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The Importance of Clay in Geotechnical Engineering

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Abstract

Clay is a very important material in geotechnical engineering, because it is often observed in geotechnical engineering practice. Generally, this soil type has numerous problems due to its low strength, high compressibility and high level of volumetric changes. Clay needs to be improved before it can be used in road construction, dams, slurry walls, airports and waste landfills. Improved gradation, a reduction in plasticity and swelling potential, as well as an increase in strength and workability, generally improve the stability of clay. Clay is a fine-grained soil, but not all fine-grained soils are clay. Clay minerals are very electrochemically active; thus, they affect soil microstructures. Due to these characteristics, many important soil problems related to clay have been observed in the past, the importance of which is understood. In this chapter, the properties of clay, as well as the use of clay in geotechnical engineering and geotechnical studies on clay, are examined.

Keywords: clay, soils, geotechnical properties, soil problems, microstructure

1. Introduction

Geotechnical engineering is a broad discipline consisting of soil mechanics and foundation engineering. Geotechnical engineering is also called geotechnique engineering or geomechanics. Geotechnical engineering addresses the application of engineering mechanics to soil and rock problems. The properties, behavior and performance of soils are addressed by engineering mechanics. Subsequently, the obtained data are processed and interpreted [1]. Geotechnical engineers consider landslides and earthquakes when planning and designing structures for buildings, roads, embankments and landfills. Geotechnical engineers also examine billions of years of geological history through soils. Therefore, examinations of the heterogeneous nature of soils require the resolution of complex problems. All types of

engineering structures such as residential buildings, service buildings, bridges, dams, roads and airports are located on or in the ground. As Richard said in 1995, “is supported by almost every construction ground or rocks. Unsupported are either fly or float or fall” [2]. Even when they are well designed, the safety of an engineering structure cannot be ensured when there is inadequate bearing capacity, high swelling/shrinking potential and settlement (compression) of the soil. For this reason, geotechnical applications in soils have become obligatory. Many studies were carried out in the 1910s due to the large number of landslides and docks that occurred in Sweden. The recommendations that resulted from these studies are now being applied as a landslide analysis method known as the Swedish slice method. With an increasing number of wall demolitions, Skempton presented calculations in 1979 [2]. Today, the latest technologies used in geotechnical soil applications are problematic for transportation power with the increase in industrialization and different kinds of construction.

Looking at the history of geotechnical engineering, Turkey is an important place. Karl von Terzaghi, who is the founder of geotechnical engineering or the father of soil mechanics, investigated Haliç clay in Turkey and laid the foundation of geotechnical science. In his investigations of a clay-rich ground, which is abundant today, Terzaghi managed to obtain clay samples from the Black Sea coast (Kilyos) with the assistance of two brave students who endured many difficulties, including bandits, and being 20 km from the nearest motorway. The clays in Terzaghi’s study in 1925 are numbered II and IV in the book, which is entitled “Erdbau Mechanic.” This book is accepted as the foundational document of modern soil mechanics. The mathematical formulation of clay consolidation under constant pressure over time was investigated in this book, and it was discovered that there may be an analogy between heat conduction and the damping of additional void water pressure. Thus, the “clay consolidation problem” has been solved in all its aspects. In 1925, the results of Terzaghi’s research in Turkey were published in the book “Soil Physics Fundamentals of Soil Mechanics” by the Franz Deutick Publishing House in Vienna. This book is recognized by the World Society of Civil Engineers as the foundational document for modern ground engineering [3].

The first building which comes to mind regarding soil problems is the Pisa Tower. Its construction began in 1173 and took approximately 200 intermittent years to complete. The tower began to lean during construction and the leaning has continued after the construction was completed. In 1982, the hill was 58.4 m long and deviated by 5.6 m from the plumb (**Figure 1**). This soil problem is explained by clay soil settlement of up to 11 m from the surface [2]. The soils of interest in geotechnical engineering are formed from rock degradation. This process consists of physical and chemical weathering. Clay is largely composed of chemically altered and different materials of bedrock. The change in contents and structures due to physical, chemical and biological processes that occur in rocks is called weathering. Physical weathering is the mechanical disintegration of rocks by heat exchange and the effects from glaciers, waves and wind. Biological weathering results from the activities of plants and animals within a rock. Chemical weathering is caused by the effects of oxidation, reduction, hydrolysis, carbonation and organic acids in rocks. As a result of weathering, all kinds of soils are formed. In physical weathering, blocks of rock, gravel, sand and silt materials are formed, whereas clay minerals are formed by chemical weathering [4]. In geotechnical engineering practices, clay is generally seen as a problematic soil. When these soils are seen during the construction of road



Figure 1. Pisa tower [2].

dams, slurry walls, airports and waste landfills, it becomes even more important to address. Clays generally have low strength, high compressibility and high volumetric changes. Because of clay's high plasticity, permeability, bearing capacity and settlement characteristics, it is a material that has been studied and is still being studied in geotechnical engineering. In this study, the characteristics of clay are discussed and its importance in geotechnical engineering practices is noted. This chapter is composed of five main sections. In the first section, the importance of clay in geotechnical engineering is presented. In Section 2, clay is defined and its properties are discussed. Section 3 presents the use of clay in geotechnical engineering practices. In Section 4, previous, related studies are summarized. Finally, in Section 5, the subject of clay is summarized and conclusions from this chapter are provided.

2. Clay definition and properties

2.1. Clay definition

Clay minerals are called secondary silicates, because they are formed from the weathering of primary rock-forming minerals. Clay minerals occur in small particle sizes (<0.002 mm) and are very fine grained and flake shaped; they are separated from sand, gravel and silt due to the negative electrical load on the crystal edges and positive electrical load on the face. Clay

minerals consist of two basic structures. First, silica oxygen is formed through the bonding of silicon ions to the oxygen atoms on all four sides (tetrahedron). Second, an octagon forms with aluminum and magnesium ions coordinated on eight-sides with oxygen and hydroxyl ions (octahedron). All clay minerals are formed from octahedral and tetrahedral sheets with certain types of cations, which are in various forms and connected to each other in a certain system. Changes in the structures of the octahedral and tetrahedral sheets result in the formation of different clay mineral groups [4]. More common clay mineral groups include kaolinite, illite and smectite (montmorillonite). Kaolinite consists of silica and alumina plates, and these plates are connected very strongly, because kaolin clay is very stable (**Figure 2a**). Illite has layers made from two silica plates and one alumina plate (**Figure 2b**). However, illite contains potassium ions between each layer; this characteristic makes the structure of the clay stronger than smectite. Smectite has layers made from two silica plates and one alumina plate. Because there is a very weak bond between the layers, large quantities of water can easily enter the structure (**Figure 2c**). This event causes the swelling of such clay [5].

2.2. Clay properties

Certain features of the clay affect the structure of the soil, which determines its properties such as strength, hydraulic conduction, settlement and swelling. These features include isomorph substitution and surface anion and cation exchange capacity. This event is called isomorphic substitution if the octahedral or tetrahedral sites are replaced by a different atom normally found elsewhere. The specific surface area is the property of solids, which is defined as the total surface area of a material per unit of mass. With the separation of hydroxyl ions from the clay surface, which results in crystal deficiency at the crystal head, anions subsequently attach to the surface and organic molecule content causes an electrical load imbalance. This imbalance results in clay’s extreme affinity to water and cations in the environment (**Figure 3**). Water is a dipolar molecule, namely, it has one positive and one negative charge. The surface of the clay crystal is electrostatically held to the water molecule. In addition, water is held to the clay crystal by hydrogen bonding. Also, negatively charged clay surfaces attract cations in

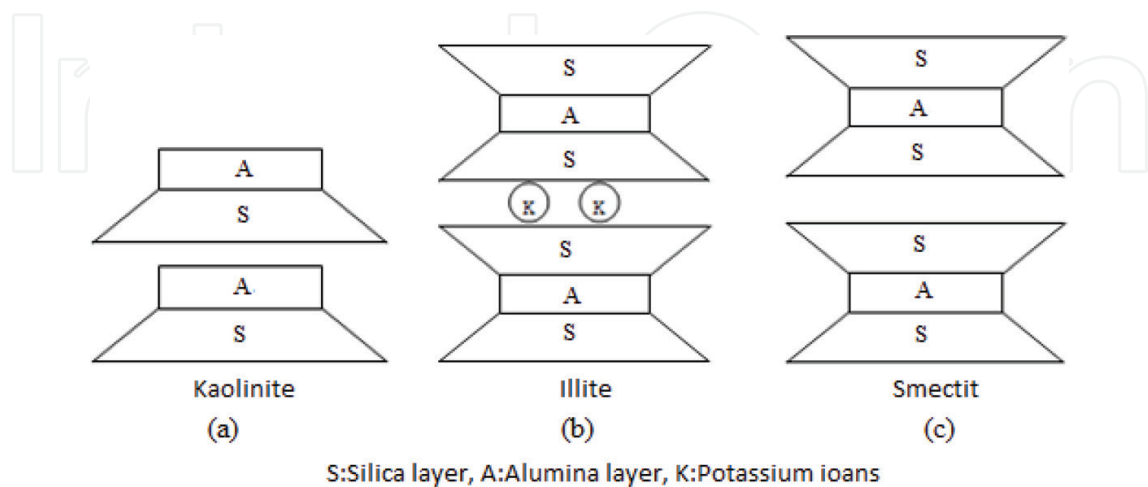


Figure 2. Display of structure of common clay minerals.

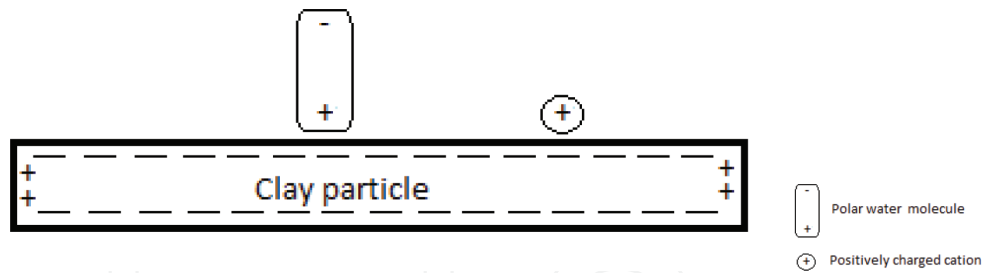


Figure 3. Clay particle and surface charge display.

the water. The cation/anion changes in the clay minerals are different between clay minerals. Therefore, it is expected that the clay that attracts more water molecules to the surface will have more plasticity, more swelling/shrinkage and more volume change, depending on the load on it. Thus, water influences clay minerals. For example, the water content changes consistency limits and this affects the ground plasticity. Ultimately the change in clay plasticity directly affects the mechanical behavior of the soil. Studies generally accept clays as fully saturated in geotechnical engineering. Therefore, the behavior of clays is affected by the individual clay particle arrangements and pore water content. The surfaces of clays are negatively charged, and so they tend to adsorb the positively charged cations in pore water. In this way, the cations on the surface of a clay particle that are entering the water spread into the liquid. This spreading is called the double layer. Briefly, the cations are distributed around the negatively charged surface of the clay particles, with the greatest density near the surface and decreased density with increasing distance from the surface. The cations form a positively charged layer and the double layer is created with a negatively charged surface of the clay particles. The double layer affects the arrangements of the clay particles, and hence, the physical and mechanical properties of the soil are also affected [6]. The interaction of these forces controls the engineering behavior of soils to a great extent. At the same time, this interaction leads to the formation of different compositions and settlements in the soil planes, which are defined as structures in clay soils [4]. Environmental temperature, precipitation, groundwater level and pH and salinity all play roles in clay properties, as well as in the conversion of rock into clay. Clay derived from the same rock can be different under different environmental conditions.

2.3. Structure of clay and physico-chemical properties

Around the clay that is faced with a liquid, there are distance-varying push-pull curves. If there is a force lifting the two clay minerals, the particles clump together. This is called flocculation. If the net force is thrust, the particles are separated from each other; this is called dispersion. Particle orientations of soils vary between flocculated and dispersed (**Figure 4**). Forces between the particles are important for clay, because the behavior of clay depends on the geological history and structure. This difference in the orientation of fine-grained soils affects the engineering behavior of the soil. The geological process in the formation of soils in nature constitutes the arrangement of soils. For this reason, geotechnical engineering studies are interested in the physical and mechanical behavior of soils-bearing structures, as well as the strength between the structure, texture and performance of soils. There are many studies

on the soil-orientation effects on the soil properties such as strength, hydraulic conductivity and the swelling-shrinkage relative to each particle [7–12]. Ingles [7] examined soil fabric during consolidation. Due to an increase in the degree of particle orientation, the total volume of the voids was reduced.

Flocculation increases depending on the electrolyte concentration, ion valence, temperature, decreasing dielectric constant, hydrated ion diameter, pH value and surface absorbed ions. Soil engineering properties depend on the size, shape, a high amount of surface area and a negative surface charge of clay particles. In 1925, Terzaghi proposed the concept of clay arrangement. He said that clay minerals stick to each other at the points of contact, with forces sufficiently strong to construct a honeycomb structure. In 1932, it was shown by Casagrande that this honeycomb shape is a special structure in clay-containing soils and this structure can vary depending on many characteristics of the environment [4]. **Figure 5** shows further compression with progress of soil sedimentation. Later, other researchers also proposed fabric models [13–17].

Collins and McGown [17] defined the elementary particle arrangement, particle assemblages and pore spaces in the fabric model. Researchers provided an elementary particle arrangement,



Figure 4. Clay particle orientations.

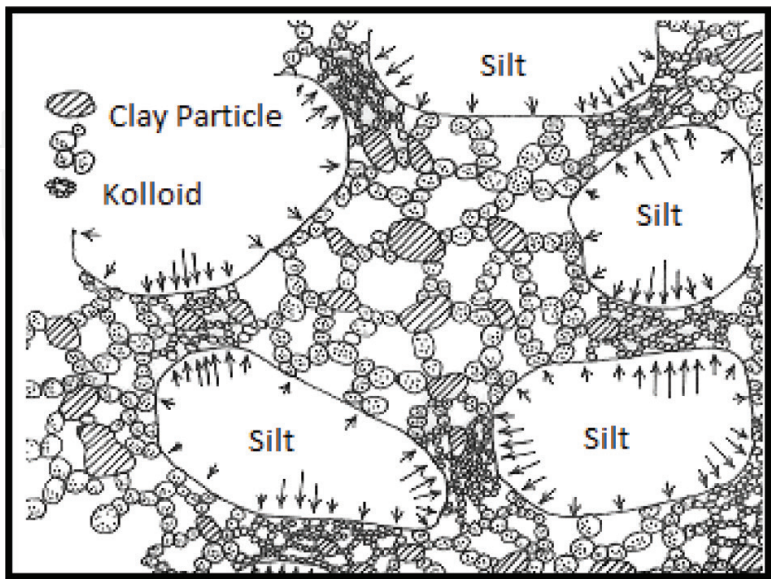


Figure 5. Casagrande’s fabric model (1932) [4].

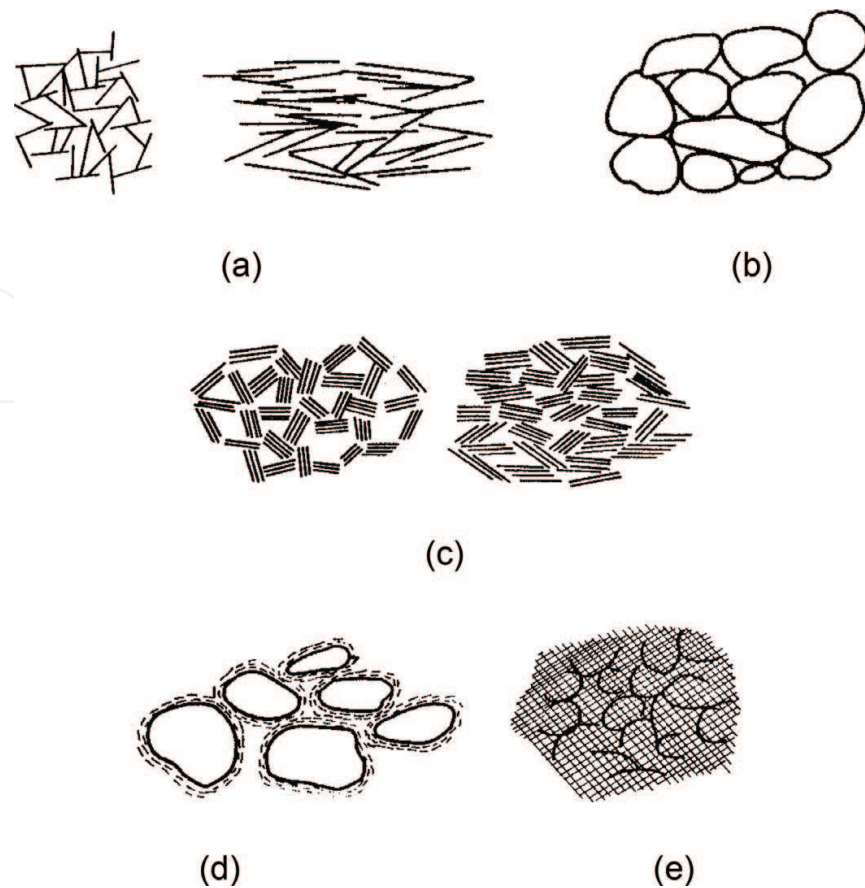


Figure 6. Arrangement of clay particles [11]. (a) Elementary particle arrangements of clay; (b) elementary particle arrangements of sand and silt; (c) clay assemblages; (d) clay coated silt and sand arrangement; (e) not fully defined arrangement.

a single clay, silt or sand, which is shown in **Figure 6a** and **b**; the group effect of clay plates is shown in **Figure 6c**, and the interaction between silt and sand is shown in **Figure 6d**. Particle assemblages contain one or more elementary particle arrangements or small particle clusters. Pore spaces are defined with spacing between elementary particle arrangements and particle assemblages. Bennet and Hulbert [18] suggested that the fabric of soils is mostly determined by the physical arrangement of particles, which is gained at the time of sediment deposition by the physical–chemical conditions of the depositional environment. The fabrics of soils describe clusters, clusters are formed by other clusters and space between the clusters and structure of the soils describes the fabric, mineral content and decontamination forces. Also, the fabrics of soils can sometimes be visualized under a microscope. The structure of soils can be examined more extensively by an X-ray diffractometer (XRD) and a scanning electron microscope (SEM).

3. Role of clay in geotechnical engineering

Studies on soil behavior that do not consider the physico-chemical and microstructural properties of clay soils may be missing important information regarding the soil's physical and mechanical

properties. This is because most physical and mechanical behaviors can be explained by the soil’s physico-chemical and microstructural properties. In general, clay is an unwanted material because it creates significant engineering problems. Unlike other minerals of the same size, clay forms mud when mixed with water. Clay has plasticity and can be shaped into dough, and when cooked it turns into a solid with great strength increments. Clay generally shows a volume increase when wet, and when it is dried, its volume decreases, which creates many cracks.

3.1. Physical and mechanical behavior of clay

In geotechnical engineering, it is important to identify a clay type, as the type directly affects the important properties of clay, such as Atterberg’s limits, hydraulic conductivity, swelling-shrinkage, settlement (compression) and shear resistance. Atterberg’s limits, known as consistency limits, define the relationship between ground particles and water and the state of the soil relative to varying water contents. With increasing moisture content, clay changes from solid state, to semisolid state, to plastic state and to liquid state, which is given in **Figure 7**. In **Figure 7**, the clay-water mixture shows a total volume reduction, which is equivalent to the volume of water lost around the liquid and plastic limits, as the clay transitions from liquid to dry, and if the decrease in water content continues, no reduction in volume is observed. This limit value is called the shrinkage limit. Therefore, the shrinkage limit is the moisture content at which the soil volume will not reduce further if the moisture content is reduced. The plastic limit is the moisture content at which the soil changes from a semisolid to a plastic (flexible) state. The liquid limit is the moisture content at which the soil changes from a plastic to a viscous fluid state [19]. In geotechnical engineering, the liquid and plastic limits are commonly used. These limits are used to classify a fine-grained soil, according to the Unified Soil Classification system, AASHTO system or TS1500 (Turkey).

3.1.1. Hydraulic conductivity properties of clay

Water is a problem in geotechnical engineering, such as water in voids in the ground mass, flowing in pores, or in the pressure or stress that water creates in the pores. Clay plays an important role in the emergence of water problems, especially on fine soils, and these

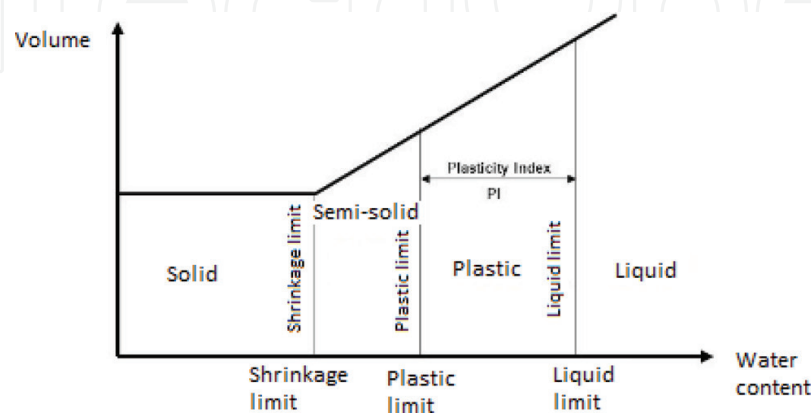


Figure 7. Water content-volume relationship of soils.

problems include permeability, shear resistance, setting and swelling problems. In addition, capillarity, freezing and infiltration can be additional issues. Structures built on clay and slope stability are particularly problematic when affected by water. Dams and dikes also cause the destruction of structures without leakage and piping [4]. Therefore, it is necessary to estimate the quantity of underground seepage under various hydraulic conditions to investigate problems that involve pumping water for underground construction and for stability analyses of earthen dams and earth-retaining structures that are subject to seepage forces [19].

The hydraulic conductivity coefficient commonly used in geotechnical engineering is also used for permeability. Hydraulic conductivity is a property that expresses how water flows in the soil. Soils are permeable due to the existence of interconnected voids, through which water can flow from the points of high energy to the points of low energy [4]. Fluid viscosity, pore-size distribution, grain-size distribution, void ratio, roughness of particles and the degree of soil saturation affect the hydraulic conductivity of soils. Clay soil has electrical ions, so the hydraulic conductivity of clays affects the ionic concentration and thickness of water layers held to the clay particles. **Table 1** provides the typical values for soils. The hydraulic conductivity value of soils determines the constant head test (for coarse soils) and the falling head test (for fine-grained soils) [19].

3.1.2. Swelling-shrinkage behavior of clay

The effect of swelling-shrinkage on fine-grained soils is often seen as a problem in geotechnical engineering applications. Shrinkage behavior in clay soils is effective in reducing the strength in a slope and a foundation's bearing capacity. Shrinkage is usually visible from evaporation in dry climates, reduction of groundwater and sudden arid periods. Swelling can be seen due to rising water. These volume changes are harmful to heavy construction and road coverings. Swelling occurs when the inflation pressure is greater than the pressure from the covering or structure. The material damage from the swelling-shrinkage of soils is more likely to occur in the United States due to greater water pressure, floods, typhoons and earthquakes [4].

Jones and Holtz [20] estimated that shrinking and swelling soils cause approximately \$2.3 billion in damage annually to small buildings and road surfaces in the United States. This amount of damage is twice the amount of damage incurred from floods, earthquakes and hurricanes. Krohn and Slosson [21] estimated that swelling soils cause approximately \$7 billion in damage each year. According to Holts and Hart [22] 60% of 250,000 newly constructed

Soil type	k (cm/s)
Clean gravel	100–1.0
Coarse sand	1.0–0.01
Fine sand	0.01–0.001
Silty clay	0.001–0.00001
Clay	<0.000001

Table 1. Hydraulic conductivity of soils [19].

homes incur minor expansive soil damages and 10% incur significant expansive soil damage each year in the United States. Coduto [2] noted that expansive soils caused \$490,000 in damage to a building over a 6-year period. The estimated annual cost due to significant structural damages, such as cracked driveways, sidewalks and basement floors, heaving of roads and highway structures, condemnation of buildings; and disruption to pipelines and other utilities in Colorado, is \$16 billion, according to AMEC [23].

Swelling pressure depends on the type of clay mineral, soil structure and fabric, cation exchange capacity, pH, cementation and organic matter. Any cohesive soil can involve clay minerals, but montmorillonite or bentonite clay minerals are more active regarding swelling-shrinkage. Swelling is calculated by swelling experiments with chemical and mineralogical analysis, soil indices and some empirical formulas from soil classifications. The shrinkage limit is determined from a laboratory test or approximate calculation recommended by Casagrande. Properties of clay improve with chemical additives such as cement, lime, lime-fly ash, cement-fly ash, calcium chloride and so on. [24].

Structures transfer loads to the subsoil through their foundations. The imposed stress from the structure compresses the subsoil. This compression of soil mass leads to a decrease in the volume of the mass, which results in the settlement of the structure, and this should be kept within tolerable limits. Therefore, settlement (compression) should be estimated before construction. The settlement is defined as the compression of a soil layer due to the construction of foundations or other loads. The compression is seen in deformation, relocation of soil particles and expulsion of water or air from void spaces. In general, the soil settlement under load falls into three categories: immediate or elastic settlement, which is caused by the elastic deformation of dry soil or moist and saturated soils without change in the moisture content; primary consolidation settlement, which is the result of a volume change in saturated cohesive soils because of the expulsion of water occupying void spaces; and secondary consolidation settlement is the volume change under a constant effective stress due to the plastic adjustment of soil fabrics [19]. The consolidation settlement is seen when a structure is built on saturated clay or the water level is permanently lowered. Simultaneously, consolidation settlement is seen under its own weight or the weight of soils that exists above the clay. The consolidation settlement of clay takes a long time, and the reason for this is the low hydraulic conductivity and slow drainage of clay. Settlement of the soil is determined by one-dimensional consolidation (odometer) and hydraulic consolidation (Rowe). In experiments, the vertical loads and void ratios are recorded. Afterwards, the relationship between the pressure and void ratio is determined from the measured data. These data are also useful in determining the consolidation coefficient. The consolidation coefficient is determined by the root of time method and the log-t method. **Figure 8** shows the relationship between the void ratio and stress for a typical odometer test for consolidation.

3.1.3. *Shear strength behavior of clay*

The shear strength of soils is one of the most important aspects of geotechnical engineering. The strength of the soil provides safety for geotechnical structures. The bearing strength, slope stability and bearing wall of the bases are influenced by the shear strength of the soils. Failure in the soils occurs in the form of shear. If the stresses in the soil exceed the shear strength, failure occurs. The shear failure of the soil depends on the interactions between the

soil particles. These interactions are divided into friction strength and cohesion strength [2]. When the clay soils are subjected to shear, the volume change in the drainage shear depends on the environmental pressure, as well as the stress history of the soil. In addition, loading on clay soils does not allow water to escape from the pores, and thus, this creates excess water pressure. If the loading does not cause failure, the excess water pressure is dampened, consolidation occurs and volume change is observed. The long process of this volume change in the clays is due to very low hydraulic conductivity. Determination of the shear strength of the clay is performed by a direct shear test, triaxial compression test, vane test and standard penetration tests [4]. **Figure 9** presents the relationship between the shear stress and normal stress for a typical shear strength test and triaxial compression test. After the failure envelope is drawn, the cohesion (c) and internal friction angle (ϕ) are obtained.

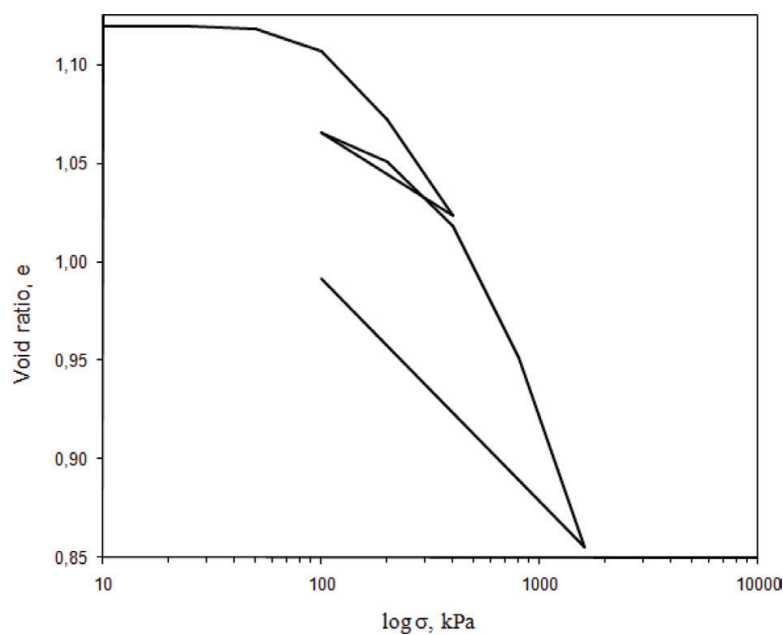


Figure 8. The graph of a typical test for consolidation test by oedometer.

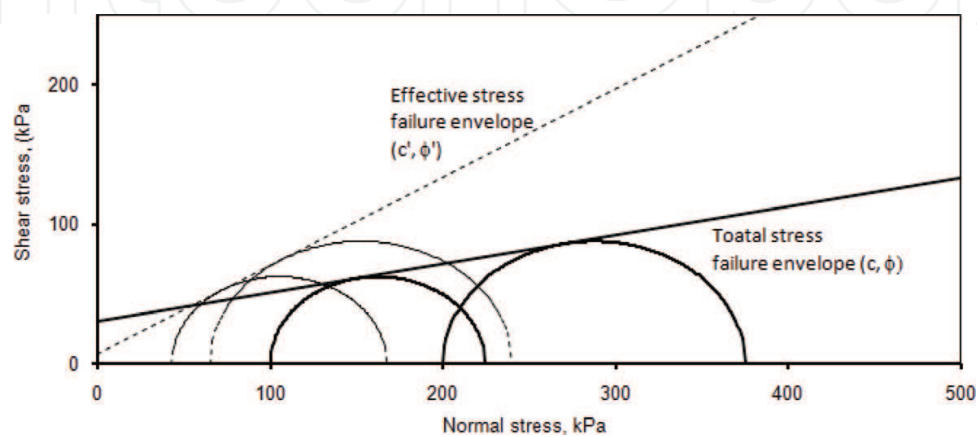


Figure 9. The graph of a typical test for shear strength test by triaxial compression test.

3.2. Physico-chemical and microstructure behavior of clay

For the determination of the physico-chemical and microstructural properties of clay soils, X-ray diffractometer (XRD) and scanning electron microscope (SEM) are commonly conducted. In addition, to determine the physico-chemical properties and structure of the soils, a pH test, electrical conductivity, cation exchange capacity, helium pycnometer, mercury intrusion porosimetry (MIP), surface area analysis (SSA), Brunauer-Emmett-Teller (BET) method or likewise, zeta potential and wavelength dispersive X-ray fluorescence test and Differential Thermal Analysis (DTA) are conducted. The pH value indicates the degree of H^+ or OH^- ions present. The change in pH affects the soil-water relations. Low pH indicates flocculation, and high pH indicates dispersion. The electrical conductivity of clay is defined by its ion number and type. Cation exchange capacity is a measure of isomorph displacement capacity. Isomorph displacement is when other ions of equal or different valence to those of the ions are left. This change emerges from the unbalanced electrical charge for every change. To prevent this imbalance, the cations in the environment enter the edges of the clays and between the blocks.

X-ray diffractometer (XRD) analyses: The mineralogical composition of soils is critical due to its significant influence on soil behavior; the soils are affected at first degree, especially by physical, chemical and mechanical properties of clay and by the mineral content. In geotechnics, it is important to find the type of minerals present in clay, as well as their proportions to understand the mechanical behavior. The XRD curve for typical clay is displayed in **Figure 10**. The X-ray diffraction patterns of clay show a mineralogical composition of montmorillonite, anorthite, quartz, calcite and silica.

Mercury intrusion porosimetry (MIP) analyses: In geotechnical engineering, the pore-size distributions for clay significantly influence the geotechnical behavior of soil. The pore-size distributions for typical clay from the MIP tests are displayed in **Figure 11**. This figure shows the relationship between incremental intrusion and pore-size diameter.

Scanning electron microscope (SEM): The microstructure of soils, especially clays, is observed using a versatile, analytical and ultrahigh-resolution field-emission SEM. An SEM provides

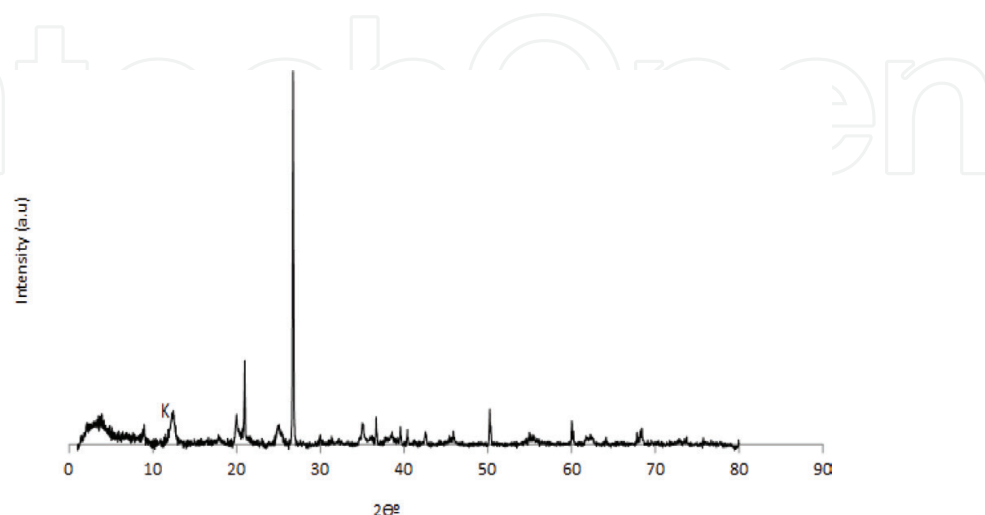


Figure 10. The XRD curve for typical clay.

a high level of magnification. Soil specimens that are magnified up to 1,000,000 times enable the evaluation of differences in the surface by imaging the surface structures. The changes in the microstructural development of soils play a significant role in the behavior of soils. In particular, these parameters could lead to a better understanding of the engineering properties of compacted soils. The SEM images of typical clays are present in **Figure 12**. Thus, flocculated and dispersed structures are observed in the soil samples.

Surface area analysis (SSA): The specific surface area is affected by grain-size distribution and the types and amounts of different clay minerals. Specific surface area is affected by the physical and chemical properties of soils.

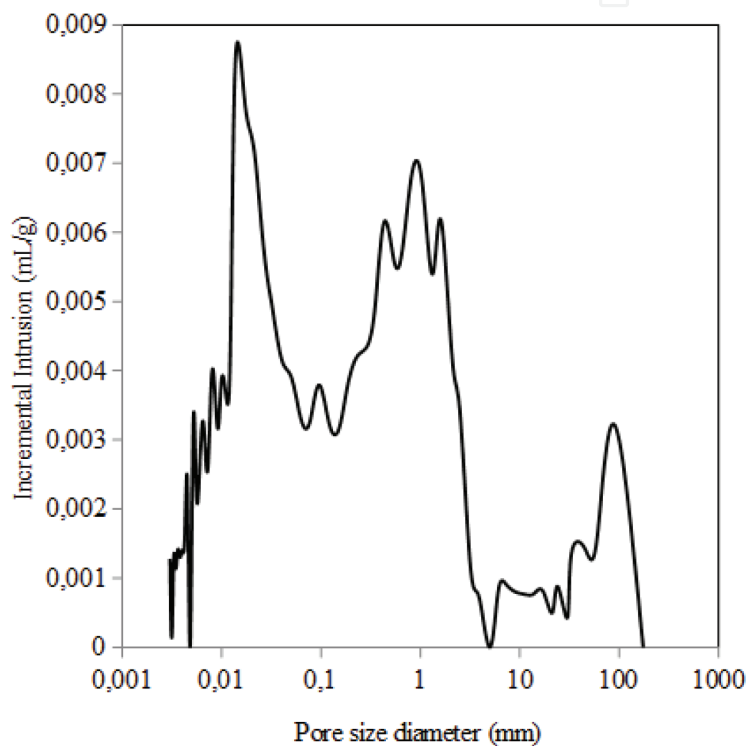


Figure 11. The pore size distributions for typical clay from the MIP tests.

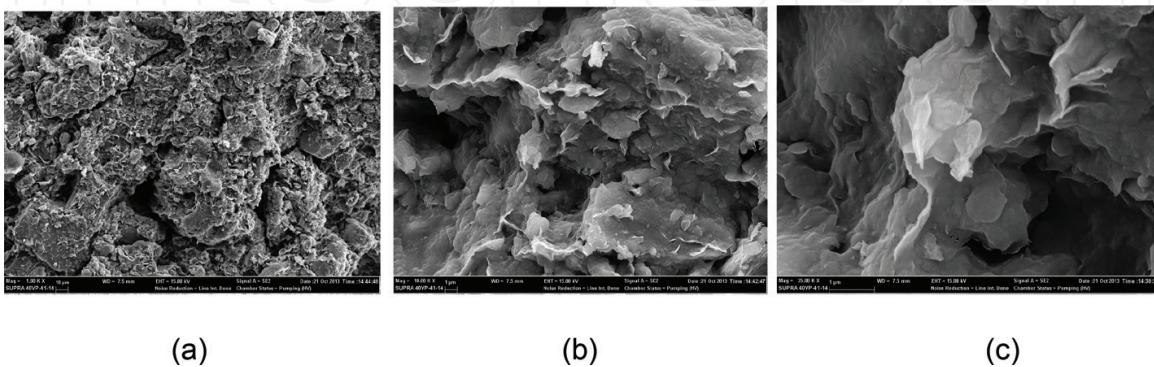


Figure 12. The SEM images of typical clay for different magnification (a. 1000×, b. 10,000×, c. 35,000×).

4. Previous related studies

Clay soils are important in the construction of buildings, dams, roads, airports, pavements and highways [25–34]. Soil problems encountered in geotechnical engineering need to be solved. Because of its double layer, clay can absorb water 10–500 times its own weight. In addition, it is considered to be a problematic soil that can show settlement under loading, with swelling or compression when it receives water. Karimi et al. [26] investigated two case studies of embankment dams in Iran. Researchers indicated that for large dams, the internal friction angle plays a more critical role in stability analyses than the cohesion parameter. Çabalar [28] investigated various fine contents and their effects on the triaxial behavior of coarse sand. Consequently, the high compressibility and other clay-like behaviors of mixtures were attributed to the particle characteristics (size and shape). Shanyoug et al. [31] investigated the effects of fine contents on the mechanical behavior of completely decomposed granite during dynamic compaction grouting. Consequently, researchers indicated that the compaction efficiency increases with the increasing fine content.

Naik et al. [32] investigated the settlement of an institutional building located in South Goa, India. This building developed cracks when the construction reached the beam level. Some foundations were located in unconsolidated filled ground, according to the standard penetration test, and thus, differential settlement was observed in the foundations. Dafalla [34] investigated the cohesion and angle of internal friction for granular soils using the direct shear test for different clay contents and different moisture contents. Consequently, researchers observed a steep drop in both cohesion and angle of internal friction in a moist, clay-sand mixture when the clay content was high. In addition, many researchers have studied the geotechnical engineering behavior of clays and their microstructure [35–39]. Rajasekaran et al. [35] investigated the influence of lime and sodium hydroxide on the microchanges in two marine clays using scanning electron microscopy (SEM). These researchers suggested that the addition of lime and sodium hydroxide created an optimal pozzolanic reaction.

Horpibulsuk et al. [36] investigated the strength development and microstructural changes of stabilized, silty clay. SEM, mercury intrusion and thermal gravity analyses for qualitative and quantitative analyses of the sample microstructures were conducted in this research. Researchers suggested that the volume of large pores increased due to the presence of coarser particles in a short period, whereas the volume of small pores decreased due to the solidification of the hydrated cement. Some studies indicated that Atterberg's limits and grain-size distribution are indicators of the soil mineralogy and for the determination of many fine-grained soil properties [37–38]. Simultaneously, Atterberg's limits affect grain-size distribution and mineral composition. For example, an increase in the surface area is observed with increased liquid limits [37, 40–43]. Grabowska-Olszewska [44] investigated the relationship between the colloidal activity and the specific surface area of model soils of kaolinite and bentonite mixtures. Researchers observed that when the clay fraction increases, the total surface area also increases. Rahardjo et al. [45] investigated the index property and engineering property tests on residual soils from two major geological formations in Singapore. These researchers suggested that the variations in the index and engineering properties of the residual soils

at different depths were largely influenced by the pore-size distributions, which vary in accordance with the degree of weathering.

Dananaj et al. [46] investigated the microstructural formation and geotechnical properties of Ca-bentonite and Na-bentonite by XRD, chemical analysis and scanning electron microscopy (SEM). Researchers suggested that the differences in bentonite quality and smectite quantity influence the permeability. Dimitrova and Yanful [47] examined the factors affecting the shear strength of mine tailings. These researchers suggested that adding clay to mine tailings would cause a decrease in the frictional strength, but the magnitude of this decrease was greater when the clay was bentonite and lower when it was kaolinite. The stabilization of clays generally requires sand, lime, cement and fly ash as additive materials. Soil stabilization using additives comprises the oldest and most common method of soil improvement. Known applications date as far back as ancient Greek, Egyptian and Roman times [48]. In clayey soils, sand is preferred due to its ease of application and economy. Some researchers have observed clays with sand stabilization to investigate the mechanical and microstructural changes of the soils [49–56]. Other researchers have used chemical additives (lime, cement, fly ash and bitumen) in the stabilization of clayey soils [57–62]. Chemical stabilization may be the most economical and practical method of soil stabilization techniques, as well as for problematic soils under existing structures.

Al-Mukhtar et al. [61] examined the effect of the lime stabilizers on the geotechnical properties of highly plastic clay using microscopic data. These researchers suggested that the treatment of the expansive soil behavior in the geotechnical properties was primarily due to pozzolanic reaction. Al-Mukhtar et al. [62] examined lime consumption by 10% lime improvement, kaolinite, illite, smectite-kaolinite, smectite-illite and smectite, using X-ray diffraction and thermogravimetric tests. These researchers suggested that the amount of lime consumed during the short-term reaction varies from nothing for kaolinite to the maximum with sodium-smectite. Khemissa and Mahamedi [63] examined improvement with a mixture of various ratios of cement and lime on expansive over-consolidated clay. These researchers observed an increase in soil strength and durability due to the reaction between the soil and additive materials. In chemical stabilization, cation exchanges, flocculation and agglomeration, carbonation reactions and pozzolanic reactions occur. The soil workability affects the cation exchange, flocculation and agglomeration mechanisms, and in addition, the bearing strength affects the carbonation reactions and pozzolanic reactions [64].

Also, clay is desirable in many cases due to its properties, which may be used to benefit a geotechnical engineer's design. Clay provides impermeability in fill dams, and waste landfill clay provides effective support in the form of gellable slurry for the untreated soils when excavated for pond water retention. Clay also becomes a binding material when it joins a certain ratio to coarse-grained soils.

5. Conclusions

Geotechnical engineering is one of the most important parts of any kind of construction. No matter how well the superstructure is projected, there is no sense in beginning construction

if the ground materials are not considered. As Karl Terzaghi said in 1939, “...*In engineering practice, difficulties with soils are almost exclusively due not to soils themselves but to water contained in their voids. On a planet without any water there would have been no need for Soil Mechanics.*” It is not adequate to only see the soil from the surface, also it must be determined whether the soil classes and groundwater are changing. Clay has a great influence on the engineering behavior of soils. Clay soils are found in nature. Deposition, weathering and stresses during geological processes ensure that the natural structure is different. In geotechnical engineering, besides determining the settlement, swelling and strength properties, mineral properties of the soil, particle structure and strength must be known when clay is encountered. In this chapter, the properties of clay, the role of clay in geotechnical engineering and geotechnical studies on clay were reviewed. In this chapter, the importance and benefits of determining clay properties before building construction were determined. Consequently, clay is shown to have different properties, and it is understood that some soils behave differently. This chapter contains material drawn from different sources, as well as a literature review, and will provide available information to civil and geotechnical engineers regarding clay.

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