CHAPTER

5

PHYSICAL PROPERTIES OF CLAY AND SOIL MECHANICS

In this chapter genesis of soil and distinction with clay are discussed. Soil mechanics and related properties are also elaborated.

5.1 PHYSICAL PROPERTIES

Clay mineral particles are commonly too small for measuring precise optical properties. Specific gravity of most clay minerals are within the range from 2 to 3.3. Their hardness generally falls below 2.5. Refractive indices of clay

Table 5.1: Description of minerals

Name of minerals	*Size, shape and form of natural occurrences*
Keolinite	Well formed, six-sided flakes, with a prominent elongation in one direction.
Halloysite	Tubular units with an outside diameter ranging from 0.04 to 0.15 micrometre.
Smectite	Undulating mosaic sheets.
Illite	Poorly defined flakes commonly grouped together in irregular aggregates.
Chrysotile	Slender tube-shaped fibres having an outer diameter of 100–300 Å. Their lengths commonly reach several micrometres.
Palygorskite	Elongated laths, singly or in bundles. Frequently the individual laths are many micrometres in length and 50 to 100 Å in width.
Sepolite	Similar lath-shaped units.
Allophane	Very small spherical particles (30–50 Å in diameter), individually or in aggregated forms.
Imogolite	Long (several micrometres in length) thread-like tubes.

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minerals generally fall within a relatively narrow range from 1.47 to 1.68. Generally the size and shape, the two properties, are determined by electron micrographs.

It is important to note that physical properties depend on various other factors controlling the behavioural pattern of the material. Clay sedimentation properties depend on porosity, water content and minerals content of different specific gravity. Electrical conductivity depends on porosity, saturation, pore fluid conductivity, water content, and clay content. Velocity is very sensitive to saturation (air-water) but hardly at all to fluid composition. On the other hand, conductivity is very sensitive to both saturation and pore fluid conductivity. If saturation is determined from velocity, the fluid type can be determined uniquely from conductivity.

5.2 SOIL

The upper layer of Earth, which contains weathered rock materials, organic matter, humus-mineral mixture, glacial deposits, loam, silt, brown clay materials etc. in varying proportion, is known as soil. Depending on these constituents colour varies from black to dark brown. Formation of vegetation also depends on the presence of constituent materials.

Table 5.2: Types of soil and relevant terms

Soil	Residual soil: Soil that remains at the place of formation by chemical or physical weathering and eventually covers the parent rock is called residual soil. Transported soil: These soils are weathered materials, taken away at other places by the process of transportation, by several agents.
Sediments	Sediment is naturally occurring from process of weathering and erosion of existing rocks and subsequently by transportation process by fluid and wind, having large variation in size from boulder to colloidal.
Dirt	When plants and other things die, bugs, worms and other animals help to break the plants into little bits. Dirt is black and dark with lots of plants in it. When rock stay outside in sun and wind for long time, they start to disintegrate into small pieces until they become little tiny grains.
Sand	A loose granular substance, naturally occurring, typically pale yellowish brown composed of finely divided rock and mineral particles, resulting from the erosion of siliceous and other rocks and forming a major constituent of seabed, riverbed, etc. The composition of sand is highly variable, but the most common constituent of sand is silicon dioxide, or SiO_2, usually in the form of quartz.

Soil is a natural body having variable thicknesses. Soil differs from the parent materials in their morphological, physical and chemical characteristics due to interactions between the lithosphere, hydrosphere, atmosphere and biosphere. It is a mixture of mineral and organic constituents that are in solid, gaseous and aqueous states. In soil, particles are packed loosely, forming a soil structure filled with pore spaces. These pores contain soil solution (liquid) and air (gas).

Depending upon the nature of transporting agents, the transported soil may be of types described in Table 5.3.

Table 5.3: Types of soil depending on transporting agent

Type	*Definition*
Aeolian	Soil is transported by the action of wind.
Alluvial	Soil is transported by the water action.
Glacial	Soil is transported to the area through glaciers.
Colluvial	Soil is transported by gravity.

5.3 SOIL FORMATION

Soil formation process is known as pedognesis; it is the combined effect of physical, chemical and biological processes on soil parent material. In soil profile, soil horizons are formed from soil formation and this process involves additions, losses, transformation and translocation of material that compose soil. The formation of soil happens over a very long period of time. Due to process of weathering the surface rocks breakdown into smaller pieces and then mix with moss and organic matter. With progressing it creates a thin layer of soil. The plants attract animals, and when the animals die, their bodies decay. Decaying matter makes the soil thick and rich. Plants have a vital role for development of soil. Due to weathering process minerals are derived from weathered rocks which undergo changes that cause the formation of secondary minerals. These materials are variably soluble in water and so by this solving process these constituents are translocated from one area to another by water factor or animal activity. These movements and alteration are reasons of formation of different soil horizons.

In soil the most widespread mineral is quartz, feldspar and mica flakes though calcite and gypsum are present occasionally. Also there are important accumulations of kaolinite, zeolite and montmorillonite etc. Characterization of soil indicates its mechanical composition, i.e., the size of grains in it. The size of particles determines the various names of soil; thus there are stony, silty, sandy soils. In soil, organic matter is usually represented by humus, which consists of stable humic degradation matter, and their type depends on the plants from which it forms. Due to presence of humus in soil, various tint of grey, brown and black colours are attributed. Type and quantity of humus may be different depending on the natural conditions in which soil forms. Decomposition of plants and micro-organism forms humus. Due to the process of decomposition, organic matter lose their original shape. Cellulose and albumins are first to decompose. Lignite resists decomposition longer. Sometimes mineral part of plant tissues is preserved in humus.

Ground water plays an important role in soil, dissolving nutrient substances and thus these substances are absorbed by roots of plants. This solution contains large quantities of various salts and organic materials. Decomposition of organic matter which takes place in soil has complex reactions. These reactions increase the CO_2 content and release gases not contained in atmosphere. Soil air has less oxygen than atmospheric air. Soils largely consist of microorganism; there are tens of millions in one gram of soil. Composition of soil is influenced by climatic factors. Soil undergoes very great changes as a result of man's activity in cultivating and ploughing.

5.4 SOIL HORIZONS

The name of soil horizon is based on soil materials which reflect the specific process of soil formation. There are six horizons, named as with increasing depth: O horizon, A horizon, E horizon, B horizon, C horizon and R horizon. They are described and classified by their colour, size, texture, structure, pH, consistency, root quantity etc. Soil is consisting of O horizon, A horizon, E horizon and B horizon. Regolith is consisting of O horizon, A horizon, E horizon, B horizon and C horizon and bedrock consists of only R horizon.

Table 5.4: Types of horizon

Name of horizon	*Constituents*	*Description*
O horizon	High percentage of organic matter	The "O" stands for organic. It is a surface layer, dominated by the presence of large amounts of organic material in varying stages of decomposition. The O horizon contains no weathered mineral particles and is not part of the soil itself. O horizons may be divided into O1 and O2 categories, whereby O1 horizons contain decomposed matter whose origin can be spotted on sight and O2 horizons containing only well-decomposed organic matter, the origin of which is not readily visible.
A horizon	Humus-mineral mixture	The A horizon is the top layer of the soil horizons, consists of dark decomposed organic materials, which is called "humus". In this zone biological activity occurs. Soil organisms such as

(*Contd.*)

Table 5.4: (*Contd.*)

Name of horizon	*Constituents*	*Description*
		earthworms, arthopods, nematodes, fungi and many species of bacteria are concentrated in this zone. Thus the A horizon may be referred to as the biomantle. The soil biomantle is the organic-rich bioturbated topsoil where most biota lives, reproduce, die and become assimilated. So it is predominantly a product of organic activity, where bioturbation is a dominant process.
E horizon	Composed of silicates, stone layer	The horizon that has been significantly leached of its mineral and/or organic content, leaving a pale layer largely composed of silicates. These are present only in older, well-developed soils, and generally occur between the A and B horizons. In soils that contain gravels, due to animal bioturbation and stonelayer commonly forms near or at the base of the E horizon.
B horizon	Loam, silt, brown clay	The B horizon is commonly referred to as "subsoil", consists of mineral layers which may contain concentrations of clay or minerals such as iron or aluminium oxides. This layer is also known as the "zone of accumulation". Plant roots penetrate through this layer, but it has very little humus. It is usually brownish or red because of the clay and iron oxides washed down from A horizon. The B horizon may be divided into B1, B2 and B3 types. B1 is a transitional horizon to an A3 containing some A-horizon characteristics. B2 horizons have a concentration of clay, minerals, or organic debris. B3 horizons are transitional between the overlying B layers and materials of whether C or D horizons beneath it.
C horizon	Glacial deposits	This layer is little affected by soil forming processes. The C horizon may contain lumps or more likely large shelves of unweathered rock, The C horizon also contains parent material.
R horizon	Bed rock	R horizons basically denote the layer of partially weathered bedrock at the base of the soil profile. Unlike the above layers, R horizons largely comprise continuous masses of hard rock. Soils formed in situ will exhibit strong similarities to this bedrock.

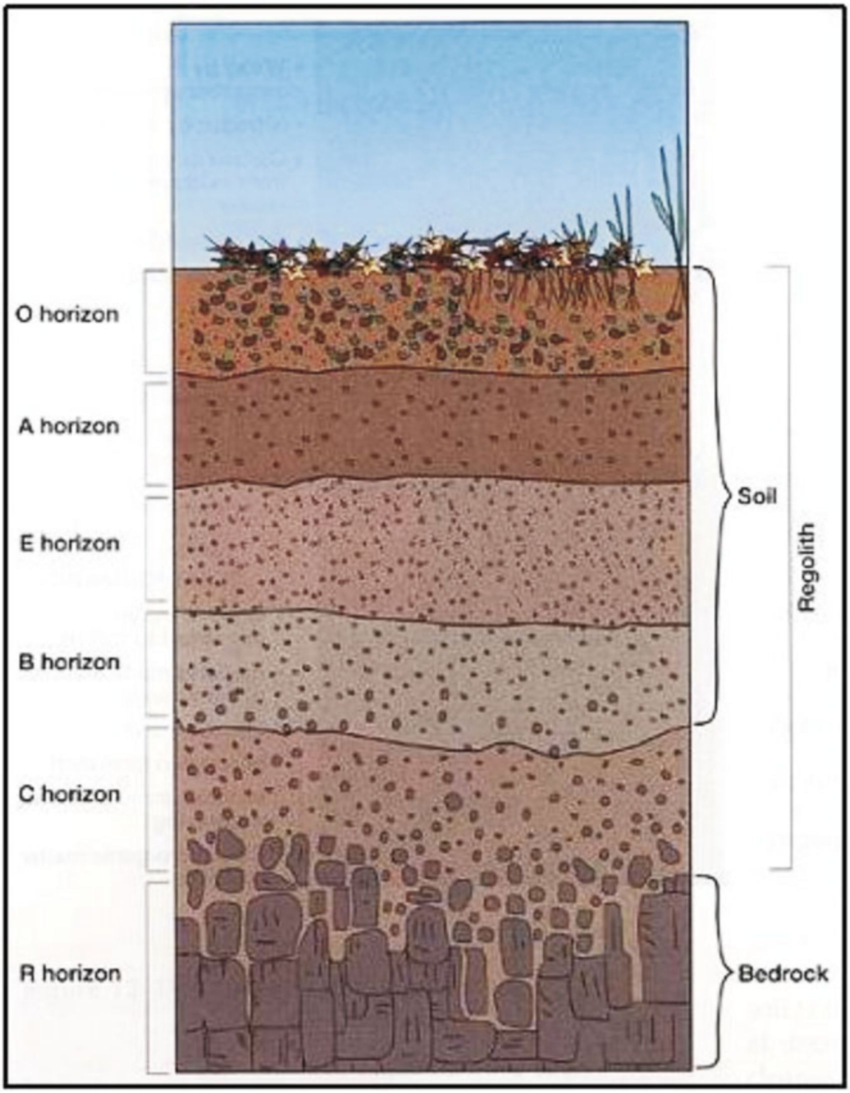
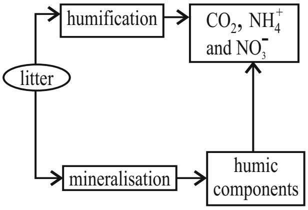


Fig. 5.1: Diagram of soil horizons.

5.5 SOIL GENESIS

The primary mechanism of soil creation is the weathering of rock. All types of rock (igneous rock, sedimentary rock and metamorphic rock) may be broken down into small particles to create soil. There are three types of weathering mechanisms: physical weathering, chemical weathering, and biological weathering. Some human activities such as blasting, waste disposal etc. may also create soil. Sometimes deeply buried soils may be altered by pressure and temperature to become metamorphic or sedimentary rock, and if melted and solidified again, they become igneous rock.

Table 5.5: Types of weathering

Type of weathering	*Soil formation processes*	*Remarks*
Physical effects	Physical weathering (refer Fig. 5.2) means mechanical disintegration, includes temperature variation effects, rain water impact, water seepage in cracks, frost action and other similar mechanisms which influence soil formation methods.	Creating fractures in the rock due to temperature variation and mechanical effects and consequent reduction of rock size.
Chemical reactions	Chemical weathering includes carbonation, oxidation, hydration and dissolution of matter composing rock and soil. Clay minerals, for example, can be formed by weathering of feldspar. The most common mineral constituent of silt and sand is silica. Though feldspar is most common rock forming mineral, silicon is more prevalent in soils due to its stable crystalline structure and less solubility as compared to feldspar. The broken pieces of rock are called gravel (size 4.75 mm to 100 mm) and larger pieces known as cobbles and boulders.	Alteration of rock composition by various natural chemical processes in action.
Biological interactions	Vegetation adds organic matter to the mineral components thus forming a litter. So the amount of organic matter in the soil depends not only on the abundance of litters but also on the resistance of plant debris to bio-degradation. Indeed, microorganism through their own biological activity, transform the litters into CO_2, NH_4^+ and NO_3^- (mineralization). The organic residues become humic components (humification). Humification is a slow and complex process in which both soil microorganisms and non-biological physico-chemical reactions take part. The amount of organic matter in the soil is influenced by the difference in velocity between mineralization and humification processes.	Abundance of organic matter produces litter and biodegradation of plant debris is the main physico-chemical reactions. 

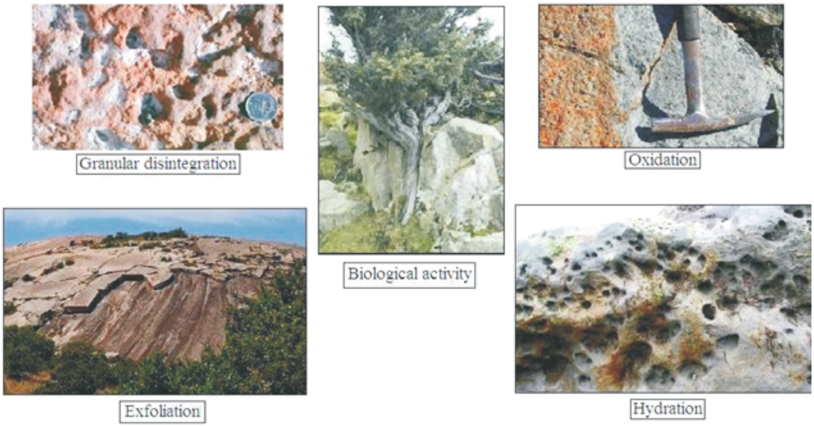

Granular disintegration
Biological activity
Oxidation
Exfoliation
Hydration

Fig. 5.2: Various types of weathering.

Table 5.6: Types of soil

Type of soil	*Characteristics of soil*
Ferruginous tropical soil	These soils are found in the northern part of the humid tropical zone which is characterised by the lateritic zone. They have been described by Aurbert (1951) in the zone of the Sudanese savana, by Maignien (1959) in northern Guinea and in Senegal and by Sieffwrmann (1959) in north Cameroon. The humid tropical zone is characterised by rainfall close to one metre per year and the humid season spread over five and six months. Unweathered minerals of the parent rock, especially potash or sodic feldspars are the constituent element of these soils. The clay fraction often shows kaolinitic types of clay minerals associated with iron hydroxide without free alumina. In alluvial zones soils show red to beige range of colours due to fractionation of minerals.
Mediterranean red soils	Red soils are found in many mediterranean countries. The greater part of these formations correspond to climatic conditions that no longer exist, as can be proved in many places by the development at their expense of a brown or leached soil at present. Rubefaction occurs today only in those special sites where rainfall is more abundant and microclimate contrast. It has been observed in Morocco, Oran and Portugal.
Calcimorphic soils	Calcimorphic soils which are not connected with limestone outcrops have in common an abundance in Ca and Mg ions saturating the absorptive complex of soils devoid of carbonates. The most famous examples are the black earths, of temperate steppes, such as those in the Ukraine and the Dakotas, calcimorphic soils of semi arid Mediteranean and sub-tropical

(*Contd.*)

Table 5.6: (*Contd.*)

Type of soil	*Characteristics of soil*
	American steppes, the tires of Morocco and of dark clays of the tropics, which are also called regurs or margallitic soils.
Lateiritic soils	Laterite is a weathered product of intertropical zone. It has been used with extremely varied meanings, but at present, this term is so widely used that it no longer has any pedologic significance, for the last hundred and fifty years.
Podazolic soils	This soil is characterized by soils evolved with raw materials and with rapid decomposition. Variation in mineralogical composition of clay fraction throughout the profile increases, chlorite decreases from bottom to top and subsequently intensity increases. Sometimes chlorite-vermiculite and illite-vermiculite mixed layers are present.
Calcareous brown soils	The argillaceous fraction of calcimorphic soils developed on limy parent rock shows little evolution in pedological profiles, many of which present a mineralogical composition which does not vary from the bottom to the top of profile.

5.6 SOIL MECHANICS

Soil mechanics indicates the behaviour of soil. Soil consists of a heterogeneous mixture of fluid and some solid particles. Fluid means usually air and water and on other hand solid means usually clay, silt, sand and gravel. Besides these some organic solids, liquids and gases also may be present, so soil is a heterogeneous mixture. Soil mechanism depends on genesis and composition of soil. Soil mechanics is used to analyze the deformations of flow of fluids within natural and manmade structures that are buried in soils. Example applications are building and bridge foundations, dams etc. Change of volume of soil due to squeezing water out of tiny pore spaces, also known as *consolidation*, *shear strength* and stiffness of soils. The shear strength of soil is primarily derived from friction between the particles and interlocking. Examples of geotechnical engineering applications of the principles of soil mechanics are slope stability, lateral earth pressure on retaining walls etc.

Functional relationship between normal stress and shear stress on a failure plane can be expressed in the following form

$$T_f = f(\sigma)$$

The linear function of normal stress is

$$T_f = c + \sigma \tan$$

where T_f is shear strength, c – cohesion, σ – normal stress on the failure plane and ϕ is angle of internal friction. This equation is called the Mohr-Coulomb failure criterion.

In saturated soil, the total normal stress at a point is the sum of the effective stress (σ') and pore water pressure (u)

$$\sigma = \sigma' + u$$

The Mohr-Coulomb failure criterion is expressed in terms of effective stress.

$$T_f = c' + \sigma' \tan \phi'$$

where c is cohesion and σ' is frictional angle, based on effective stress.

5.7 ATTERBERG LIMITS

The Atterberg limits are a basic measure of the nature of a fine-grained soil. Depending on the water content of the soil, it may appear in four states: solid, semi-solid, plastic and liquid. In each state the consistency and behaviour of a soil is different and so are its engineering properties. Thus, the boundary between each state can be defined based on a change in the soil's behaviour. The Atterberg limits can be used to distinguish between silt and clay, and it can distinguish between different types of silts and clays. These limits were created by Albert Atterberg, a Swedish chemist. They were later refined by Arthu Casagrande.

Some laboratory tests are listed below.

The values of these limits are used in various aspects. There is a close relationship between the limits and properties of a soil such as compressibility, permeability and strength. Thus the Atterberg limits are not only used to identify the soil's classification, but it also allows for the use of empirical correlations for some other engineering properties. Liquid limit test is to classify soils and to find the plasticity index of soil because different soils have various plastic limits. The shrinkage limit is much less commonly used than the liquid and plastic limits.

Table 5.7: Description of limits

Properties	*Description*	*Laboratory tests*
Shrinkage limit	The shrinkage limit is the water content where further loss of moisture will not result in any more volume reduction.	ASTM International D4943.
Plastic limit	The plastic limit is the water content where soil is in transition between brittle and plastic behaviour.	ASTM standard test method D4318
Liquid limit	The liquid limit is the water content at which a soil changes from plastic to liquid behaviour.	Fall cone test and Casagrande test

5.8 PLASTICITY INDEX

The plasticity index is a measure of the plasticity of a soil. The plasticity index is the size of the range of water contents where the soil exhibits plastic properties. The PI is the difference between the liquid limit and the plastic limit (PI = LL – PL). Soils with a high PI tend to be clay, those with a lower PI tend to be silt.

Table 5.8: Types of plasticity

PI	*0*	*(1-5)*	*(5-10)*	*(10-20)*	*(20-40)*	*>40*
Plasticity	Non-plastic	Slightly plastic	Low plasticity	Medium plasticity	High plasticity	Very high plasticity

5.9 ACTIVITY

It has been observed that the mineralogy of clay has direct relation with its geotechnical parameters. It is expected that clay mineralogy has got some direct bearing on the slope stability of a particular area containing those clays in the soil profile. As such, determination of the geotechnical parameters of clay, along with detailed clay mineralogy of the soils of the areas where slope stability problem have recorded, may be of importance for suggesting remedial measures or to eliminate the concerned area for construction of any important civil engineering structures. Some geotechnical properties to be studied:

- Detailed grain size analysis
- Consistency limits determination (L.L., P.L., P.I.)
- Swelling index
- Determination of dry density and optimum moisture content by proctor compaction (if adequate samples are available)
- Shear parameters, if sufficient sample is available.

On the basis of experimental evidence for several natural clay soils, the relationship between plasticity index and percent finer than 0.002 mm for any given clay was represented by a straight line passing through the origin and thus the activity of clay is defined by

$$A = \frac{\text{Plasticity index}}{\text{Clay content (percent finer than 0.002 mm)}}$$

where A is activity of clay.

On the basis of change of clay content, a modified definition of the activity of clay was proposed as follows:

$$A = \frac{\text{Change in plasticity index}}{\text{Corresponding change in clay content}}$$

The relationship between plasticity index and clay content is shown in Fig. 5.3. It shows that the slope of the line is different, from 10-40% , is a bit steeper compared to the other part (40-100%). At low clay content condition, presence of other non-clay minerals deviate the plasticity index trend from that of high clay content samples.

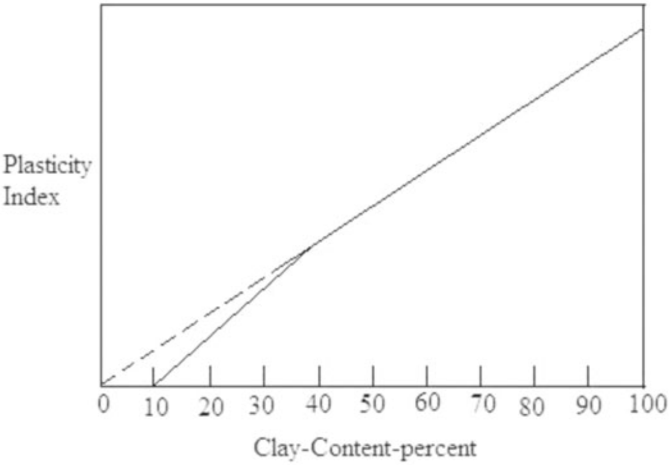


Fig. 5.3: Simplified relationship between plasticity index and clay content.

The direct linear relationship between PI and clay fraction content for any particular clay enables this degree of colloidal activity to be expressed very simply by the ratio:

$$\text{Activity} = \frac{\text{Plasticity index}}{\text{Clay fraction}}$$

This ratio is in fact the slope of the line.

Table 5.9: Types of clay with activity value

Type of clay	Activity
Inactive clay	<0.75
Normal clay	0.75-1.25
Active clay	>1.25

The relation between liquid limit and clay fraction, although linear, is not one of the direct proportion and is therefore less convenient than the ratio PI by clay fraction.

The three minerals – quartz, calcite and mica – tested by Von Moons, were ground to a very small particle size and the PI then determined on the fraction finer than two microns. The activity of these minerals is low, as might be expected from their relatively simple crystal structure. Illite is probably the most widespread of all clay minerals but it usually occurs in conjunction with other minerals. The clay known as bentonite consists almost exclusively of the mineral montmorillonite. In its natural state bentonite is usually a sodium clay

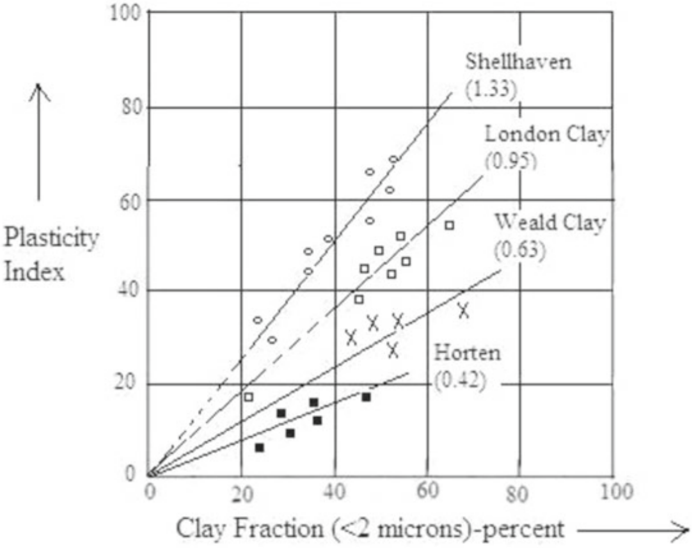


Fig. 5.4: Relation between plasticity index and clay fraction.

Table 5.10: Activity of various minerals

Mineral	*Activity*	*Reference*
Quartz	0.0	Von Moos (1938)
Calcite	0.18	Von Moos (1938)
Mica (muscovite)	0.23	Von Moos (1938)
Kaolinite	0.46	Samuels (1950)
Illite	0.90	Northey (1950)
Ca-montmorillonite	1.5	Samuels (1950)
Na-montmorillonite	7.2	Samuels (1950)

and, in this state, it has a very exceptionally high activity. By effecting a base exchange from sodium to calcium, Samuels (1950) has shown by repeated tests that the activity is considerably lowered; although even the Ca-bentonite has high activity. He has also shown that bentonite carrying a tri-valent base Al has an activity of about 1.3. No base exchange tests appear to have been made on illite, since this material shows moderate activity. It is clear from the above results that activity is, broadly speaking, related to the structural complexity of the minerals: ranging from quartz through kaolin up to montmorillonite.

Concluding Remarks

Industrial application of most of the clays directly depends on their physical properties. This chapter prepared a background for the studies of industrial application of clays in Part II. Beside this the chapter highlights the relation between weathering and soil formation.

QUESTIONS

1. Different types of weathering depend on particular agents; explain it.
2. Soil generation is closely related with weathering; give examples of various types of soils.

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