

The Characteristics of Clay

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Preview

The behaviour of clay soils is dependent on both its condition and composition. Its composition depends on both the species of clay mineral present, and the state of the electrolytes (dissolved salts) in the soil pore water.

Objectives

The structure of clay from the atomic level to the macro level is explored. The concepts of adsorbed water, cation exchange capacity, and flocculation and dispersion are introduced.

Readings



Required



Suggested

Holtz, R.D. & Kovacs, W.D. An Introduction to Geotechnical Engineering, Prentice-Hall, 1981. Chapter 4

Introduction

Where the structural characteristics of strength and stiffness are at a premium, soils containing clay perform poorly in comparison with well-graded gravel and sand. They are valued most where water retention is required, but even there their presence may be restricted. In a large earth dam, outer shells of rock fill will provide strength, enclosing a thin central clay core that provides the water seal.

The range of physical, chemical and mineralogical observations demonstrates the complexity of clays.

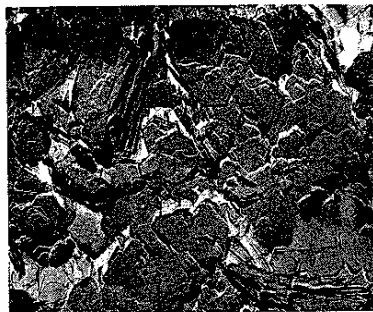
- They exhibit a plastic state where shear strength and compressibility are closely related to water content.
- The addition of small amounts of Portland cement produces benefits that exceed those expected by its use in conventional concrete.
- Some clay soils are extremely prone to erosion by water, while others are much more resistant. This behavior can be reversed in any instance when the water's electrolyte (dissolved salts) characteristics are altered.
- Soils with a relatively small amount of clay size particles can be as equally "clayey" as other soils with a larger proportion of clay size particles i.e. not all clays show the same response.

Structure of clay minerals

Clay is structured at an atomic, molecular and macro level, and these structures interact to produce the variations in observed behavior.

Physical features.

Clay particles are smaller than 2 micron (2×10^{-3} mm), and because this is about twice the wavelength of light, such particles can only be seen with an electron microscope. Electron micrographs show that clay particles have the shape of thin sheets. This shape and small size combine to give clay a very large surface area for a given volume of solid, making surface effects dominant. They are an example of a colloid. Note that quartz sand ground to clay size by glacial action is not a clay mineral, so that particle size alone does not make a substance a clay mineral.



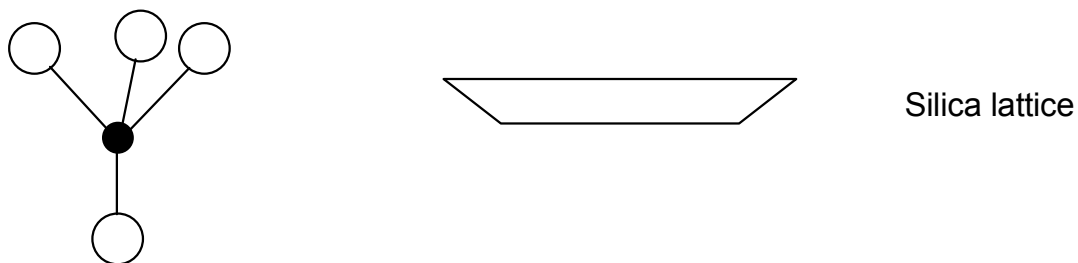
Photomicrograph of Kaolin (X15000)

Mineralogical features

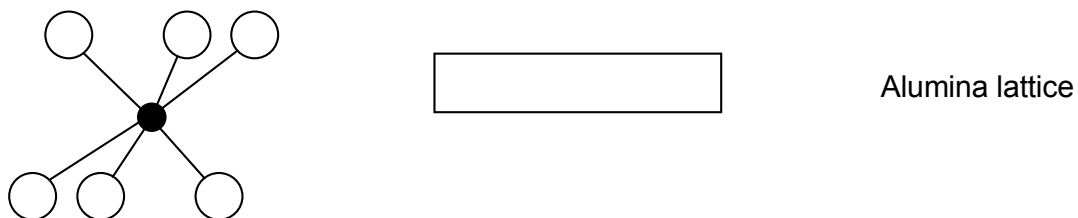
A. Basic structure - atomic level

Clays are aluminosilicates with a two-dimensional sheet lattice structure. In contrast, quartz, the common mineral of sand and silt, is a silicate with a three dimensional tetrahedral structure.

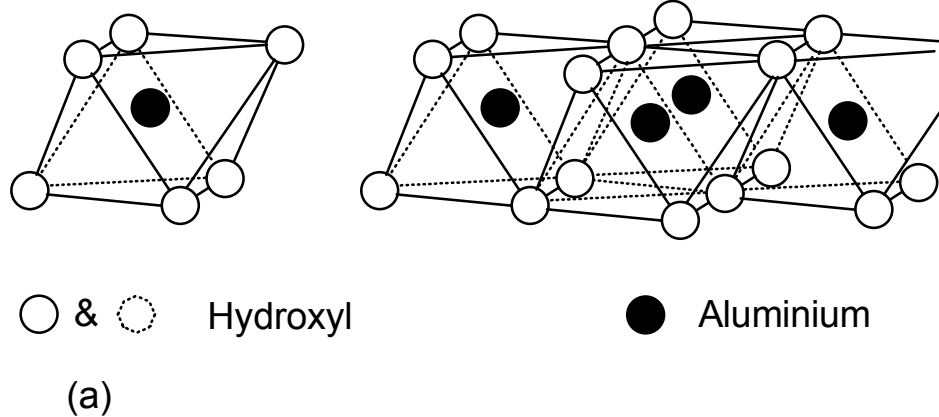
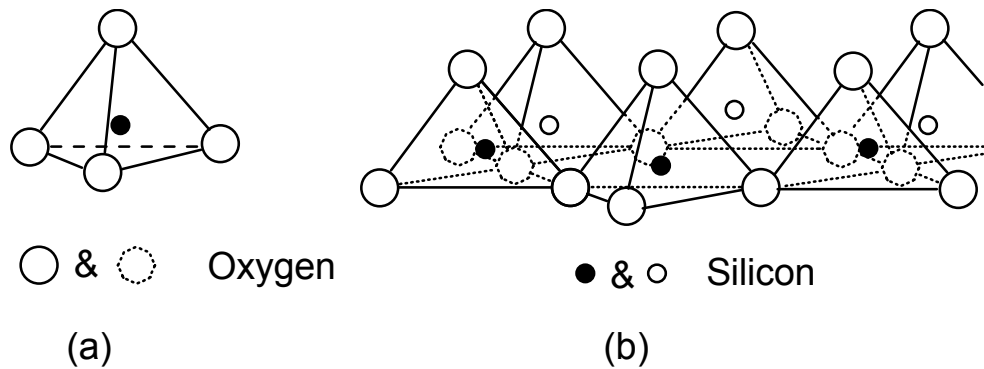
The relatively small silicon atom binds with four larger oxygen atoms to form a sheet of silica tetrahedra. This sheet is not symmetrical, with oxygen atoms (O^-) in a closely packed basal layer, and a less closely packed apex layer, as indicated below.



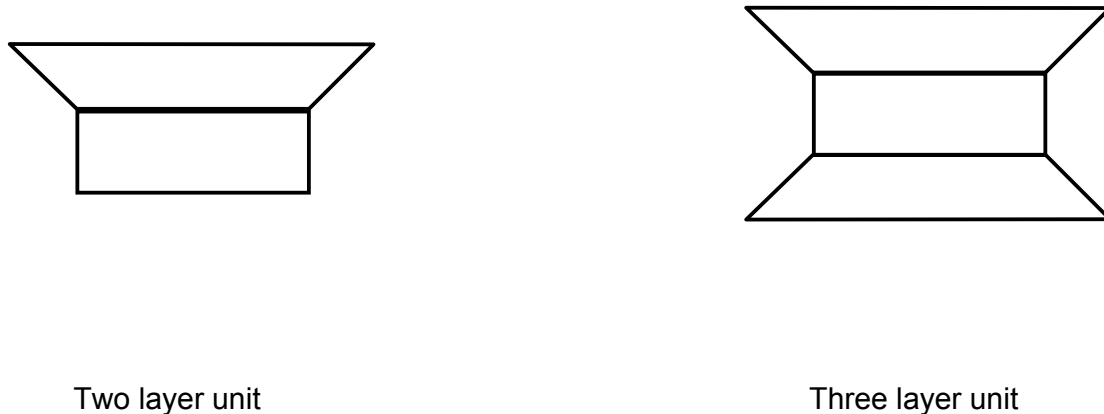
This silica lattice is joined with a sheet of alumina octahedrons. In this sheet the aluminium atom bonds with six hydroxyl ions (OH^-), and it can exist as a mineral in its own right (Gibbsite). The OH^- distribution is symmetrical on each face and may be represented as shown below.



Another representation of the lattices is shown below



The spacing of both the OH^- in the alumina lattice and the O^{2-} apex layer of the silica lattice favours a bonding of these two lattices. Either a two layer, or three layer structure is formed, as shown below, leading to a variety of clay minerals



These sheets are electrically balanced provided that they are infinite in extent, and so particles of finite size have unsatisfied bonds at the edges of the sheet, where unbalanced positive electrical charges are found.

B. Specific mineral forms – molecular structure

Clay minerals consist of repeating layers of the basic structure. The clay mineral Kaolinite consists of stacked sheets of the two layer unit. The minerals Illite and Montmorillonite are both stacks of three layer units. The layers of Illite are bonded with potassium (K^+) ions, a structure that is very similar to the mineral mica found in granitic rocks. Layers water molecules containing cations separate the basic sheets of Montmorillonite. This mineral can undergo large volume changes as wetting or drying adds or removes molecules of this inter-layer water.

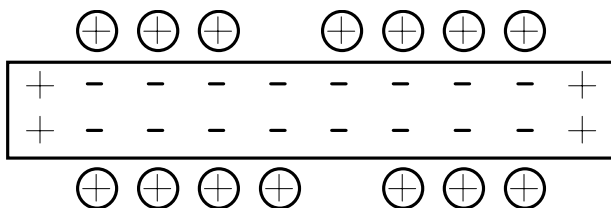
The external atom of the clay mineral is oxygen as O^- or OH^- , making it chemically stable in the air and water environment.

Isomorphous substitution and particle charge

The size of the aluminium and silicon atoms is similar to each other, and to that of other metal atoms in the geologic environment. Thus it is possible for the Si^{++++} or Al^{+++} in the basic crystal structure to be replaced by Al^{+++} , Fe^{++} , Mg^{++} , or Ca^{++} without undue disturbance to the crystal structure. This *isomorphous substitution* results in a charge imbalance, leaving the bulk of the clay particle negatively charged, and this charge appears across the face of the particle.

The net charge of the clay particle is negative and this must be balanced exactly by **adsorbed** cations, adsorbed because they are not internal to the particle but at its surface. They are also referred to as *exchangeable cations* because when the free water flowing around the particle contains a different type of cation, it may be exchanged with those adsorbed on the clay particle. The extent of isomorphous substitution varies in different clay minerals giving them varying cation exchange capacities.

The charge distribution of positive edges and negative faces is as shown below.



Clay particle charge distribution

Adsorbed water layer

Because water is a polar fluid it has many unique characteristics. The fundamental water unit H_2O , although electrically neutral, has a small net separation of positive and negative charge, making it a dipole. Thus the hydrogen atoms of the one water molecule are attracted to other oxygen atoms. As well as other water molecules, this can include the oxygen or hydroxyls of the clay. This allows a distinctive water layer, more structured than that of free water, to form around the clay particle. Water is also adsorbed around the exchangeable cations. This adsorbed water is measurably different from free water, having a specific gravity of about 1.4. Another characteristic of significance in geoengineering is its ability to withstand a tension (or negative compression) up to 10 MPa, whereas free water will vaporize at tensions (relative to atmospheric pressure) of about 100 kPa.

Adsorbed water layer thickness

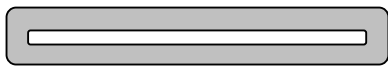
Although the structure of the adsorbed water gradually merges to that of free water as the distance from the clay particle increases, it is possible to identify thicker or thinner adsorbed water layers.

Electrolyte concentration

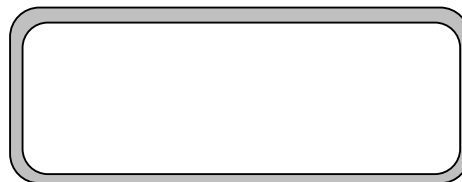
It is seen that the adsorbed water layer thickness is inversely proportional to the electrolyte concentration of the free water. The clay particle requires a set number of adsorbed cations for electrical neutrality, and these must be in diffusion equilibrium with the free water, ie in near equal concentrations. As the free water electrolyte concentration increases, so must that of the adsorbed water layer, and a thinner adsorbed water layer achieves this.

Cation valence

It is observed that divalent cations (Mg^{++} , Ca^{++}) result in a thinner adsorbed water layer than the monovalent cations (Na^+ , K^+). Twice as many monovalent ions are needed for electrical neutrality, and for comparable ion concentrations, a thicker adsorbed water layer will be required.



Adsorbed water layer around a Montmorillonite particle



Adsorbed water layer around a Kaolinite particle

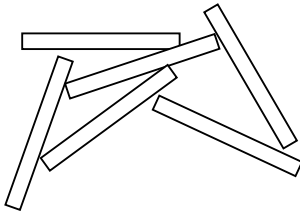
Montmorillonite particles being smaller with a very large surface area per unit mass, and with larger cation exchange capacity have proportionately more adsorbed water than Kaolinite particles.

Flocculation and dispersion

Clay particles interact with each other to form a macro clay structure.

Flocculation

Where conditions promote a thin adsorbed water layer, the positive edges of the clay particle may approach close enough to the negative face to form an effective electrostatic bond. This permits an open “card house” structure, based on “edge to face” attraction, to form the structure indicated below



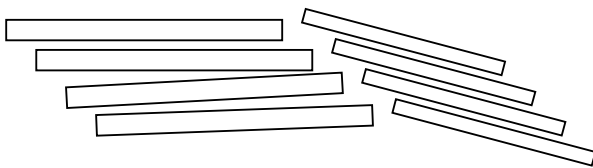
Card house structure

In a soil suspension, this results in the formation of flocs. In some soils the flocculation can be so strong that the soil behaves as if composed of larger particles, with higher water conductivity but less plasticity, and better engineering properties.

Dispersion

Where particles accumulate with a thick adsorbed water layer, edge to face attraction is not possible and aggregations form with the clay sheets parallel to each other, separated by the adsorbed water layer. Here the basic strength and stiffness closely involve the adsorbed water layer, and increases in water content can lead to large reductions in strength and stiffness.

Dispersive soils have poor durability. With contact of an unconfined soil surface with free water the clay particles are very prone to go into suspension. Such soils are susceptible to erosion, and much care is needed if they are to be included in a water-retaining embankment.



Dispersed structure

This dispersive structure is most desirable where a very low hydraulic conductivity is required. Here a greater portion of the soil water is adsorbed on the clay mineral making the water harder to move, and the soil less permeable. Further, there is fewer gaps containing free water as found with a flocculated structure

Soil treatment

Altering either or either the electrolyte concentration or the cation type in the soil water may change the flocculation – dispersion state of a soil. Soil stabilisation, by the addition of Portland cement or slaked lime makes divalent calcium ions available to the soil, promoting flocculation. Adding detergent that promotes a dispersed state may reduce the hydraulic conductivity of clay soil.

Natural environments

Where soils have been deposited under strong flocculating conditions, such as the ocean, and later environmental condition, such as the infiltration of fresh water (rain) have altered the soil water potential to dispersive, any disturbance can change the soil structure from flocculated to dispersed. For some Scandinavian and Canadian “quick” clay soils the associated strength reduction can lead to dramatic slope failures.

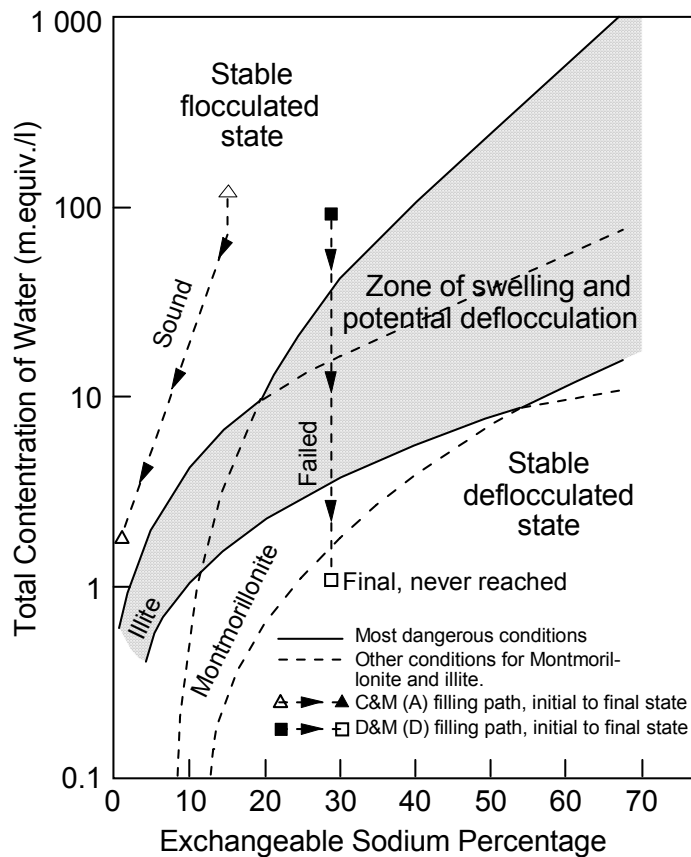
In Australia, farm dams that have stored “hard” runoff water with a high electrolyte content, and predominantly Ca^{++} ions have later failed by internal erosion when filled with “soft” water from a reticulated water supply, with a low electrolyte content and predominantly Na^+ ions.

Where a soil profile consists of a flocculated surface horizon overlying a dispersed horizon, tunnel erosion is likely when the surface layer is disturbed, allowing greater water flow through the dispersive layer.

The relationship between soil behaviour and the electrolyte condition of the soil water is shown in the figure below.

Interaction with pollutants

Polluted ground water will contained exotic metallic ions and complex organic molecules that will interact with the clay particle. In some instances the objectionable metallic ions can be adsorbed by the clay particles and removed from the ground water. Some organic compounds have such an affinity for the clay particles that the clay contracts and cracks, allowing the ready passage of water in an otherwise low permeability material.



Soil fabric

Soil fabric is the spatial arrangement of soil particles forming aggregates (1 - 100 mm size), aggregates forming horizons (100 – 1000 mm size), and horizons forming a soil profile (1000 + mm size). The distribution of pore size throughout these components is most significant. In some environments, biological action eg bacteria, can be a significant factor in establishing the soil fabric. A desirable feature of compaction is to produce a uniform low void structure with the best strength and stiffness values for the soil.

Conclusion

Clays are the smallest particles in a soil mass, and they behave as colloids. Different mineral types are found, each with its own characteristic behaviour. The clay mineral present in a soil reflects the weathering and deposition history of the site. For residual soils where the clay has come from the local rock, basalt will weather to predominantly Illite / Montmorillonite, whereas the feldspar of granite weathers to a Kaolinite. Clays themselves are not immune from weathering and Montmorillonite will weather to Illite, in turn altering to Kaolinite, then to Bauxite. The final product is the alumina oxide remains after the slightly more soluble silica has been removed. Why does Australia have such large reserves of Bauxite?

The engineering behaviour of clay is sensitive to many aspects of the water in the pore spaces around the particles. As well as water content and water pressure (positive or negative), clay behaviour is influenced by the amount and type of dissolved salt in the water.

References

- Holtz, R.D. & Kovacs, W.D. An Introduction to Geotechnical Engineering, Prentice-Hall, 1981.
- Ingles, O.G. & Metcalf, J.B. Soil Stabilisation – principles and practice, Butterworths, 1972
- Mitchell, J.K. Fundamentals of Soil behaviour, John Wiley, 1993

Appendix

General clay characteristics

Clay mineral	Kaolinite	Illite	Montmorillonite
Typical thickness (nm)	50 - 2000	30	3
Typical diameter (nm)	300 - 4000	10000	100 - 1000
Specific Surface (m ² /g)	10 - 30	50 - 100	200 –800
Cation Exchange capacity meq/100g	3	25	100
Activity (PL / %clay)	0.3 – 0.5	0.5 – 1.3	1.5 - 7
Swell potential	low	medium	high

Characteristic	Flocculated	Dispersed
Origin	Marine deposition	Fresh water deposition
Stiffness	high	low
Swell potential	low	high
Strength	high	low
Remoulding sensitivity	high	low
Erosion potential	low	high
Hydraulic conductivity	high	low