2 SOIL WATER SYSTEM

2.1 General:

An adequate qualitative background to the investigation reported herein calls for the utilisation of the accepted knowledge of micro-structure and chemistry of soils and to show thereby engineering significance of fundamental soil chemistry and physics involved in its stress - strain - time characteristics.

2.2 Liquid-in-Solid System:

Soils occurring in nature can be visualised as liquid-in-solids systems hence the solid fabrics, its composition, bonding and voids are matters of primary concern with regard to their engineering behaviour, Ingles (28, 1968). The organisation of the soil minerals into a solid skeleton and tortuous pore system forms a subject of soil fabric studies. On the microscale, the electron microscope photographs of the commonly occurring clay minerals in soil reveal

(i) parallel plate arrangement
(ii) the prevalence and irregular shape of voids
(iii) tendency of fine particles to adhere to course particles.

The graphical representation of soil fabric helps in differentiating the high strength components of skeleton from those of moderate strength components of
clay matrix and of zero strength components of pores. It is the clay matrix which is important in present investigation hence would be discussed in greater details.

2.3 Clay Minerals:

Clay minerals are hydrated alluminium silicates in a crystalline form of relatively complicated structure. These clay minerals are divided into three general groups according to their crystalline arrangement and it is now established that general engineering properties are similar with all the clay minerals belonging to the same group.

The structures of the clay minerals - Kaolinite, Montmorillonite and Illite groups have been shown schematically in Fig. 2.1.

2.3.1 Kaolinite Group:

In Kaolinite group of clay minerals, it is possible for a gibbsite sheet and a silica sheet to fit together to produce an electrically neutral layer because of the unsatisfied valence forces in the upper oxygen atoms of silica sheet. Successive sheets of the crystal lattice may be stacked one on top of the other to form particles of Kaolin with the forces holding the layers together being hydrogen bond type between \( \text{O}^2- \) and \( \text{(OH)}^- \) ions. Different stacking arrangements give rise to different
FIG. 2-1
STRUCTURES OF CLAY MINERAL PARTICLES

FIG. 2-2
STRUCTURAL INFLUENCE OF CATION REPULSION
clay minerals with the same general formula as of Kaolin.

Kaolin particles are generally having hexagonal shape and occur as plates whose diameters typically range in size from 0.5 to 1.0 micron and having thickness of about 0.05 micron. The size may be connected with the structures and formation conditions or may possibly bear a relationship to the average distance between lattice imperfections which have been found at similar spacing in clay minerals, Amelinckx et al (62, 1931). Cleavage usually takes place between the double sheets. Since the plates are interrupted at their edges, it follows that while the electric charge for a Kaolinite sheet are theoretically neutral, broken bonds will be found at the edges developing positive or negative charge deficiency and thus absorbing foreign ions if available.

In this Kaolin group, one typical mineral deserving mention from its structure is that of Halloysite. Although the formula is same as for Kaolin, the arrangement of atoms is somewhat different since the basic Kaolinite structure is slightly distorted to allow the fitting of extra water molecules into the structure. The mineral may therefore occur with the silica tetrahedra located on outside. Some of the excess water molecules can be removed from naturally occurring halloysite by heating it to about 60° C but for removing all the water,
temperatures of the order of 400° C are necessary. The structural distortion, leads to the formation of metahalloysites.

The properties of these two halloysites differ considerably and hence requires care in its laboratory testing and interpretations, Terzaghi (62, 1968).

2.3.2 Montmorillonite Group:

The schematic diagram of montmorillonite structure consists of three layer primary element as shown in Fig. 2.1. Successive sheets of such primary elements may be stacked resulting in polymorphic mineral variations in montmorillonite. The bonds, in this case, between the elementary sheets are of \( O^{2-} \) and \( O^{2-} \) ions. These bonds are naturally weak when compared to the bonds of Kaolinite layers having \( O^{2-} \) and \( OH^- \) bonding. Hence water molecules can enter in the montmorillonite sheet and may have the size to fit in the structure. The swelling characteristics of this mineral can be explained on this basis.

Due to poor bonding prevalent between the adjacent oxygen layers, montmorillonite break into extremely small particles of 0.05 micron in diameter and a ratio of diameter to thickness of about 400 : 1, Van Olphen (75, 1951).
Similar to Kaolinites, in addition to the negative charge on the surface of the sheet, there will be positive and negative charges on the broken edges. The number of such charges will therefore be linked directly with the size of clay particles, since the proportion of molecules along broken edges to the total number in a particle increases with diminishing particle size.

2.3.3 Illites:

The third group of clay mineral termed as Illite consists of the same structural element as montmorillonite with the exception that K$^+$ ions occupy positions between $\text{O}^{2-}$ base planes. This cation in turn bonds the two sheets together more firmly resulting in lesser susceptibility of cleavage for the lattice.

This helps explaining the non-swelling characteristic of illite when compared with montmorillonite. The illite particles have diameter of about 0.5 micron and diameter to thickness ratio of about 50:1, Van Olphen (76, 1951).

2.4 Surface Electro-Chemistry:

Radoslovich (28, 1962-3) has given full account of the factors controlling crystal size, morphology and chemical composition in the layer lattice silicates. Structural control is vested primarily in the octa-hedral layer to
which the tetrahedral layer adjust itself. The principal forces responsible for interatomic spacings are the cation-cation repulsive forces which are ultimately balanced by the stretching limit of the cation-anion bonds as shown in Fig. 2.2. Other factors influencing to a lesser extent the lattice structure control are:

1) interlayer cation
2) polarization of anions
3) hydrogen or hydroxyl bonding.

A few natural clay minerals are found to possess electrically neutral crystal lattices of aluminosilicate composition. In the tetrahedral layer, Al$^{3+}$ are found in place of Si$^{4+}$, a replacement that has been suggested as the cause of sub-plastic behaviour in clays. These are heavy clays which resist all attempts at dispersion and behave for all practical purposes as sands rather than clays.

In the octahedral layer, substitution of Mg$^{2+}$ for Al$^{3+}$ is of very common occurrence. When this is in incomplete stage, the crystal lattice may exhibit a high positive charge deficiency whose neutralization at the crystal surface gives rise to some of the most troublesome phenomena encountered in the engineering use of soils.

2.4.1 Cation Exchange Capacity:

The ability of a clay to adsorb ions on its surface
or edges is termed as Base Exchange Capacity or Cation Exchange Capacity (B.E.C. or C.E.C.). This forms an important property of the clay mineral and will be used in this investigation to explain the mechanism of the process of consolidation of a clay. The role of electrical surface forces in controlling the mechanical, physical and chemical properties of crystal aggregates is well known and the meaningful utilization of such concepts would necessitate the understanding of the nature of these forces presented in the following paragraphs.

The cation exchange capacity as mentioned earlier, measures those ions loosely bound to the mineral surface by charge deficiencies in the particular crystal lattice. Their source has been a matter of dispute in the literature. Common claim has been advanced that the isomorphous replacement is responsible for this cation exchange capacity. Mukerjee, (50, 1950) discount isomorphous replacement for the two layer clays and favour the dissociation of surface hydroxyl. However, in the two layer clays a considerable proportion of the surface area consists of broken crystal edges, Quirk (57, 1960).

It has also been established in the field of metal physics that chemical and mechanical properties are dominated by the presence of defect structure in the crystal lattice. Thus dislocations cause plastic behaviour,
though to what extent the known defects of the clay mineral lattices are supplemented by other defects of the surface is at present unknown, Boas (22, 1965).

2.4.2 Interatomic and Intermolecular Forces:

The two principal types of bonds having interatomic spacing less than $3\text{Å}$ are the ionic bond and the covalent or Homopolar bond. The weakest of the so-called chemical bonds are hydrogen and Hydroxyl bonds.

The variation of potential energy with the interparticle spacing is shown in Fig. 2.3. Inspection of this figure reveal that a new position of equilibrium such as that at point $A$ occurs due to the balance of long range attractive and repulsive forces. Attractive forces mainly comprise of electrostatic dipole and electromagnetic Van der Wall's forces while the repulsive forces arise from the repulsion of the ion cloud surrounding the particles and of steric forces resulting from ion hydration and surface adsorption.

As the depth of well at point $A$, at a high inter-particle spacing, is small compared to the ordinary thermal vibration energies, possibly these are the zones in which thixotropic behaviour appears and small amounts of work will lead to greater deformations.
Potential Energy

Repulsion

The Double Layer

Break Down of Double Layers

Intermolecular Stable Zone

Thixotropic Phenomena-Zone

Electrostatic Attraction

Fig. 2:3

Molecular and Colloid Particle Interaction
2.5 Clay-water Interactions:

The attraction of ions, of the solid surface of clay minerals due to the charge deficiency for water of hydration has generally been inferred by measurements of their behaviour in solution. It has been established that higher valence ions normally possess larger hydration shells.

On the surface of the clay minerals, at distance over 60 Å, diffuse double layers are formed. The cations neutralizing the negative surface charge arising from the isomorphous substitutions in clay minerals are separated by a layer of adsorbed water or better by hydroxyl ions.

It has been observed that diffuse double layer form more readily when the liquid phase contains monovalent ions than multivalent ions. This can be explained on the basis of higher hydration of multivalent ions than monovalent ions and the lesser attraction of monovalent ions to the surface charges prevalent. Of importance in this investigation is the physical change of property of the oriented water around the clay minerals as the distances increase and this is discussed in the following section.

2.5.1 Viscosity:

The viscosity of a liquid refers to intermolecular friction and in case of colloidal solutions the particles
are hydrated and that friction takes place between the water molecules of the hull and the dispersion medium.

Further, it has been established that viscosity of colloids is a function of the volume occupied by the disperse phase. Einstein has proposed an equation for the evaluation of system viscosity as

\[ n_s = n_m (1 + 2.5\phi) \] \hspace{1cm} (2.1)

where

- \( n_s \) = Colloidal system Viscosity
- \( n_m \) = Dispersion Medium Viscosity
- \( \phi \) = Volume of dispersed phase per Unit Volume of Sol.

Meyer and Marks have modified this equation and the relationship has been expressed in terms of relative viscosity as

\[ \frac{n_s}{n_0} = 1.25 \frac{\phi}{V - \phi} \] \hspace{1cm} (2.2)

where

- \( n_s / n_0 \) = Relative viscosity
- \( V \) = Total volume of Sol.
- \( \phi \) = Effective volume of the dispersed phase

The hydration as achieved for the clay mineral can have different forms of water. These forms can be grouped as:
(i) Water held in the form of film around the particle by adsorption forces
(ii) Water adsorbed within the clay minerals
(iii) Presence of water due to hydration of the ions of an electrolyte.

It has been recognised that viscosity changes are associated with changes in the degree of hydration. The nature of this hydration undoubtedly is a function of the ions adsorbed on the surface of the particle or of the water occluded between the particles in case of aggregations.

The laboratory investigations have revealed that the addition of small amount of electrolytes to colloidal systems produce drop in viscosity. Further additions either produce no change or cause an increase in viscosity depending upon the nature of the colloid and the type of electrolyte, Fig. 2.4. The viscosity changes appear to follow a course similar to that of the electro-kinetic potential of colloidal system, Fig. 2.5, Lambe (41, 1969).

Of importance are the electro viscous effects which lead to the change in viscosity of the system when the interparticle spacings are reduced. Such electroviscous effects lead to the increase in the viscosity of a system and will help explaining the physics involved in stress-transmission and deformation of liquid-in-solid systems.
ADSORBED CATIONS AND VISCOSITY VARIATIONS

FIG. 2-4
BASE EXCHANGE CAPACITY

FIG. 2-5
CHANGE IN SYSTEM PROPERTIES
2.6 Structures in Clay:

The mode of occurrence of different structures in the clay systems has an important bearing on its engineering behaviour. Different flocculation modes are shown in Fig. 2.6. In the dense state, either coagulated or flocculated, which is the characteristics of soils as applied to engineering, these particles are normally aggregated or are even aggregated of aggregates. Quite apart from aggregates cemented and bridged by extraneous materials, the clay minerals, are themselves capable of self-aggregation owing to their surface and edge charges.

Face-to-face flocculation is similar to the bonding within the domains of mechanical and other forces. Edge-to-face flocculation is frequently advanced as the source of strength in highly porous, flocculated clays. In soil systems, however, two major factors - impurity and the geometrical effect - reduce considerably the bond strength.

Edge-to-edge flocculation has been shown by potential field calculations to be the state of lowest potential energy, Reese, (28, 1951), and supported by swelling studies, Emerson (18, 1962).

To explain the engineering behaviour of the clay fabric, various forms have been put-forth as are shown in Fig. 2.7.
FIG. 2.6
FLOCCULATION MODES

EDGE-EDGE
FLOCCULATION

EDGE-FACE
FLOCCULATION

FACE-FACE
FLOCCULATION

FIG. 2.7
FLOCCULATION STRUCTURES

CARD HOUSE STRUCTURE

BOX STRUCTURE

INTER SHEET REPULSION

CEMENTIVE
ATTRACTION

TACTOID STRUCTURE

(Na⁺ FORM)

(Cd⁺ FORM)

1900 Å

20,000 Å

1900 Å

20,000 Å
Card-house model has been advanced to explain the sensitivity of certain clays, Hosenquist (59, 1959) however this model need not be extended to explain the presence or absence of cohesion in all clays, Michaels (46, 1959). Tactoid-model has its utility in explaining successfully the swelling and shrinkage characteristics of certain clays, Emerson (18, 19, 1962, 1963). Fox-model as proposed by Norrish (28, 1952) helps explaining the restricted swelling.

2.7 Rheology of Clay-fabrics:

Of direct importance to the engineers is the engineering soil behaviour as analysed in the form stress-strain-time characteristics. This has been dealt herein in two subsections - the first forming the transmission of stress and the second one in the general form as compressibility.

2.7.1 Stress Transmission:

It would be of interest to visualise the stress transmission in a varied liquid-in-solid system. One would find it convenient to compute the stress if the system consisted completely of equidimensional particles or at best having the parallel arrangement of clay particles, Bolt (8, 1956), as shown in Fig. 2.8, Lembe (41, 1939).
Stress transmission evaluation will still be more complicated when the three-phase system - air, water and solid skeleton - is considered. Attempts have been made by considering physics of equilibrium condition between the liquid and gaseous phases to analyse such a state of stress, Hilf (26, 1956). Rheological models have been advanced to explain stress-strain characteristics by considering the soil as an anelastic polyphase material. In this it has been conceived that soil is an elastico-plastico viscous polyphase semi-infinite porous mass, Erich (17, 1956).

2.7.2 Compressibility:

Compressibility of clay systems have been studied extensively and is found to be dependent upon clay minerals, nature of pore fluid and temperature, Finn (20, 1951), Salas and Serratosa (61, 1953), Bolt (8, 1956), Lambe (39, 1959), Leonard (43, 1964).

Further, consolidation and rebound characteristics have also been reported for clays by Quirk and Alymore (57, 1960) and Katti - Sadashivan (60, 1965). The structural changes which would be formed during the consolidation - rebound state in a clay are shown schematically in Fig. 2.9.

As the consolidation progresses, the reduction in voids is achieved by preferred orientation of clay platelets. The
inspection of the Fig. 2.9 reveals that from the initial card-house structure (Edge-face contacts, Tan (67, 1957)), second stage of tactoid structure is reached. This in turn finally leads to a parallel arrangement of clay platelets.

No sooner the aggregation of crystals starts forming the tactoid structure, reduction of pressure will not lead to a reversible swelling phenomena. It has been demonstrated by Greacen that CVR (critical void ratio line, Roscoe, Schofield and Wroth (58, 1958)) line correspond to the theoretical diffuse double layer curve. However it should be noted that CVR line is a function of electrolyte concentration.