

A Review of Clayey Soils

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ABSTRACT— *Clays in general and expansive soils in particular have been a major concern to geotechnical engineers for many years. Moisture variations produce big volume changes in these types of soils. Several factors like amount and type of clay minerals, soil structure, dry density, confining pressure, moisture content and climate changes influence the amount of swell and shrinkage. These volume changes finally result in serious damage to the various structures including pavements. In addition, clayey soils are usually stiff when they are dry and give up their stiffness as they become saturated. Soft clays (i.e. illite/kaolinite/ montmorillonite) are associated with low compressive strength and excessive settlement. This reduction in strength due to moisture leads to severe damages to buildings and foundations.*

Keywords— Clay structure; Cation Exchange Capacity; Atterberg limits

1. INTRODUCTION

Naturally occurring expansive soils have been found in various regions across the globe [1]. Soils with higher percentage of clay minerals like montmorillonite, expandable illite and vermiculite, are susceptible to swelling and shrinkage. They cause numerous costly damages to the roadways, buildings, bridges and other civil engineering infrastructures. Furthermore, clay soils are generally stiff in dry state but when become saturated, they lose their stiffness.

Soft clays are characterized by low compressive strength and excessive compressibility. The reduction in bearing capacity of soft clays results in compressive failure and excessive settlement, leading to severe damage to buildings and foundations [2-4]. Maintenance and rehabilitation costs for the infrastructure on these soils reach billions of dollars annually. These problems primarily stem from the presence of montmorillonite clay minerals which are derived from basic and ultrabasic igneous rocks; essentially the minerals are a by-product of the decomposition of these rocks [5, 6]. These minerals swell when moisture is introduced and shrink when the same moisture is retracted. In the case where the soil undergoes excessive heat, i.e. drought, expansive soils tend to contract and shrink excessively [7-12]. Al-Rawas and Goosen [10] noted that clay minerals and cations come in various forms and that it is the relative quantities of each type of these minerals that are important factors contributing to the swell/shrink behavior along with the dry density, soil structure, and loading conditions present. Other researchers added that the arid climate, alkaline environment, and local geology are accountable for the expansive nature of soils [11, 12]. The main objective of this paper is a review on properties of clay soils which have more effects on geotechnical properties.

2. CLAY STRUCTURE

Clays are generally composed of micro-crystalline particles of a group of minerals. Since clay science has been the interest of people from different backgrounds, a specific definition of this material is not available [12]. Generally, clays are naturally occurring material primarily composed of fine-grained minerals, show plasticity when mixed with appropriate amount of moisture and become hard when dried or fired [13, 14]. Das [14] indicated the characteristics of clay, which included:

- a) Small particle size (usually smaller than 0.002 mm)
- b) Net negative charge
- c) Show plasticity when mixed with moisture

2.1 Clay Mineralogy

Clay minerals are crystalline sheet like structure, which consist of hydrous aluminosilicates and metallic ions. There are two fundamental crystal units of clay minerals, i.e. tetrahedral and octahedral. A tetrahedral unit belongs to four oxygen enclosing silicon, where as an octahedral unit composes of six oxygen or hydroxyls at corners surrounding aluminum, magnesium, iron or other ions. The schematic of basic tetrahedral and octahedral unit are presented in Figures 1 and 2, respectively.

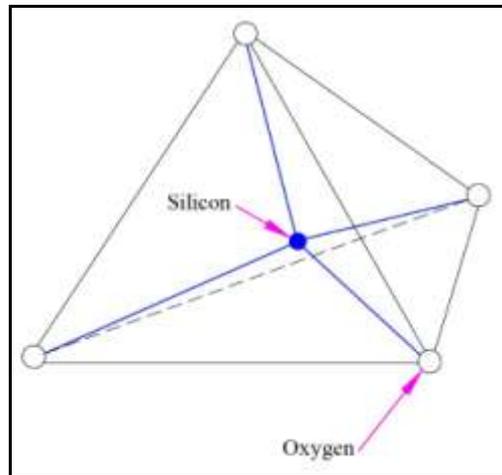


Figure 1: Single unit of tetrahedral mineral [19]

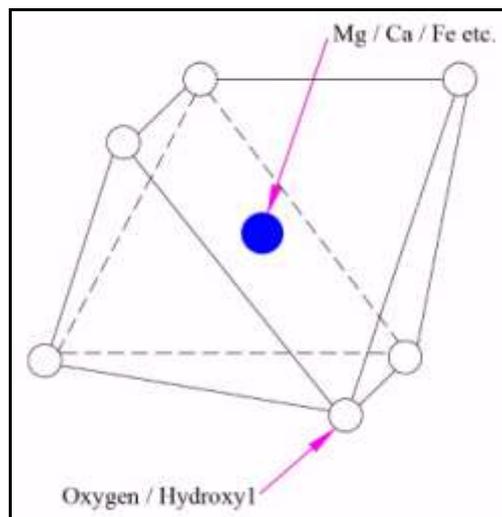


Figure 2: Single unit of octahedral mineral [19]

Based on the arrangement of stacks, bonding, isomorphous substitution, and presence of metallic ions, different clay minerals can be constituted. Some of the common clay minerals are kaolinite, montmorillonite, illite, nontronite, muscovite, etc. [15]. However, for engineering purpose kaolinite, montmorillonite and illite have particular importance in geotechnical engineering [18].

2.1.1 Kaolinite

Kaolinite is known as 1:1 mineral because the inherent crystal structure consists of one tetrahedral and one octahedral sheet. Successive basic layers are bonded together by hydrogen bond between hydroxyls of the octahedral sheet and oxygen of the tetrahedral sheet. Due to this hydrogen bond, a large crystal of kaolinite is developed. The thickness of the basic crystal layer is 0.72 nm. A schematic of the crystal structure of kaolinite is presented in Figure 3.

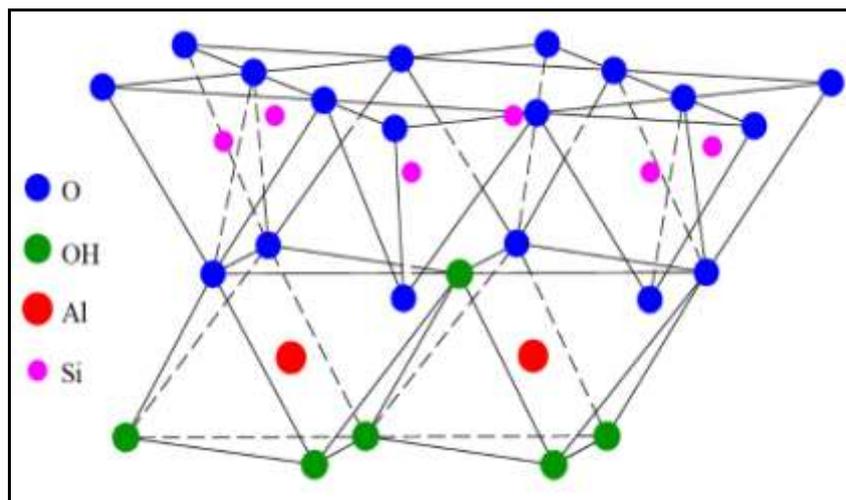


Figure 1: Structure of kaolinite crystal [19]

Typically, exposed hydroxyl can be replaced by exchangeable ions, and Al^{3+} can be substituted for Si^{4+} . Moreover, the presence of a divalent ion can cause a substitution of divalent ion for Al^{3+} . The ranges of cation exchange capacity in [19] kaolinite are in between 3 to 15 meq/100g. The surface morphology of kaolinite mineral is characterized by six-sided hexagonal plates. The lateral dimension and thickness of the plates are ranged from 0.1 to 0.4 μm and 0.05 to 2 μm , respectively because of the crystal structure and morphology, the typical specific surface area of kaolinite ranges between 10 and 20 m^2/g .

2.2.1 Montmorillonite

The basic unit of montmorillonite consisted of two silica sheets and one alumina sheet. This mineral is known as 2:1 mineral where the distance between the unit cells is approximately 0.96 nm. The top of the silica sheets are bonded by van der Waals force, and there is a net negative charge deficiency in octahedral sheet. Therefore, water and exchangeable ions can center and break the layer. The structural unit of montmorillonite is presented in Figure 4. Because of the layer separation and hydration, montmorillonite mineral is characterized by swelling behavior. In addition, montmorillonite minerals show extensive isomorphous substitution for Si^{4+} and Al^{3+} by available cations. According to the literature, Al^{3+} can replace as much as 15% of Si^{4+} in the tetrahedral sheet [15]. The overall charge deficiency resulting from the ion substitution ranges from 0.5 to 1.2 per unit cell. The typical ranges of cation exchange capacity of montmorillonite are between 80 and 150 meq/100 g.

The surface morphology of montmorillonite mineral is characterized by equidimensional flakes, and may appear as thin films. Furthermore, directional strain may cause by large amount of substitution of Fe^{3+} and/or Mg^{2+} for Al^{3+} , which may result needle shaped fabric structure in montmorillonite. Due to the inherent configuration and high surface activity, the specific surface area (exclusive of interlayer zone) of montmorillonite can vary from 50 to 120 m^2/g .

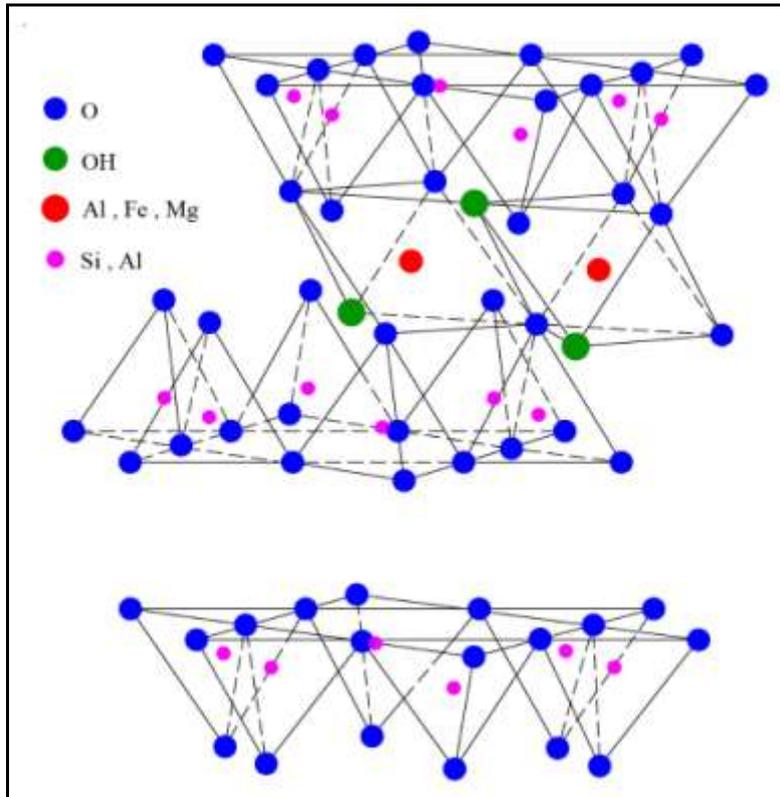


Figure 2: Structure of montmorillonite crystal [19]

2.3.1 Illite

Illite mineral is composed of two silica sheets and one alumina sheet, and known as 2:1 mineral. The basic unit configuration is similar to montmorillonite; however, the basic layers are bonded by potassium. The diameters of hexagonal aperture in silica sheet are exactly similar to the ionic radius of potassium (K^+). Therefore, the presence of potassium (K^+) makes the bond between the layers very strong. The schematic of the structure of illite is presented in Figure 5. The overall charge deficiently is mostly in the silica sheets, and ranged between 1.3 to 1.5 unit per cell. The additional charge is balanced by non-exchangeable potassium (K^+) ions. The typical cation exchange capacity of montmorillonite ranges from 10 to 40 meq/100 g.

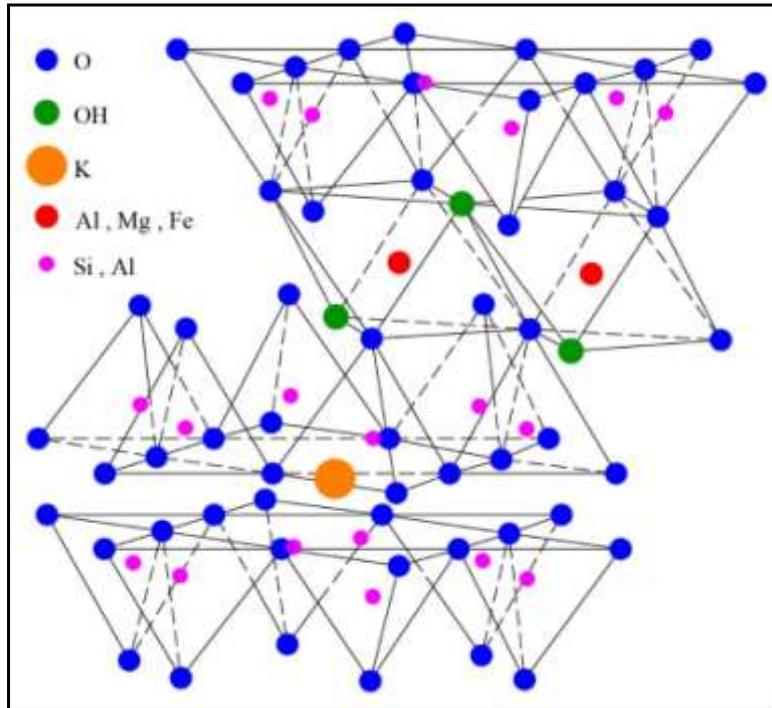


Figure 3: Structure of illite crystal [19]

The fabric morphology of illite is characterized by hexagonal small flaky particles when well crystallized. According to Mitchel [19], the surface area of this mineral ranges from 65 to 100 m² / g . The typical chemical formula of the clay minerals are presented in Table 1.

Table 1: Chemical formulas of clay minerals [20]

<i>Clay Mineral</i>	<i>Layer type</i>	<i>Typical Chemical Formula</i>
Kaolinite	1 : 1	Al ₂ Si ₂ O ₅ (OH) ₄
Montmorillonite	2 : 1	(Na, Ca) _{0.3} (Al, Mg) ₂ Si ₄ O ₁₀ (OH) ₂ × nH ₂ O
Illite	2 : 1	(K, H ₃ O)(Al, Mg, Fe) ₂ (Si, Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)]

3. CLAY WATER INTERACTION

It is evident that the engineering and physico-chemical behavior of clay are largely influenced by the moisture. Therefore, it is important to know the mechanism of clay water interaction. The clay particles contain adsorbed counterions and excess ions in the form of precipitated salts at dry condition. The addition of water hydrates the counterions adsorbed in the particle surface. During the hydration process, some of the counterions lose their primary hydration shell (all or partly) and develop inner sphere complex. The ions with primary hydration shells also exist in the form of outer sphere complex. The hydrated counterions are attached to the particles due to the presence of surface charge. The rest of the counterions are separated from the surface of the particles by water. Uday et al. [17] summarized the possible causes of clay water interaction, which included hydrogen bonding, attraction by osmosis, hydration of exchangeable cations, charged surface dipole attraction, and presence of dispersion force as illustrated in Figure 6.

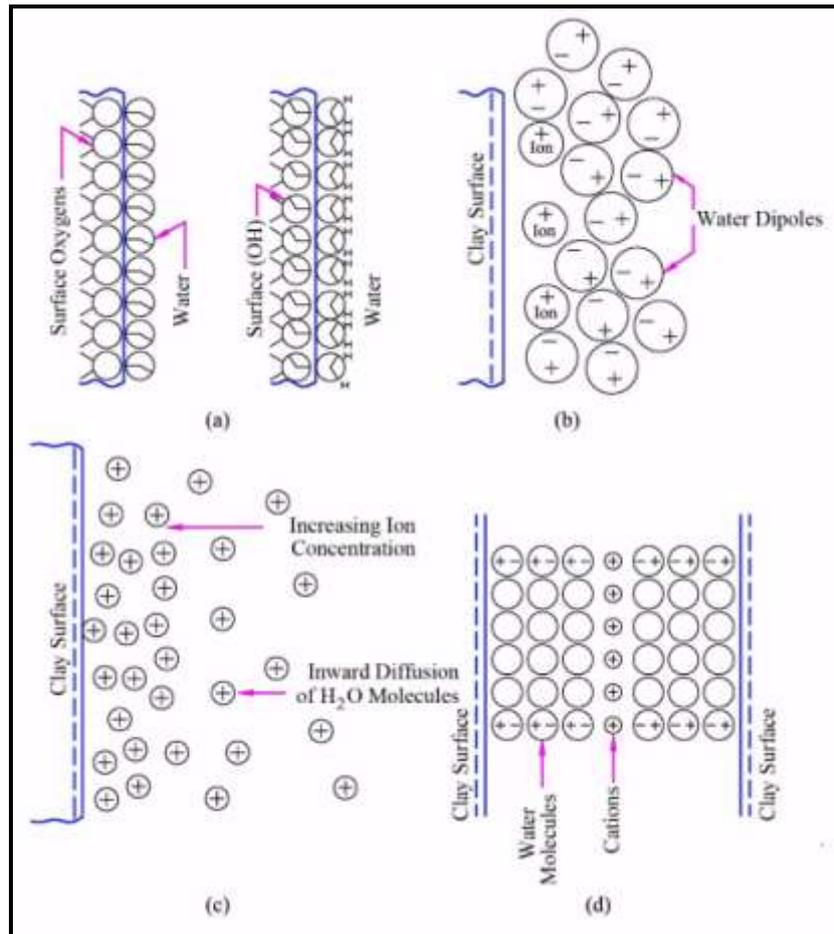


Figure 4: Different causes of clay water interaction (a) hydrogen bonding (b) ion hydration (c) attraction by osmosis (d) dipole attraction [17]

4. CHARACTERIZATION OF CLAY MINERALS

The characterization of clay mineral is necessary for the identification of engineering and physico-chemical behavior of fine-grained soils. In addition, design of stabilizers also requires a specific determination of clay mineral [8, 19, 32]. Nayak and Singh [20] utilized Atterberg limits to determine the qualitative mineralogical content of soils. Das [14] indicated that ranges of activities in clays minerals were different, and provided an indication about the dominant mineral in a soil sample. Based on the experimental results, a chart was developed for the identification of dominant mineral. Although the chart provides a mean for preliminary assessment of mineral, the information can be useful from engineering point of view. The typical ranges of liquid limit (LL), plastic limit (PL) and activity of different minerals are presented in Table 2.

Table 2: Typical ranges of LL, PL and activity of minerals [12]

<i>Mineral</i>	<i>Liquid limits</i>	<i>Plastic limits</i>	<i>Activity</i>
Montmorillonite	100-900	50-100	1-7
Illite	60-120	35-60	0.5-1
Kaolinite	30-110	25-40	0.5

Viennet et al. [23] presented a study on the quantification of clay minerals in fine fraction of soil. The Cation Exchange Capacity (CEC), Specific Surface Area (SSA), and total potassium tests were performed on the natural and artificial soils. Based on the experimental results, artificial neural networks were developed to quantify the minerals. It was reported that the performance of the neural network incorporating three parameters were in good agreement with mineralogical distribution of the tested soils. Prandel et al. [24] correlated free swell ratio of soils with the mineral contents. An extensive experimental program consisting of seventy soil specimens was developed to determine the free swell ratio. Thereafter, a chart was developed (Table 3) to determine mineralogy of the specimen using free swell ratio.

Table 3: Mineralogy based classification of soil using free swell ratio [24]

<i>Free swell ratio</i>	<i>Soil expansivity</i>	<i>Clay type</i>	<i>Dominant clay mineral type</i>
≤ 1	Negligible	Non-swelling	Kaolinite
1.0-1.5	Low	Mixture of swelling and non-swelling	Kaolinite and Montmorillonite
1.5-2.0	Moderate	Swelling	Montmorillonite
2.0-4.0	High	Swelling	Montmorillonite
> 4.0	Very high	Swelling	Montmorillonite

4.1 Cation Exchange Capacity

The cation exchange capacity or the CEC level is the measure of isomorphous substitutions that occur with the clay minerals [19]. The isomorphous substitutions are due to tetrahedral and octahedral sheets containing cations instead of an idealized structure (i.e. aluminum in the places of silicon, magnesium instead of aluminum, etc.). When the isomorphous substitution occurs, multiple cations are replaced with other cations of other valences within the structure to maintain equilibrium within the clay structure. The ability to measure the cation replacement is computed as milliequivalents (meq) per 100 g of clay. The milliequivalents are determined by knowing the atomic weight, and the weight and valence of the element. The CEC value is a guide to estimate the predominant clay mineral. In addition, the CEC shows how stable the clay mineral is to isomorphous substitution. When the measurable CEC increases the isomorphous substitution within the clay mineral also increases. Table 4 outlines CEC values for common clay minerals. As one can see, kaolinite has the lowest CEC, while vermiculite has the highest CEC.

Table 4: CEC value for common clay minerals [19]

<i>Clay mineral</i>	<i>meq/100 g</i>
Kaolinite	5
Halloysite	12
Illite	25
Vermiculite	150
Smectite	85
Chlorite	40

4.2 Specific Surface Area

The specific surface area (SSA) is the measure of the surface area of a clay sample, which is determined by the amount of the polar molecule (i.e. glycol, glycerol, or ethylene glycol mono-ethyl ether (EGME) retained under laboratory controlled conditions and it is then converted to SSA [19]. The SSA of the sample is an indication the governing clay mineral within the test sample. Table 5 shows different ranges of SSA for common clay minerals.

Table 5: SSA values for common clay minerals [19]

<i>Clay mineral</i>	<i>SSA (m²/g)</i>
Kaolinite	10 to 20
Halloysite	35 to 70
Illite	65 to 100
Vermiculite	40 to 80
Smectite	50 to 800

As shown in Table 5, the range of SSA for the different minerals can overlap significantly. For example, if a soil sample has a SSA of 65 m²/g, it can be classified as halloysite, illite, vermiculite, or smectite. In this case, to define the governing clay mineralogy will require additional testing (i.e. X-ray diffraction).

4.3 Atterberg Limits

The concept of the Atterberg limits was introduced to geotechnical engineering by Casagrande [25]. Under Casagrande, a uniform test method was developed to determine the liquid limit (LL), plastic limit (PL), and the plasticity index (PI) of soil. The liquid limit and the plastic limit correspond to different shear strengths of the soils. Holtz and

Kovacs [26] used the Atterberg limits to create a soil classification system (Figure 7), which was then modified by the United Soil Classification System (USCS).

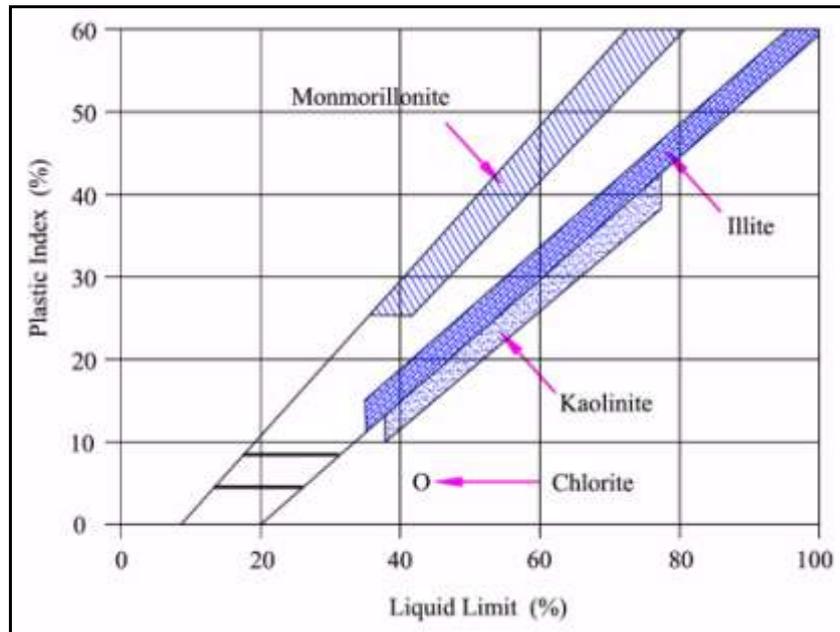


Figure 7: Location of clay mineralogy bands on USCS soil classification [23]

Figure 7 is only a guideline for clay mineralogy classification based upon the Atterberg limits. There are a multitude of soils that do not fall within the clay mineralogy groupings that governing the behavior of the soil sample/stratigraphy.

4.4 Clay Fractions

Depending on the classification system the clay fraction size can vary. AASHTO states the clay fraction is determined by the percent passing 0.005 mm while USCS and USDA both state the clay fraction is determined by the percent passing 0.002 mm. Skempton [27] introduced the idea of activity that he specified is determined by the percent passing 0.002 mm, which is obtained from a hydrometer analysis.

4.1 Activity

Skempton [27] introduced the concept of activity which is used as an index property to determine the swelling potential of expansive soil. The clay soil can be classified inactive ($A < 0.75$), normal ($0.75 < A < 1.40$) and active ($A > 1.40$).

$$A = \frac{PI}{C} \tag{1}$$

where: PI : Plasticity Index
C : % of clay – size fraction, by weight

5. FREE SWELL AND FREE SWELL INDEX

Free swell is the difference between the final height and the consolidated height divided by the consolidated height. The consolidated height is the height of the sample achieved within a certain amount of time, per the referenced standard, under a prescribed token load, prior to inundation (or adding water to the sample). The token load for the free swell can range from 1 kPa to 5 kPa (20 psf to 100 psf), which is dependent on the test standard that is used. ASTM D4546 the token load is 1 kPa and the prescribed token load in Arizona is 5 kPa. ASTM D4546 states that the compactive effort and the moisture content are determined by the laboratory that is running the test, while the Arizona method predetermines the compactive effort and moisture content. The Arizona method requires the moisture content two percent less than the optimum and 95 percent of the maximum dry density. Free Swell Index (FSI) is defined in equation 2.

$$FSI = \frac{100 (V_{\text{water}} - V_{\text{kerosene}})}{V_{\text{kerosene}}} \quad (2)$$

where: V_{water} : is the volume of the soil sample in water

V_{kerosene} : is the volume of the soil sample in kerosene

5.1 Guidelines of Swell Potential Determination Based on Engineering Properties

The most common soil properties used to determine the swell potential of expansive soils include activity, Atterberg limits, clay fractions, colloidal content, plasticity index, swell percent, shrinkage limit and the shrinkage index. Skempton [27] proposed a methodology to classify expanse potential for various types of soils. His methodology is based on the percent of clay fraction (percent passing 0.002 mm) and the plasticity index. Figure 8 describes the swell potential related to the plasticity index and the clay fraction. It was observed that once the swell potential is “medium” or “marginal”, the potential for a geotechnical hazard is significant.

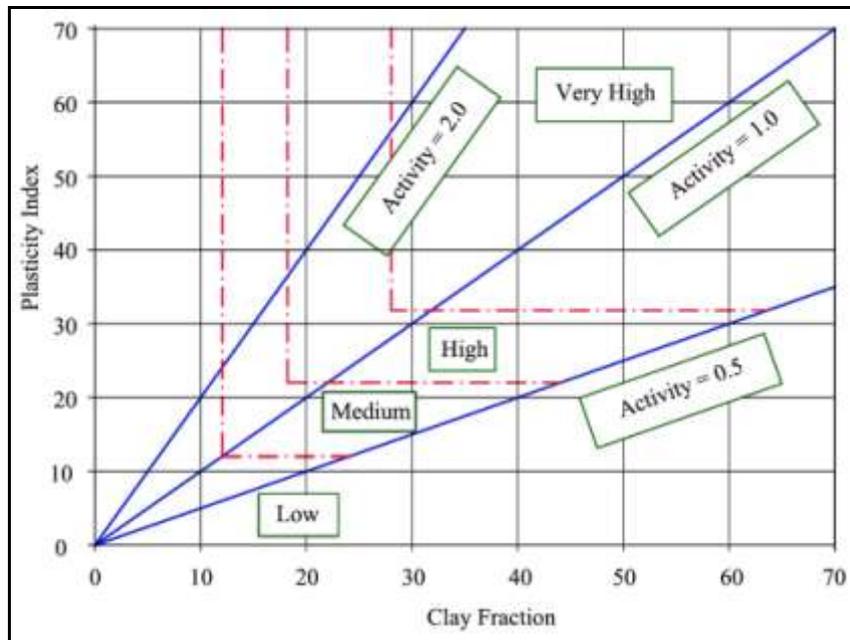


Figure 5: Swell potential related to PI and CF [27]

Holtz and Gibbs [28] proposed methods for determining the swell potential of soils, as given in Table 6. Furthermore, Holtz [26] recorded the volume change of the material from an air-dry state to a saturated state under 1-psi (7-kPa) surcharge pressure in an odometer apparatus. The swell potential criterion that was determined by Holtz [29] is presented in Table 6.

Table 6: Swell potential [28, 29]

<i>Swell Potential</i>	<i>% Swell</i>	<i>Colloidal Content</i>	<i>Plasticity Index</i>	<i>Shrinkage Limit</i>	<i>Source</i>
Low	< 10	< 17	< 20	> 13	Holtz and Gibbs (1956)
Medium	20	12 – 27	12 – 34	8 – 18	
High	30	18 – 37	23 – 45	6 – 12	
Very high	> 30	27	> 32	< 10	
Low	< 10	< 15	< 18	> 15	Holtz (1986)
Medium	20	13 – 23	15 – 28	10 – 16	
High	30	20 – 31	25 – 41	7 – 12	
Very High	> 30	> 28	> 35	< 11	

5.2 Differences in Desiccation Crack Formation During Drying

There is evidence of vertical and horizontal cracks formation during the drying cycle as the shrinkage process occurs and upon wetting cycle the cracks create preferential paths for water to infiltrate the sample. Figure 9 shows an example of the formation of vertical and horizontal cracks within the samples. The generation of the cracking in the drying phase becomes preferential wetting paths during the wetting phase by promoting swelling and closure of the cracks [29-33].



a) Top view of horizontal cracks that form on the top surface b) Side view of the vertical cracks throughout the sample

Figure: 6 Shrinkage cracks

When a drying soil is restrained due to external loads applied, (1-D consolidometer) the external load restricts the volume change, which leads to anisotropic volume change. During the anisotropic volume change, the soil suction can lead to the development of tensile stresses in the restrained direction [34, 35]. Once the tensile stresses exceed the tensile strength of the soil, the soil tends to crack releasing the strain energy developed in the soil. After the soil cracks, the restraints placed on the soil are partially released, which allows the soil to undergo further volume change more isotropically; however, the soil suction can build up to higher tensile forces thus leading to additional cracking in the sample. This phenomenon could describe the field behavior of large desiccation cracks that are found in arid to semi-arid regions, in the superficial upper crustal layer.

On the other hand, when a drying soil is restrained laterally (horizontal directions i.e. from a triaxial test) it tends to rely on the continuity of the structural fabric to maintain zero lateral strain in the soil [34, 36]. Until cracking occurs in the sample, the sample/soil profile volume change will occur in the vertical direction. Nevertheless, the amount of 1-D shrinkage prior to cracking of the soil/sample is dependent on the stiffness and/or the compressibility of the soil structure [34, 36]. Therefore, as a triaxial sample dries, the boundary condition stays the same in the regards of confinement, which will lead to consolidation that is induced by shrinkage instead of inducing cracks within the sample. It is possible that the horizontal and vertical cracks are not induced due to the dissipation of tensile forces along the boundary conditions.

Therefore, with the difference shown between a 1-D and 3-D sample, a 1-D sample will be best at representing field behavior above the swell/pressure. The 3-D sample, in contrast, will be best at representing the field behavior below the swell pressure.

6. CONCLUSION

The geotechnical properties of soil such as its grain size distribution, shear strength, compressibility, plastic limit, liquid limit can be defined by proper laboratory testing. Furthermore, recently emphasis has been placed on the in situ determination of strength and deformation properties of soil, because this method avoids disturbing samples during field examination. Clay minerals are formed weathering a variety of minerals. The two main processes may involve slight physical and chemical alteration or decomposition and recrystallization. Furthermore, the clay minerals and soil organic matter are colloids. And the most important property of colloids is their small size and large surface area. The total colloidal area of soil colloids may range from $10\text{m}^2/\text{g}$ to more than $800\text{m}^2/\text{g}$ depending the external and internal surfaces of the colloid. Whereas, soil colloids also carry negative or positive charges on their external and internal surfaces. The

presence of charge influences their ability to attract or repulse charge ions to or from surfaces. Clay particles play a very important role in the chemical reaction which take place in soil and influence the movement and retention of contaminants, metals, and nutrients in the soil. However, under certain conditions, not all of the needed parameters can be made certain assumptions regarding the properties of the soil. To evaluate the accuracy of soil parameters whether they were determined in the laboratory and the field or whether they were expected the engineer must have a good grasp of the basic principles of soil mechanics. Thus, that each engineer should have the knowledge about the chemical structures.

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