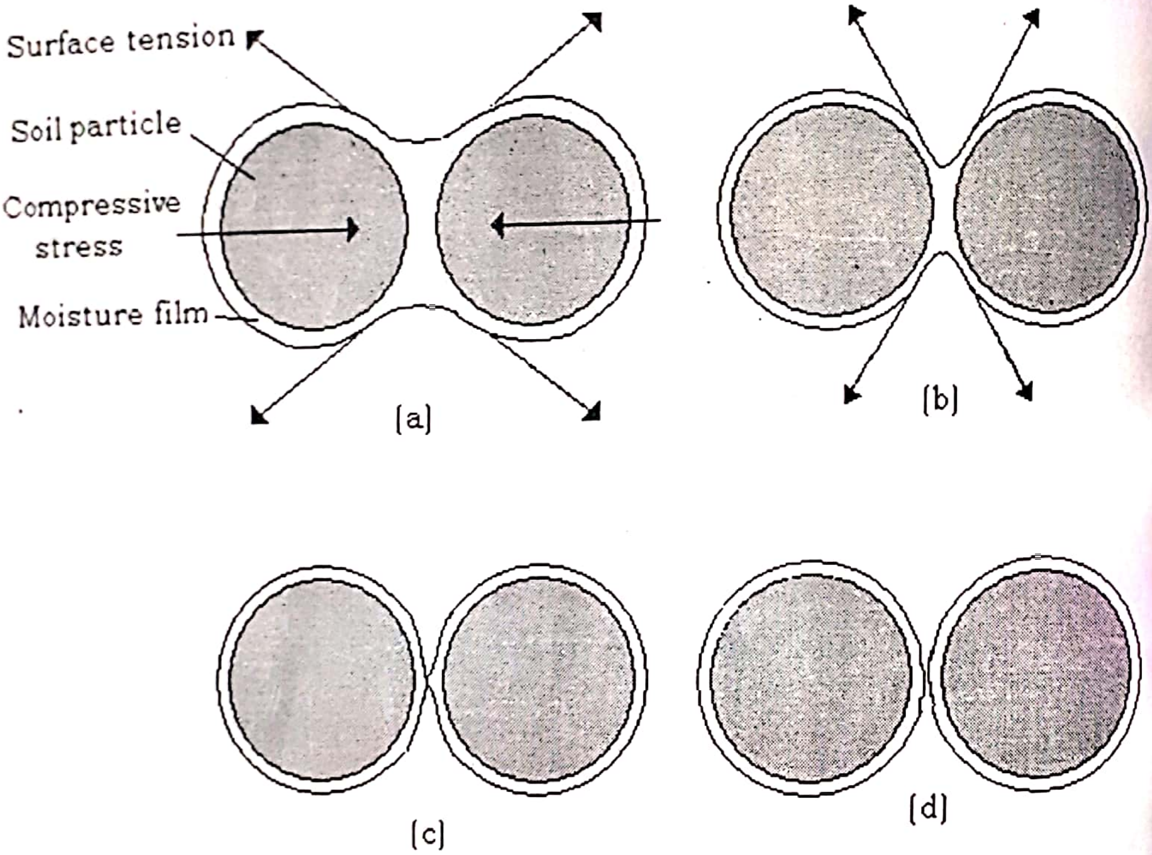


Fig.P-29 Indicating concept of surface tension forces and induced compressive stress (a) Particle separated due to thick moisture film. (b)Meniscus contracting due to drying process (c) meniscus tending to tear off (d)Meniscus fully torn off allowing entry of air

A series of polygonal cracks as shown in (Fig P-30) develop on the surface due to shrinkage of cohesive soil. These cracks may extend to a great depth (couple of meters). Upon wetting, the soil swells due to increase in volume and the cracks disappear.

Fig. P-30. Shrinkage cracks at bottom of the Rawal lake which has dried due to severe drought.

11-b Plastic Limit:

It is defined as the moisture content at which a soil can be rolled into threads of 1/8″ (3.2mm) diameter without cracking and crumbling. Thread thinner than 1/8″ (3.2 mm) diameter is possible, if the moisture is higher than the plastic limit. And if the moisture is less than plastic limit the thread will crumble before reaching the required diameter of 1/8″ (3.2 mm).

Above the plastic limit for a specific range of moisture content, depending on the type of soil, the soil mass behaves as a plastic material. The soil for that range of moisture content allows a change in shape, without a noticeable change in volume and without rupture involving a complete rearrangement of particles and will retain this shape when pressure is removed.

Sandy soils do not have plastic limit, and are known as non-plastic soils. Fine-grained soils (silt and clay) have plastic limits, and are known as plastic/cohesive soils. The plastic limit depends on the amoun and nature of clay minerals present in the soil mass. Higher clay conten usually give higher plastic limits. The plastic limit increases as the grai size decreases.

At plastic limit moisture content, the shear strength (load-carrying capacity) of soil is very low. The strength of cohesive soils varies considerably with changes of moisture content. Therefore, the earth-work structures e.g., Pavements and Embankments, which are open to seasonal changes of moisture content, should be designed on the basis of worst soil condition/strength, (i.e., at the maximum possible moisture content expected within the life time).

The plastic limit is used to find the Plasticity index, Liquidity index and the Activity of soil. It is used in the classification of soil and is also useful in predicting the optimum moisture content.

11-c Liquid Limit:

It is defined as that moisture content at which 25 blows of Cassagrande apparatus closes a standard groove cut in the soil pat along a distance of 12.7 mm (0.5 in). It is also defined as the moisture content which gives a penetration depth of 20mm of the standard cone (fall cone test) into the soil, when the cone is released for 5 seconds.

It is the cohesion, which retards the flow of soil to close the groove, liquid limit therefore, gives an indication of the soil cohesion. The liquid limit increases as the grain sizes of the soil mass decreases. A higher value of Liquid Limit therefore, indicates higher cohesion and a higher percentage of clay, which further indicates that upon wetting, the soil will possess a poor load-bearing capacity.

According to Cassagrande the number of blows required to close the groove represent a relative measure of shearing resistance of soil at that moisture content. He concluded that each blow in the apparatus corresponds to a shear strength of about 1.0 g/cm^2 ($\approx$ 2.5 Kn/m^2) In other words the shear strength of all soils at their liquid limits is constant, i.e. 25.0 g/cm^2.

The liquid limit is used in the classification of soil and is some times used to estimate the consolidation settlement. It is also useful in predicting the optimum moisture content in compaction studies.

11-d. Plasticity Index

The plasticity Index indicates the range of moisture through which a cohesive soil behaves as a plastic material. It is simply defined as the numerical difference between liquid and plastic limits. It is expressed as

$$P.I = L.L. - P.L \qquad (\%)$$

By definition it is clear that P I can never be negative. The plasticity index characterizes the plastic behavior of soil and indicates the degree of cohesiveness of the soil, e.g., the smaller the plasticity index, the less plastic is the soil. When the plasticity index is zero (Liquid limit = Plastic limit), the soil is termed as non-cohesive or non - plastic.

Atterberg defined the range of plasticity index as under:

P.I. = 0	The soil is non-plastic and non-cohesive.
P.I. < 7	The soil is low plastic and partly cohesive.
P.I. 7 - 17	The soil is medium plastic and cohesive.
P.I. > 17	The soil is high plastic and cohesive.

The fig-P-33 shows that with a decrease in plastic properties of soil, the liquid limit decreases faster than the plastic limit and ultimately for non-plastic soil the liquid and plastic limits coincide. The Fig-P-33 also reveals that upon drying, the sandy (non plastic/non cohesive) soils do not pass through the plastic state and change from liquid state to semi-solid state (or vice-versa) abruptly, resulting in a non-coherent material. This is the reason that fine sands and silts are very sensitive with respect to saturation and flow pressure (quicksand phenomenon).

Plasticity index is used for the classification of fine-grained soils. Plasticity index help, in evaluating a soil for use as a structural fill e.g. dams, embankments, landfills, highways construction and for building support. Higher the plasticity index, higher will be the loss of strength upon wetting. Therefore many construction companies in high way engineering recommend, that the plasticity index should not exceed "6" for the sub-grade soil used close to pavement structure.

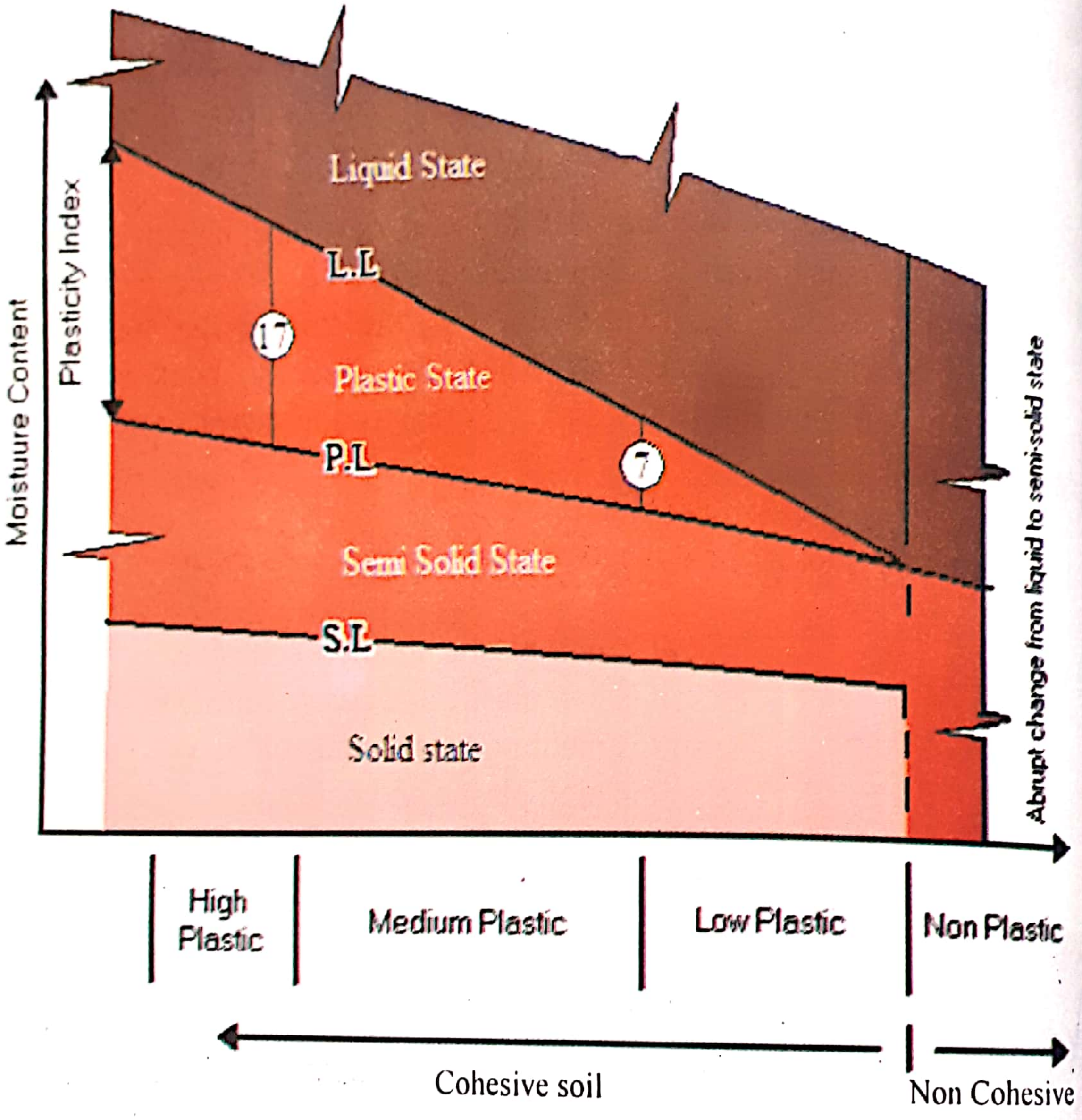


Fig.P-33: Change of liquid, plastic and shrinkage limits with plastic properties (not to scale, just to show comparison).

The plasticity index is an indicator of the suitability of the clay fraction in a stabilized soil mixture. Sand-clay mixture or clay-gravel mixture, in which the plasticity index of the binder (clay) fraction is too high, tends to soften in wet weather. A pavement constructed of such material develops ruts under the traffic and may show other signs of instability. When a pavement of this type is used without a bituminous wearing- surface, a high plasticity index indicates that the surface will become slippery in wet weather. On the other hand, if the plasticity index is too low or the mixture is non-plastic, it will become friable in dry weather, ravel at the edges and abrade severely under traffic.

11-e. Liquidity Index

It is defined as the ratio of difference between the moisture content and P.L. to the plasticity index. It is also known as Consistency index or Relative consistency and is expressed as under.

$$L.I = \frac{m - P.L}{L.L - P.L} = \frac{m - P.L}{P.I} \qquad (1.28)$$

when L.I < 0, (i.e. a negative value) the field moisture content is less than the plastic limit, and hence the soil is in a semi-solid state.

when $0 \leq$ L.I. ≤ 1, The soil is in a plastic state

when L.I. > 1, The soil is in a liquid state.

The liquidity index gives a direct indication of the consistency conditions of a soil at its field/natural moisture content.

when $0 <$ L.I. ≤ 0.25	The consistency is stiff or hard.
$.25 <$ L.I ≤ 0.50	The consistency is medium
$.5 <$ L.I. ≤ 0.75	The consistency is soft
$0.75 <$ L.I ≤ 1	The consistency is very soft.

The liquidity index helps to know the possibility of land-slides. When the natural moisture content in a soil mass, approaches to the liquid limit, the L.I approaches a value of unity. Therefore L.I. can be considered as a slide coefficient.

11-f. Flow Index

The slope of the flow curve (graph between log N and m.c., drawn for the determination of liquid limit) is known as the flow index. It is expressed by the following Eq.,

$$F.I = \frac{m.c.}{Log\ N} = \frac{m_1 - m_2}{\log N_1 / N_2} \quad (1.29)$$

Its numerical value is the difference in moisture content intercepted by the flow curve in one cycle of the logarithmic scale of number of blows.

$$F.I = \frac{m_1 - m_2}{\log N_1 - \log N_2}$$

For one cycle of logarithmic scale, e.g.,

If, $N_1 = 10$ then, $N_2 = 1$ - one cycle

or

If, $N_1 = 100$ then, $N_2 = 10$ - one cycle

$$F.I = \frac{m_1 - m_2}{\log 10 - \log 1} = \frac{m_1 - m_2}{\log \frac{10}{1}}$$

$$F.I = \frac{m_1 - m_2}{1.00} = m_1 - m_2 = \Delta m \quad \textit{for one log-cycle} \quad (1.30)$$

As discussed in the preceding sections, the number of blows required to close the groove represent a relative measure of shearing resistance of soil, therefore flow index gives an indication of the shearing strength of soil.

Any two soils, although having the same plasticity index and/or the liquid limits may have different values of flow index, and hence may possess different shear strength.

For example consider the following two cases.

Case-I: Two soils having the same values of plasticity index.

The flow curves of two soils having same plasticity index indicated by curve-1 & curve-2 are shown in Fig-P-36. The curve-1 is steep and gives a higher flow index as compared to curve-2, which is comparatively flat (lower flow index). From the curves it can be seen that a decrease in moisture content, 'Δm' in both the soils by the same amount, the soil with flat curve-2 takes a greater number of blows, i.e., $n_2 > n_1$. The comparison of the flow index therefore indicates that the soil with higher flow index (steep curve-1) possesses lesser shear strength than the soil with lower flow index (flat curve-2).

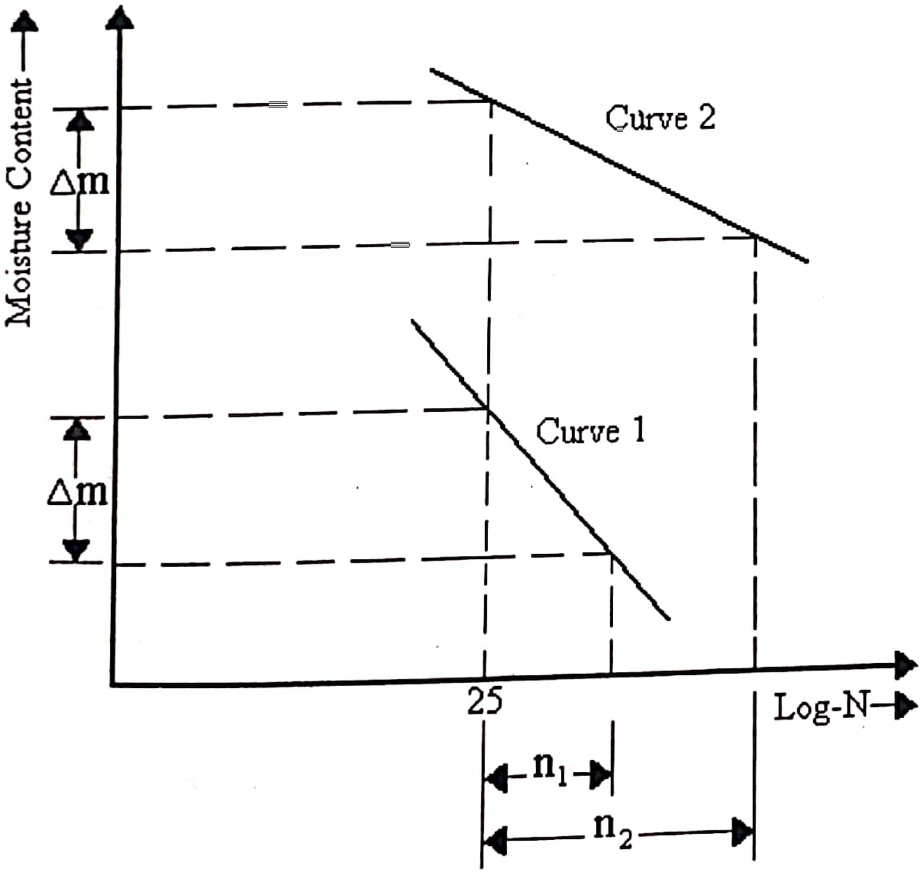


Fig.P-36: Effect of flow index on shearing strength of soil having same plasticity index.

Case-II: Two soils having the same value of liquid limit.

The flow curves of two soils having same liquid limit indicated by curve-I & curve-2 are shown in Fig-P-37. Although the liquid limits are the same, curve-2 which is flat requires greater number of blows (i.e., $n_2 > n_1$) as compared to curve-1, for the same decrease is moisture content 'Δm'. This again indicates that the soil of curve-2 (lower flow index) has a higher shear strength than the soil of curve-1 (higher flow index).

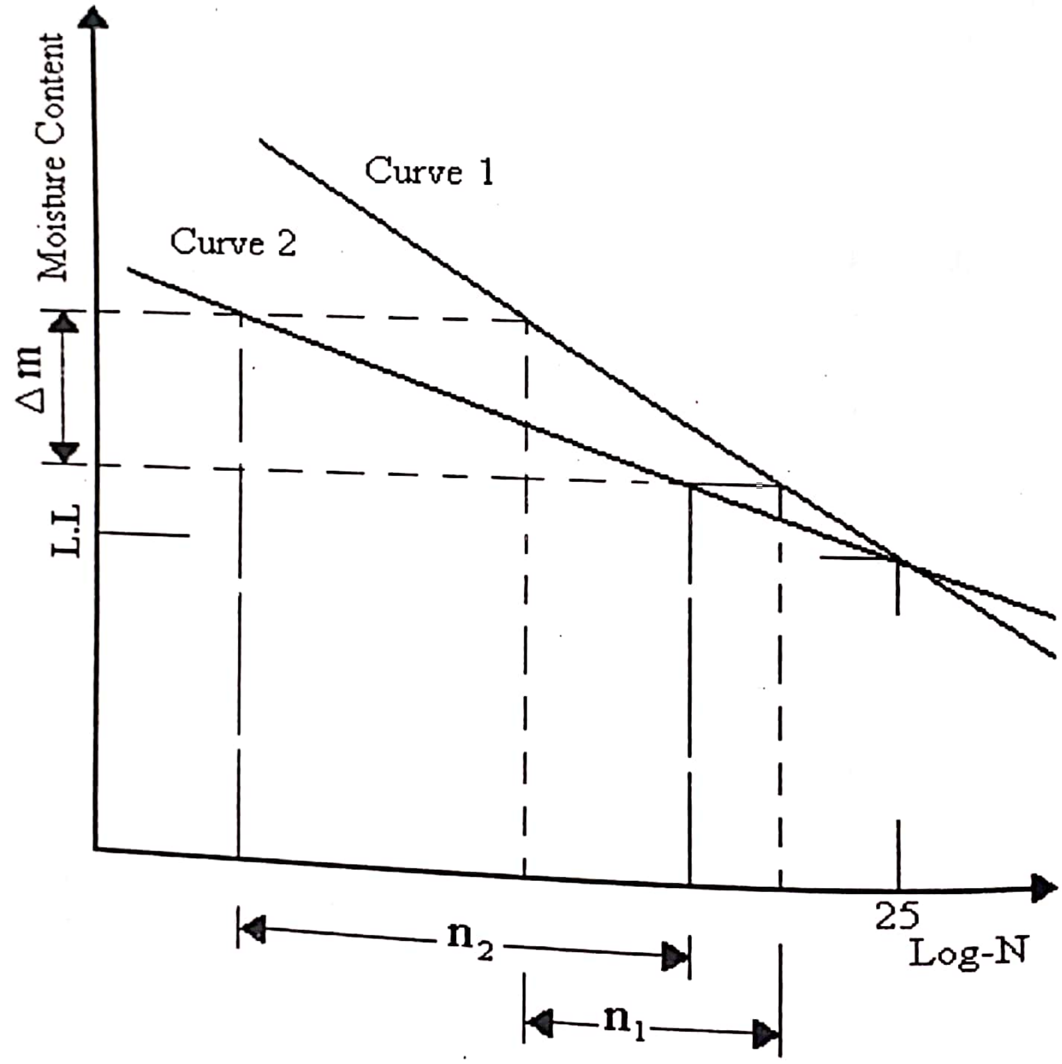


Fig:P-37. Effect of flow index on shear strength of soils having same liquid limit

11-g. Toughness Index:

Soils having same values of plasticity indices may vary in toughness. This property of a soil is expressed by the toughness Index.

It is defined as the ratio of plasticity Index to the flow index.

Thus, $$T.I. = \frac{P.I.}{F.I.} \qquad (1.31)$$

Toughness and dry strength increase with increase in toughness index.

12. Particle Size Distribution.

A soil mass is a collection of particles having a large variation in sizes and may range from relatively massive Boulders, Cobblers, Gravels down to very tiny particles of Clay. The physical and geotechnical properties of soil very much depend on the percentage of various particle sizes in a soil. Since each of the particle fractions has a unique effect on the soil properties, it is therefore important to find the particle size distribution in order to classify a soil for any engineering use. The particle size distribution analysis is made by sieving or by sedimentation.

i- Sieving method – when particle size ≥ .074 mm
ii- Sedimentation method – when particle size < .074mm.

The percentage of various particle sizes present in a soil is known as particle size distribution or gradation.

The particle size distribution of a soil is better explained in the form of particle size distribution curve or gradation curve. A gradation curve is drawn by plotting the percentage finer than various equivalent particle sizes (%age passing) as ordinate against the sizes as abscissa. The x-axis, which shows the sizes being commonly on logarithmic scale, to accommodate quite a large number of particle sizes on a sizeable (small) sheet of paper.

The gradation curves indicate the type of soil, and provide very important information related to the properties and behavior of soil as a construction material (e.g., embankments) or foundation support. A simple look on the gradation curve gives a very clear idea about the gradation of soil, e.g., well, uniformly or poorly graded as defined below

a- Well Graded Soil:

The gradation curve of a well-graded soil stretches approximately at a uniform slope covering a wide range of particle sizes (e.g., Curve-a, Fig:P-41). A well-graded soil therefore is defined as a soil containing an assortment of particles with a wide range of sizes. A well graded soil produces an ideal particle size distribution for optimum packing, because the smaller particles always remain available to fill the voids between comparatively bigger particles (Fig: P-39).

Ideal packing, due to particles ranging from large to small size (well graded).

Loose packing, as smaller particles to fill voids are missing.(uniformly graded)

Fig: P-39. Effect of gradation on packing of soil

A well-graded soil therefore has the following merits:

I- Higher shear strength—because there is more particle contact
II- Higher density – since the voids are completely eliminated due to the presence of successive smaller particles filling the voids between the next bigger particles

III Reduced compressibility – since there is no /least available voids to allow volume changes.

IV Higher stability – because there is less tendency for particles to roll, slip and slide to new equilibrium positions under applied pressure

b **Uniformly Graded Soil:**

The gradation curve of a uniformly graded soil is steep and covers a narrow range of particle sizes i.e. it contains particles of nearly the same size (e.g., curve–b, Fig:P-41). A uniformly graded soil is therefore defined as a soil containing an assortment of particles having a limited range of sizes. Such soils give low density with higher voids and therefore possess lower strength.

c. **Poorly Graded Soil:**

The gradation curve of a poorly graded soil show steps indicating an excess of certain particle sizes, and a deficiency of others (e.g., curve-c, Fig:P-41). Such soils also give lower density and strength, similar to uniformly graded soil.

Other useful information that may be obtained from the gradation curves are:

I- Effective Grain (Particle) Size:
II- Uniformity co-efficient:
III- Co-efficient of curvature:
IV- Percentage of a given size in the sample e.g., sand, silt, clay:
V Percentage larger or finer than a given size:

I **Effective Grain (Particle) Size:-**

A soil is a mixture of particles having varying sizes. For the determination of soil properties (e.g., capillarity, permeability etc.) a single size is specified, known as effective grain size, which is determined by the gradation curve. It is defined as the size against 10-percent finer (passing) and is denoted by D_{10}.

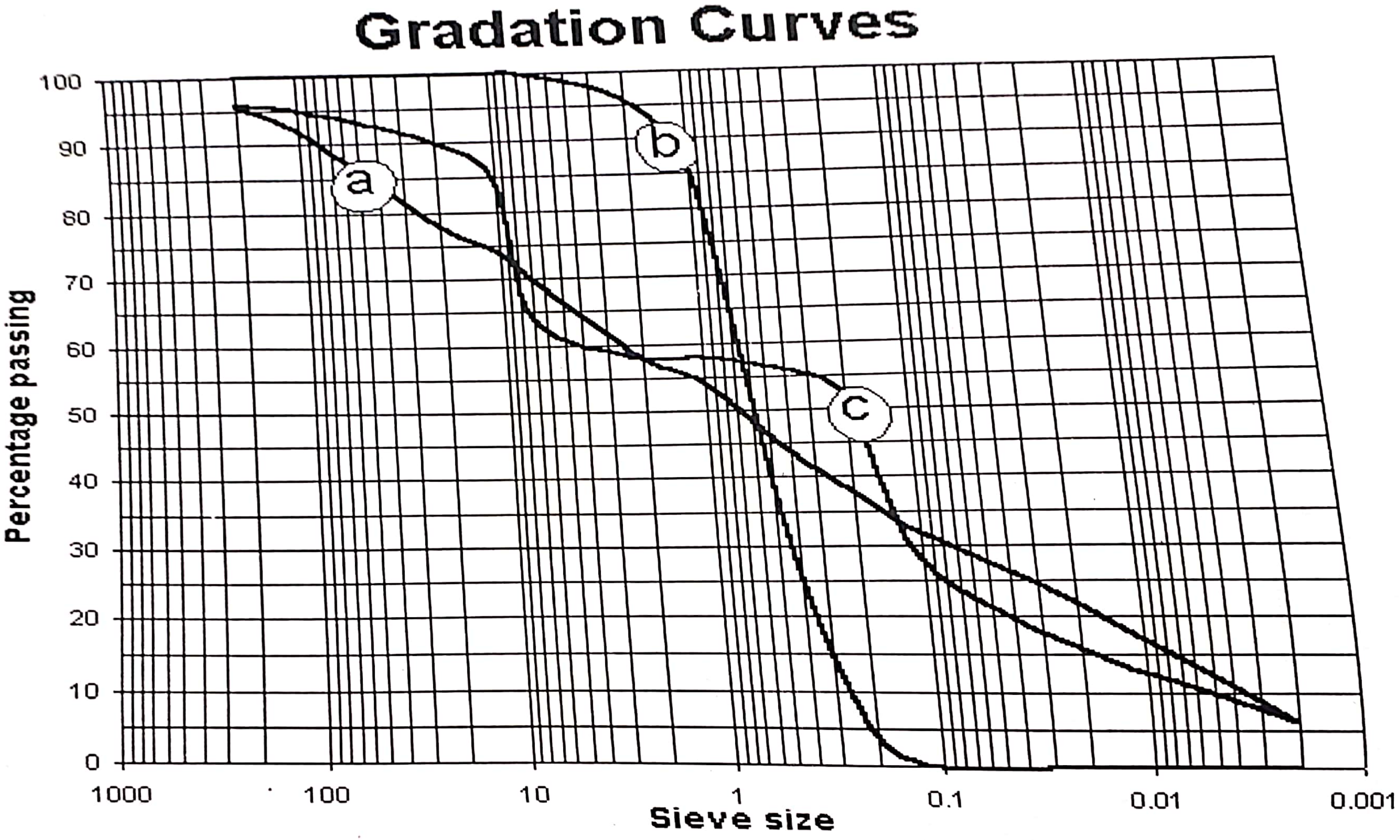


Fig.P-41: Gradation curves (a) well graded soil; (b) uniformly graded soil;(c) *poorly graded soil.*

II- Co-efficient of uniformity:

Co-efficient of uniformity is determined from the gradation curve. It is attributed to Allen Hazen, denoted by "C_u" and defined as follows.

$$C_u = \frac{D_{60}}{D_{10}} \qquad (1.32)$$

The co-efficient of uniformity "C_u" gives information about the gradation of soil. For a single-sized soil (all the particles having the same size) the value of C_u will be unity. When the value of C_u is less than 4, the soil is generally considered as uniformly graded. However a large value of the coefficient corresponds to a large range of particle sizes and the soil is termed as well graded.

III- Co-efficient of curvature or Co-efficient of Concavity:-

Coefficient of curvature is denoted by C_c and is expressed as under.

$$C_c = \frac{(D_{30})^2}{(D_{60})(D_{10})} \qquad (1.33)$$

It is determined from the gradation curve. It is also known as coefficient of gradation. A value of C_c = 1, represents that all the soil particles have the same size.

The values of C_c between 0.2 and 2.0 indicate well graded or poorly graded soil.
However as discussed earlier, the exact nature of gradation is better known by a look at the gradation curve.

12. Relative Density (D_r) or Density Index (I_D)

The term relative density is used to express the state of compactness of a granular soil. Depending upon the state of compaction, the void ratio of a soil will be between the possible minimum and maximum values, i.e., e_{min} and e_{max}. The following relationship between the void ratio values is termed the relative density.

$$D_r = I_D = \frac{e_{max} - e}{e_{max} - e_{min}} \quad (1.34)$$

or

$$Dr = I_D = \frac{\gamma_{d\,max}}{\gamma_d}\left(\frac{\gamma_d - \gamma_{d\,min}}{\gamma_{d\,max} - \gamma_{d\,min}}\right) \quad (1.35)$$

Where,

e_{max} = *Void ratio of soil in loosest state.*

e_{min} = *Void ratio of soil in densest state.*

e = *Void ratio of soil deposit (in – situ state)*

or

Void ratio of soil whose relative density is required

γ_{dmax} = dry density of soil in densest slate.

γ_{dmin} = dry density of soil in loosest state.

γ_d = dry density of soil deposit (in situ state)

or, the dry density of soil whose relative density is required.

The determination of void ratios, require V_s (volume of solids) which is difficult to measure by any direct method, the determination of relative density by Eq-1.34 is therefore not convenient. However it is quite simple to determine the relative density by Eq-1.35, since the measurement of dry density is much easier.

The dry density in the densest state (γ_{dmax}), is determined by vibrating sand subjected to a surcharge weight (ASTM D – 2049-69).

The dry density in the loosest state (γ_{dmin}) is determined by pouring dry sand into a mould from a fixed height (ASTM D – 2049-69).

The in situ density (γ_d) is determined by any of several approved methods.

Relative density is commonly used to indicate the in situ state of compactness, which reflects the stability of granular soil strata. For example, a loose granular soil, indicated by smaller value of D_r is unstable, especially when subjected to stock or vibration and give large settlement of embankments and foundations. The vibratory loads however compress the soil to a denser and more stable formation.

The range of values for D_r and the commonly referred state of compaction are given in Table: P-44.

Relative density is also determined by the standard penetration test (SPT). Empirical co-relation between SPT value and relative density is given in Table: P-44.

Table: P-44. Commonly referred state of compaction and relative densities for granular soil

State of compaction:	Very loose	Loose	Medium	Dense	Very dense
Relative density (%):	0-15	15-35	35-65	65-85	85-100.
SPT N-value:	< 4	4-10	10-30	30-50	> 50