LABORATORY EVALUATION OF TX-PROCHEM AS AN IONIC LIQUID SOIL STABILIZER

by

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November 18, 2016

Abstract

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Chemical treatment of a typical pavement and foundation soil was conducted to improve workability during compaction, increase the strength and stiffness of a foundation layer, and control potential shrink and swell due to moisture changes and/or frost action. In this study, a commercial liquid ionic stabilizer (Tx ProChem) was evaluated based on its effectiveness to reduce swell potential and improve the strength of a Texas expansive clay. This study also evaluated selected, representative liquid chemical stabilizers' effect on expansive clay soil. The research presented herein assesses how much the chemical treatments changed the relevant engineering properties of the test soil as an indicator of the potential effectiveness of the selected products. The effect of curing time on both compressive strength and the swell potential of treated soil was analyzed. A mineralogy test was developed to identify the dominating clay mineral in the test soil and to designate the mineral quantification of untreated soil. According to the basic tests, soil was classified as high plastic clay with 77% passing sieve 200. Tx ProChem test results showed a reduction in swell potential and maximum dry density of the soil samples due to addition of stabilizer. Maximum dry density decreased with an increase in stabilizer content.

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Chapter 1

Introduction

The uncertain behavior of expansive soil due to moisture change has caused many unexpected damages to the light structures built upon it such as frame buildings, pavement, and underground utilities. This change in the amount of water contained in the voids of the expansive soils begets swelling, shrinkage, and reduction in soil strength properties. According to Nelson and Miller (1992), several states in the United States have been affected by subgrade-related heaving and shrinkage problems for many years. Differential foundation settlement is due to heave expansion from ground movement caused by frost in some climates, and in Texas, by heaving minerals (Roger et al.). This heaving against foundations causes cracks that lower building strength. Therefore, various methods have been introduced to improve or treat geotechnical properties of problematic soils.

The frequency of expansive clay over Texas is shown in Figure 1.1. According to this Figure, the soil is classified high to limited expansion potential. Expansive clay problems in other parts of the state are not as severe where expansive clay material is not as common or weather conditions are less severe. Thick layers of montmorillonite and illite clay soils are nearly always present when swelling of foundation material is extensive enough to cause damage to pavement or building structures.

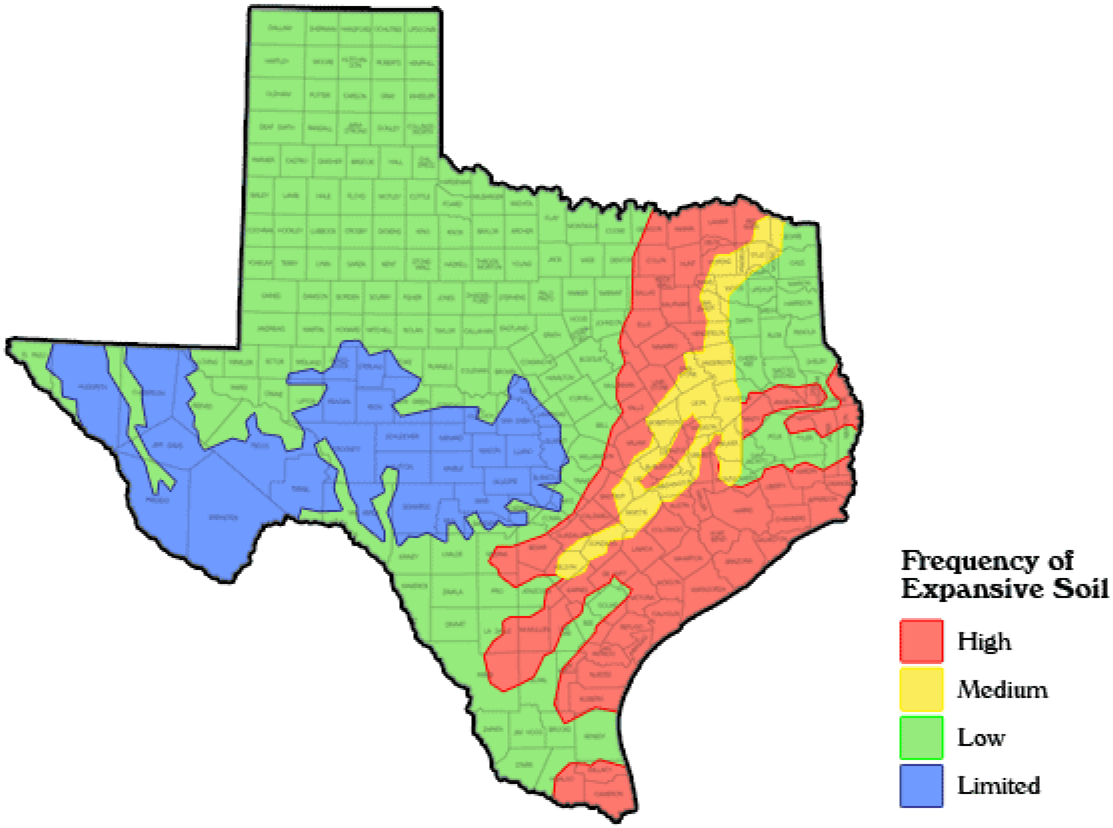


Figure 1. 1 Frequency of expansive clay in Texas
(http://allensfoundation.com/foundation-types)

Nelson and Miller (1992) defined mechanical stabilization, surcharge loading, pre-wetting, lime stabilization, and organic compound treatment that can tackle any swell and shrinkage due to change in moisture content of expansive soil. They also stated that removing the problematic soil and replacing it with good quality materials or treating soil with chemical stabilizers are common techniques for soil treatment. Finally, they mentioned the lime and cement as a traditional soil stabilization may not be effective for all type of soil. Therefore, nontraditional additive was introduced as new method to stabilize the soil. Tingle et al. (2007) classified the nontraditional additive to chemical, physical, and physicochemical stabilizer.

As most expansive clay in Texas contains high amounts of sulfates, it reacts with the calcium component of stabilizers and forms ettringite. Ettringite undergoes heaving in the presence of moisture—a phenomenon termed as sulfate-induced heaving (Hunter, 1988). Therefore, several suppliers and manufactures sell products that can be utilized for treatment of sulfate- rich soils without causing excessive expansion. In 2007, Tingle et al, classified these products to different categories including chemical, physical and physicochemical treatment and ionic liquid soil stabilizers have been identified as the chemical stabilizer which the author introduces and presents herein.

Liquid ionic soil stabilizers with various mechanisms can reduce the soil plasticity index, increase soil strength and reduce a soil's swell and shrinkage potential. They improve these related engineering properties through encapsulation of clay minerals, exchange of interlayer cations, breakdown of clay minerals with expulsion of water from the double layer, or interlayer expansion with subsequent moisture entrapment (Rauch et al., 2002).

1.1 Problem Statement

TX ProChemical is defined as liquid ionic soil stabilize and this product has been used for 20 years. This stabilizer is composed of sulfuric acid, phosphoric acid, citric acid and water. The working mechanism of TX ProChem has been questioned for 20 years; therefore, lack of standard laboratory test procedure and lack of comprehensive laboratory mechanism and engineering study on TX ProChem have been begotten to conduct a research on this stabilizer.

Although nontraditional stabilizers offer several advantages especially for the treatment of sulfate-rich soils, most engineers hesitate to utilize these products for the following reasons:

- Lack of published and independent studies of nontraditional stabilizers (Kota and Perrin, 1996)
- Limited field performance data, although Scholen (1992) surveyed some of the projects in which these products were used. Despite some remarkable failures due to the misapplication of these products, there were a number of successful projects reported.
- Lack of standard laboratory test methods to anticipate performance in the field (Scholen, 1992). Petry (1997) saw the need to qualify the improvement of soil through well-established testing protocols and cited the need for soil specimen tests that accurately record water content,
- Since the specimen preparation in the field and laboratory are not same, the positive or negative results obtained in the laboratory are questionable as predictors of field performance (Petry, 1997).
- Inadequate information provided by stabilizer suppliers, including the chemical composition of their products, as well as poorly-defined application rates recommended by manufacturers has prevented implementation of nontraditional stabilizers (Scholen, 1992).
- Unreliable suppliers who change their name or disappear make it difficult for researchers to develop confidence in soil treatment and stabilizer products. Many buyers of these products look for longevity and recommendations from users who have had good results with a product over a reasonable period (the longer the better).

1.2 Objective of Study

Since most of the available studies on the evaluation of stabilized soil with respect to liquid ionic soil stabilizers are focused on compacted soil at or near optimum moisture conditions, this research study will focus on the stabilization of highly expansive clay with optimum moisture content and clay with a 95% maximum dry density to simulate normal field conditions as relative compaction (R.C) cannot be obtained as 100%.

The behavior of the laboratory molded samples (both untreated and treated) were observed under unconfined compressive strength to measure the strength of the soil in undrained conditions. In addition, one-dimensional swell tests were conducted to obtain the swell potential and swell pressure of the tested soil. Furthermore, a mineralogy test was carried out to measure the percentage of common available mineral. Different stabilizer doses were added to achieve an economical and efficient recommended ratio corresponding to the different curing time periods. The objective of this research can be summarized as follows:

I. Treatment and stabilization of expansive clay with liquid ionic stabilizer to provide a suitable soil condition for foundation construction.

II. Selection of suitable stabilizer dosage based on degree of improvement.

III. Evaluation of clay particle improvement based on cation exchange capacity of stabilized soil.

IV. Effect of stabilized soil on environment determined by pH tests.

1.3 Scope of Study

This research study mainly consists of two parts. The first part includes: the selection of a suitable stabilizer for soil and recommendations on best stabilizer dose to use for a particular type of soil based on strength requirements from unconfined compressive strength, the plasticity indices of the soils, and swell potential. The second part includes: the evaluation of cation exchange capacity of treated soil with different dosage of stabilizer. All mineralogy tests were conducted on soil specimens to determine the percentage of common available minerals including montmorillonite, kaolinite, and illite.

This thesis includes a literature review on the behavior of stabilized soil with liquid ionic soil stabilizers. Furthermore, the stabilization mechanism of clayey soil and its reaction to the addition of a stabilizer is also reviewed. Soils with a plasticity index (PI) of 58 have been selected for this study, and the soil sample preparation procedure is presented in chapter three.

1.4 Outline

This thesis includes a total of five chapters. Chapter 1 is an introduction that presents the research limitation, objective, and scope of the research. The literature review in Chapter 2 presents a brief summary of previous studies performed by various researchers on treated soils that have been subjected to nontraditional stabilizers. Chapter 3 deals with the properties of the materials used and the methodology developed to accomplish the objectives of the research. Chapter 4 includes results and analyses of all laboratory tests performed. Finally, Chapter 5 will present conclusions derived throughout the research work and the author’s recommendations based on her supervisor’s experiences during the study period.

Chapter 2

Literature Review

2.1 Introduction

With the reduction of available land resources, more civil engineering construction is carried out over soft soil which is commonly found all over the world. The behavior of these deposits is significantly affected by their mineralogical composition and environmental condition. Moreover, due to their high compressibility, high swell and shrinkage potential, as well as their low bearing capacity, they impose extreme engineering issues. In such problematic soils, chemical stabilization techniques have been discussed as a beneficial way to improve these soil engineering properties including swell, shrinkage, strength, and workability of soil deposits.

2.2 Expansive Soils

Expansive soil is a term used for soil which reveals a moderate to high plasticity index, low to moderate strength, and high swell and shrinkage characteristics in case of change in moisture content (Holtz and Gibbs, 1956). Seasonal variation in the moisture content causes swell and shrinkage of expansive soil, which creates damage and cracking of light above-ground structures such as pavement and residential buildings as well as underground utilities (Zhao et al., 2014). The reason for this behavior is the presence of a type of heaving mineral known as montmorillonite that has an expanding lattice (Chittoori, 2008) which is plentiful in the arid and semi-arid regions such as Texas.

During the last few decades, swelling and shrinkage has caused severe damage for building and pavements by forming cracks and the breakup of pavement, building foundations, roadways, slab-on grade members, channel and reservoir linings, irrigation systems, water lines, and sewer lines (Cokca, 2001). High annual repair costs draw attention to the need for better methods to tackle this problem.

Figure 2.1 Swelling and shrinkage problem (MuscleSlab, 2016)
Photos by Peter Kelsey & Partners

The information on can be found in an online newsletter article from Geology.com (King 2016); and the above photo comes from Peter Kelsey and Partners, as shown on the website of MuscleSlab Australia. The problems that swelling and shrinkage are most commonly associated with are as follows:

A) Pavement cracks due to the swelling
B) Building damage caused by swelling clay soils

C) Soil's shrinkage can cause cracking on the wall
D) Serious cracks in soil caused by moisture lost

2.3 Clay Mineralogy

The dominating clay mineralogy in each system pertains to soil characteristics, which is less understood (Chittoori et al., 2008). As a mineral type, clay has (a) a net electrical negative charge, (b) small particle size and (c) plasticity when mixed with water, and (d) a shape that is usually platy or needle shaped or tubular (Mitchell and Soga, 2005). Kaolinite, illite and montmorillonite are the most common clay minerals found in soil (Figure 2.2).

2.3.1 Common Clay Mineral

2.3.1.1 Kaolinite

Kaolinite ($OH_8Si_4Al_4O_{11}$) is a common phyllosilicate mineral that is found where precipitation is relatively high and its formation is favored when silica is scarce and alumina is abundant (Holtz and Kovacs, 1981). Each kaolinite particle is formed by a series of hexagonal shape layers like the pages of a book. Hydrogen bonding binds these layers to other adjacent layers. As a result, cations and water do not enter between kaolinite's layers and it has low value for the cation exchange capacity (CEC) (White and Dixon 2002). Therefore, kaolinite exhibits less plasticity and swelling potential compared to other clay minerals. Figure 2.3 represents the structure of kaolinite and Figure 2.4 shows the SEM photograph of the mineral kaolinite.

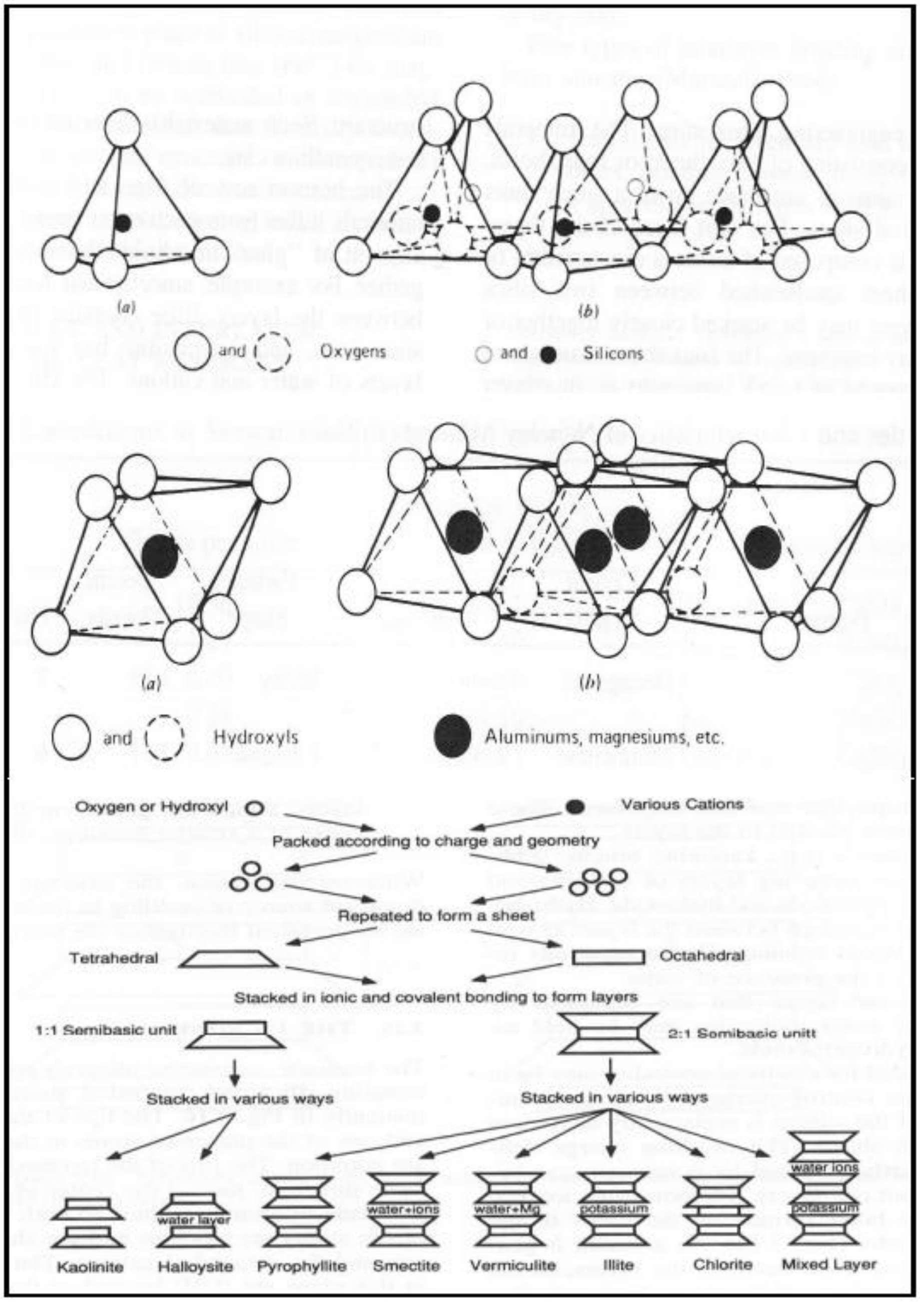


Figure 2.2 Basic sheet arrangement of aluminum octahedral and silica tetrahedral and synthesis pattern of clay minerals (Mitchel and Soga, 2005)

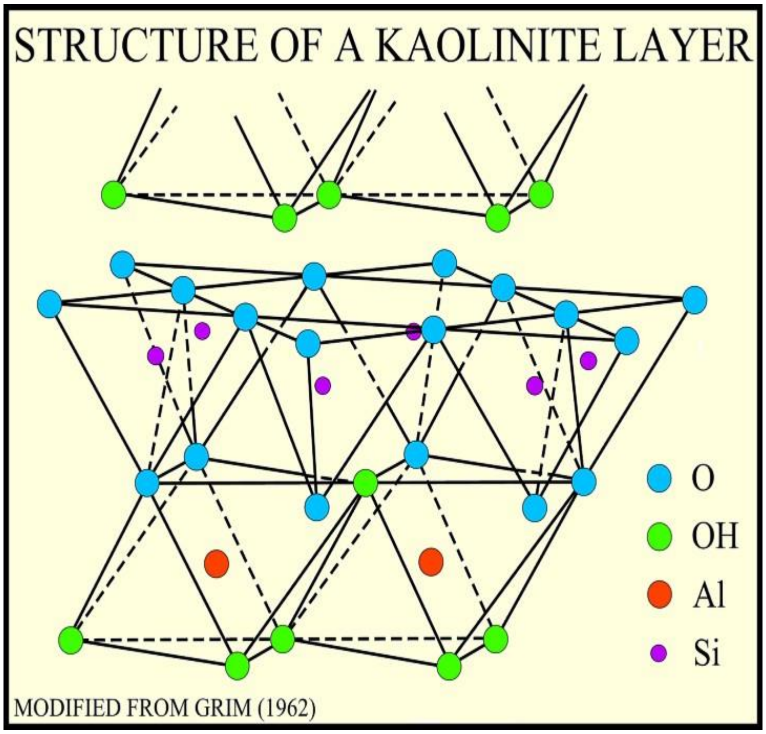


Figure 2. 3 Structure of kaolinite (USGS, 2001)
(Source: http://pubs.usgs.gov/of/2001/of01-041/htmldocs/clays/kaogr.htm)

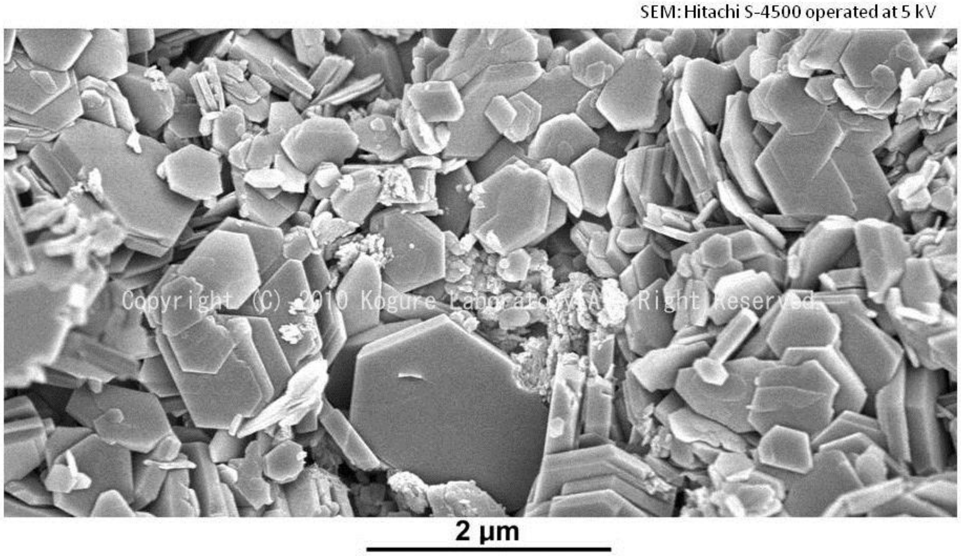


Figure 2. 4 SEM photograph of the mineral kaolinite
(Source: http://www-gbs.eps.s.u-tokyo.ac.jp/kogure/gallery/images/kaolin1.jpg)

2.3.1.2 Montmorillonite

Montmorillonite ($OH_4 Si_8 (Al_{3.34} Mg_{0.66})O_{20}$) is the most common mineral that is formed due to weathering of volcanic ash under poor drainage or marine waters (Oweis and Khera, 1998). High pH, high electrolyte content, and abundant silica provide favorable conditions for the formation of montmorillonite. Figure 2.5 shows montmorillonite's layers, which are loosely held together with very weak bonding. Therefore, exchangeable cations and associated water molecules are easily adhered in interlayer spaces that cause expansion of crystal lattices. The SEM photograph of the montmorillonite is shown in Figure 2.6

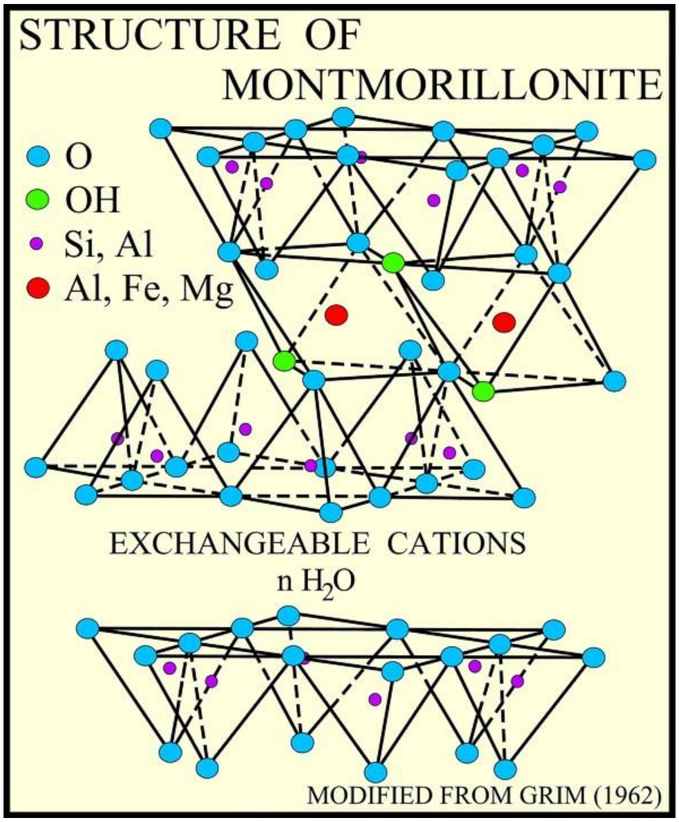


Figure 2. 5 Structure of montmorillonite (USGS, 2001)
(Source: http://pubs.usgs.gov/of/2001/of01-041/htmldocs/images/monstru.jpg)

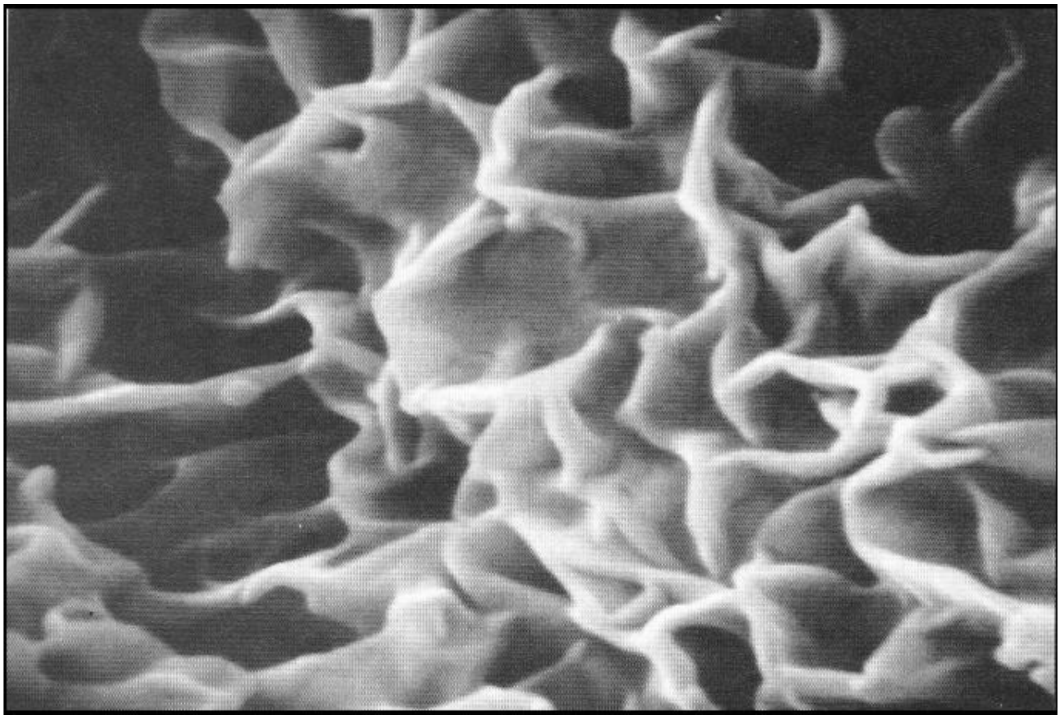


Figure 2.6 SEM photograph of the mineral montmorillonite

(Source: http://www.webmineral.com/specimens/Smectite.jpg)

2.3.1.3 Illite

Illite ($(KH_2O)_2(Si)_8(Al,Mg,Fe)_{4.6}O_{20}OH_4$) is a group named for a non-expanding, clay mineral (Chittoori, 2008). It forms under conditions similar to those that occur during the formation of montmorillonite in the presence of potassium, which is essential. Non-exchangeable potassium ions acting as a binding agent are strongly adhered to the interlayer space, thereby preventing expansion of the crystal. Hence, illite minerals are relatively non-expansive. The structure of illite and its SEM photograph are shown in Figure 2.7 and 2.8.

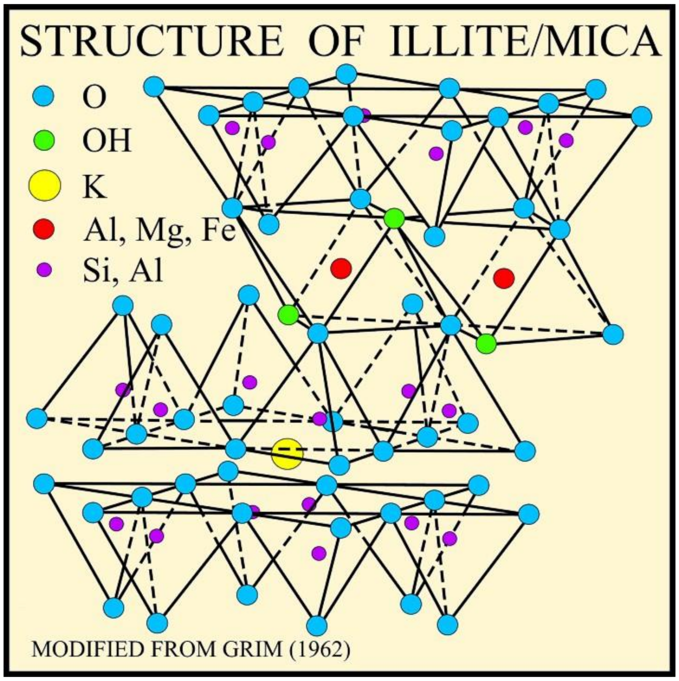


Figure 2.7 Structure of illite (USGS, 2001)

(Source: http://pubs.usgs.gov/of/2001/of01-041/htmldocs/clays/illite.htm)

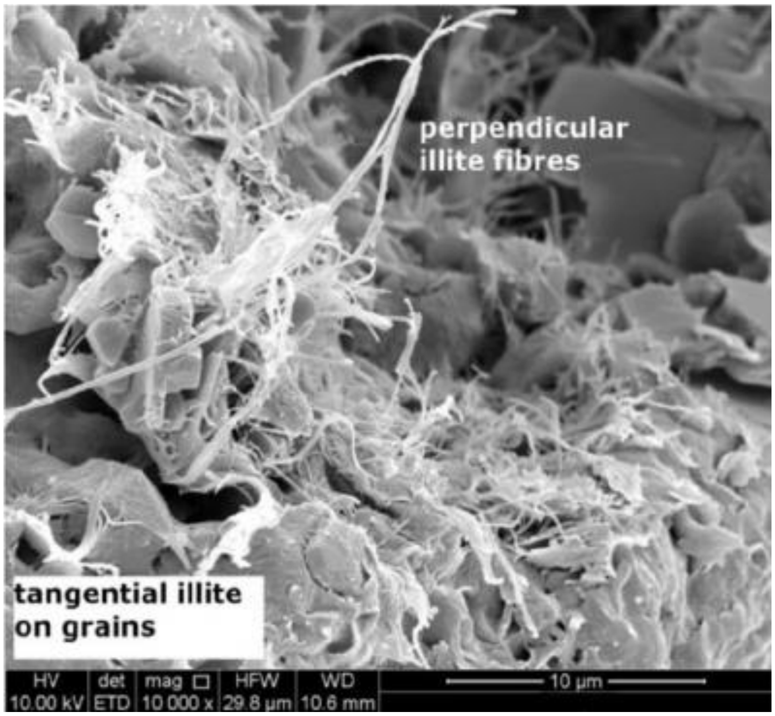


Figure 2.8 SEM photograph of Illite (Rosenbrand et al., 2015)

2.3.2 Clay-Water Interaction

Clay particles have a natural affinity for adsorbing cations and polar liquids such as water due to its unique crystal structure, platy shape morphology, and small size. The result of these interactions are sophisticated. Mitchel and Soga (2005) listed several possible mechanisms proposed for water adsorption as shown in Figure 2.9. According to Figure 2.9, in order to neutralize the negative charge surface of clay particles, adsorbed cations are tightly held onto the surface at relatively low moisture contents. Those cations are in excess of those needed to neutralize a negative charge surface and their associated anions are present as salt precipitate. In the presence of high moisture content, the precipitates can turn into a solution. The adsorbed cations try to diffuse away from the clay surface in order to equalize concentration throughout the pore fluid. As shown in Figure 2.9, the net result of a negative charge surface coupled with unfriendly cations, which have a tendency to escape in a highly diffused water layer surrounding the clay particles, is known as a diffused double layer.

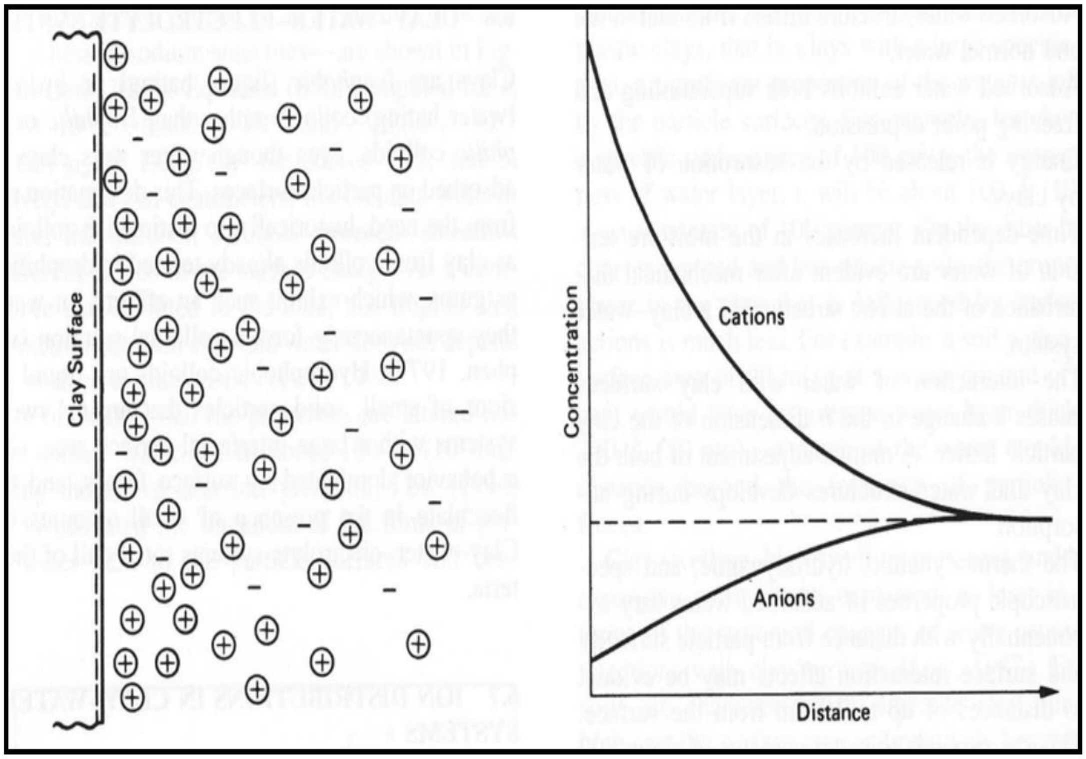


Figure 2.9 Distribution of ions adjacent to clay surface (Mitchell and Soga, 2005)

2.3.3 Clay Mineral Quantification

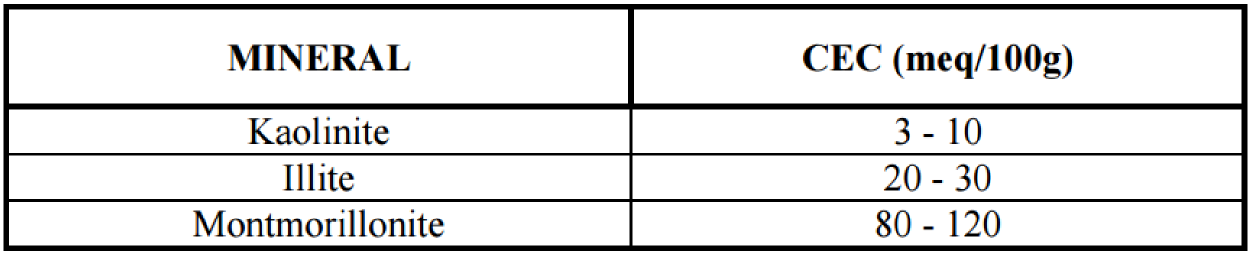
According to Chittoori and Puppala (2011), several clay mineral quantification techniques such as X-ray diffraction (XRD) have been developed by many researchers (Salyn & Drits, 1972; Jones, 1989; Smith, 1989; Hughes et al., 1994). Other methods such as absorption-diffraction, using both XRD data and chemical mass balance, and chemical mass balance alone were studied to assess each mineral percentage but Randall et al. (1994) compared different methods and specified their strength and weaknesses. Finally, the author and his research group proposed linear equations which were formulated using the elemental information of the soil specimen including cation exchange capacity, specific surface area, and total potassium. In this research, a current developed model was utilized to identify the dominating clay minerals in the soil and even approximate quantification of dominating clay mineral.

2.3.3.1 Cation Exchange Capacity (CEC)

Cations that neutralized the net negative charge on the surface of soil particles in water are readily exchangeable with other cations. Terzaghi et al. (1996) stated that the exchange reaction depends on the electrovalence of cations and relative concentration of cations in water. The cation exchange capacity is the quantity of exchangeable cations required to balance the negative charge on the surface of clay particles. CEC is expressed per 100 grams of dry clay in milliequivalents (Nelson and Miller, 1992).

There are several methods for CEC determination and their results will vary since CEC is not an independent and a single valued soil property (Rhoades, 1982). Rhoades asserted four methods to determine CEC. Camberato (2001) mentioned the primary factor to determine CEC is the clay and organic matter content of the soil. Higher quantities of clay and organic matter cause higher CEC. Different types of clay have different CECs. Terzaghi et al. (1996) determined CEC for common clay minerals as shown in Table 2.1.

Table 2.1 CEC of Principal Clay Minerals (Terzaghi et al., 1996)



MINERAL	**CEC (meq/100g)**
Kaolinite	3 - 10
Illite	20 - 30
Montmorillonite	80 - 120

2.3.3.2 Specific Surface Area (SSA)

The specific surface area of a soil sample is the total surface area contained in a unit mass of soil. Physical adsorption of molecules, heat loss or gain resulting from the adsorption, swelling and shrinkage and many chemical and physical properties are tied to the surface area (Cater et al., 1986). Therefore, soils with high specific surface areas have a high water holding capacity, more adsorption of contaminants, and high swell potentials. Moreover, specific surface area is closely related to particle size distribution. Campbell (2005) explained this phenomena with a simple experiment involving a 1 cm^3 cube with a density of 1 gm/cm^3. This cube has a specific surface area of 6 cm^2/g. If the cube is divided into smaller cubes of 1 mm on the side, the resulting 1000 cubes would have the same mass of material, but its specific surface area will be 60 cm^2/g, similarly if the cube were to be divided into 1012 cubes of 1 um on a side, the surface area would be 6 x 104 cm^2/g. Hence, the higher specific surface area will result in presence of smaller particles and the same mass.

Various approaches have been used to determine specific surface area; however, the most commonly used method uses the adsorption of ethylene glycol monomethyl ether (EGME) (Carter et al., 1986). In this approach, the researcher saturates prepared soil samples, equilibrates them in a vacuum over a $CaCl_2$-EGME solvate, and weighs them to find the point where equilibrium is reached. The specific surface is measured from the mass of retained EGME compared to the amount retained by pure montmorillonite clay, which is assumed to have a surface area of 810 m^2/gm (Carter et al., 1986). Cerato and Lutenegger (2002) conducted a comprehensive evaluation of the EGME method for geotechnical usage.

2.3.3.3 Total Potassium (TP)

Potassium is used to detect the presence of the mineral illite. A single electron of potassium is easily lost but together, they readily form stable monovalent ions (Knudsen et al., 1982). There are several methods for determining potassium in soils, but the one proposed by Knudsen et al. (1982) is one of the most widely used. Potassium is the interlayer cation in the clay mineral, illite, and illite is the only clay mineral to have potassium in its structure (Mitchell & Soga, 2003). Hence, potassium in the soil indicates the direct presence of illite.

The test procedure formulated by Knudsen et al. (1982) was followed to obtain the amount of total potassium present in the soil. Therefore, the measurement of potassium directly provides the percent of illite clay mineral in a given soil since potassium is solely contributed by the illite mineral.

2.4 Soil Stabilization

A lot of research has been conducted on expansive soil to improve its properties including strength, swell and shrinkage potential, and durability. More than 20 years ago, Nelson and Miller (1992) were expressing confidence in mechanical stabilizers, surcharge loading, pre-wetting, lime stabilization, and organic compound treatment to tackle any swell and shrinkage problem due to moisture content changes in expansive soil. These interventions are still used.

Mechanical stabilization relies on physical exchange and processes to stabilize the soil including using geotextiles or suitable well-graded aggregates (Onyelowe and Okafor, 2012), which is adequate for soil with low expansion potential, high dry density and low natural water content. Surcharge loading is defined as another soil improvement method which is an effective technique to restrain soil settlement and keep swell pressure low (Seah, 2006). The organic compounds stabilize by soil hardening the soil with resin, by water proofing, or retarding water absorption; however, this method is limited and detailed information on its how to handle this methodology has also been very limited (Turner 2016). The National Trench Safety organization’s Director of Engineering, Research and Product Development, Joe Turner, P.E., posted an article on the National Trench Safety website (NTS 2016) with a detailed account of what surcharge loading is and offers advice for engineers on how to handle. This is one of the most thorough accounts available, but it is still an overview with a disclaimer about the instructions not being site specific.

Lime and cement have been known as common stabilizers which help stabilize soil based on their reaction with minerals in the soil or with added mineral material (Sha’abani and Kalantari, 2012). Lime and cement stabilization are accomplished by mixing with the soil in low amount to change both the physical and chemical properties of the stabilized soil (Chittoori et al., 2013). Other stabilizers include fly ash, pozzolans, and blast furnace slag which can be added to soil based on the soil classification and degree of improvement needed. Chittoori et al. (2013) stated smaller amounts of additives can alter soil properties thereby affecting gradation, workability, and plasticity. These additives sometimes exceed the amount needed, which leads to thickness reduction as shown in Figure 2.10.

Many field experiences have shown that treating sulfate- rich soils with a calcium- based stabilizer such as lime and cement, causes intensive swelling and heaving because the reaction between sulfate and alumina in natural soil and calcium in a stabilizer form highly expansive crystalline minerals such as ettringite and thaumasite (Rauch et al., 2002).

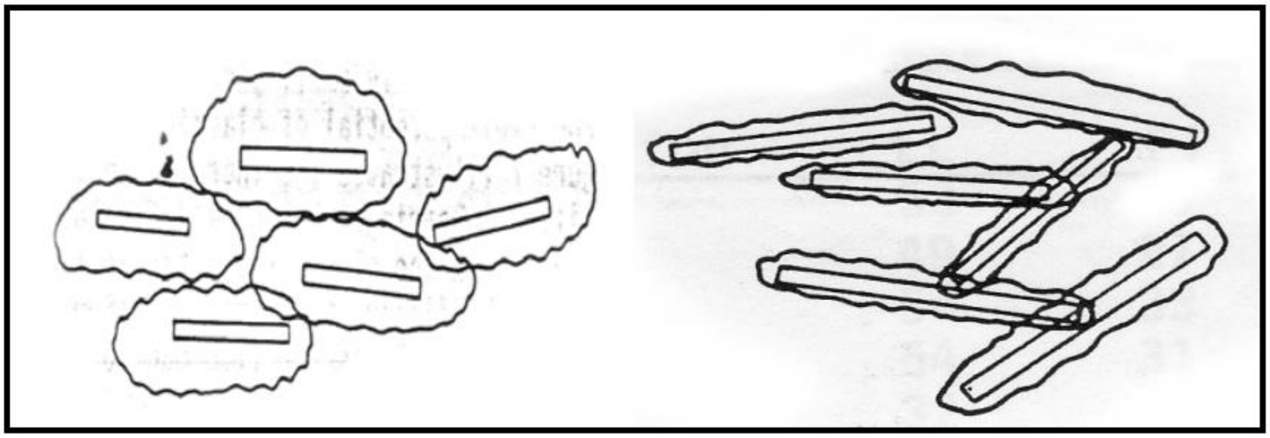


Figure 2.10 Modification of texture due to change in thickness of diffuse double layer (Little, 1995)

2.5 Liquid Soil Stabilizer

Liquid soil stabilizer was found to be a new stabilizer that does not contain calcium and can be used on sulfate- rich soils without causing excessive expansion (Rauch et al., 2002). A variety of chemical agents are marketing a wide array of these products. The use of various organic stabilization products such as Ionic Soil Stabilizer, HEC, K+, and polyvinyl alcohol have been considered the most conventional approach to controlling the swell-shrinkage behavior of expansive soil (Wang et al., 2014).

Scholen (1992) classified liquid soil stabilizer as electrolytes, enzymes, acrylic polymers, and mineral pitches based on their mechanism. Liquid chemical stabilizers work through various mechanisms including encapsulation of clay minerals with expulsion of water from the double layer or interlayer expansion with subsequent moisture entrapment. (Scholen, 1992; Petry and Das, 2001).

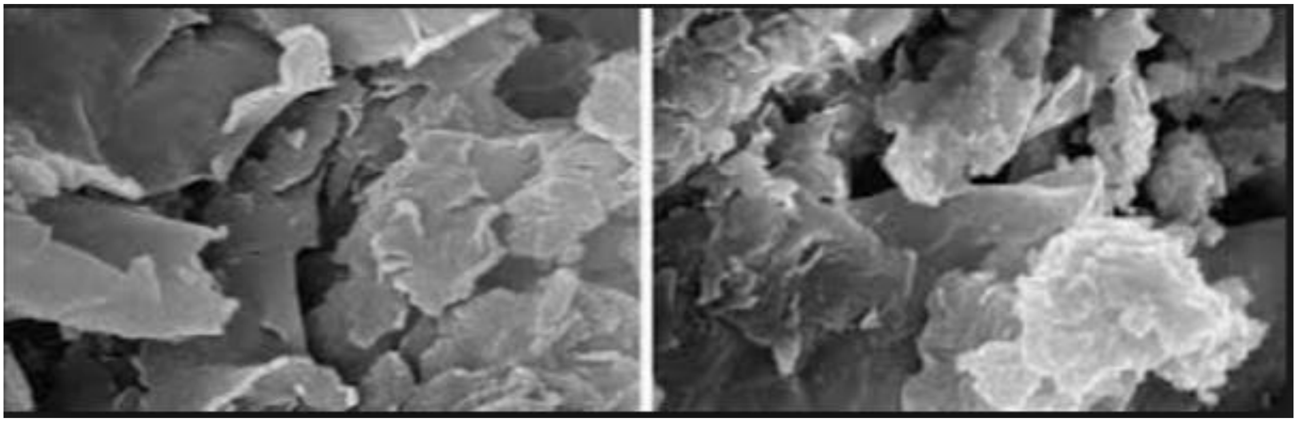

(a) (b)

Figure 2.11 Encapsulation of montmorillonite a) untreated soil b) Treated soil with ionic stabilizer (Katz et al., 2001)

2.5.1 Ionic Soil Stabilizer

Ionic soil stabilizer (ISS) is a water-soluble chemical which is composed by multiple strong ions, and it is suitable for any soil with a different clay particle content above 25% (Lu and Xia, 2015; Dong et al., 2004). Ionic soil stabilizers remove the combination water of clay minerals based on electrochemical principle, transforms the soil permanently from hydrophilic to hydrophobic, reduces the thickness of clay combination water film, and improves the engineering properties of soil when it is mixed with soil (Lu and Xia). Treatment with ISS causes the adsorbed water to be released and change in the electric double layer, minimizes the void and allows particles be compacted to higher densities. In addition, ISS has a significant effect on soil properties such as increasing their shear strength and load bearing capacity (Alhassan and Fadeyi, 2013).

Excess negative ions and attract positive ions (cations) in groundwater adhering to them to form pellicle water (Alhassan and Olaniyi, 2013). In dry clay, cations are close to the crystal surface; however, when sufficient water is present it can cause adsorbed cations to diffuse toward a more diluted solution until the forces caused by ion concentration becomes equal to the electrostatic attraction forces (Zhao et al., 2014).

According to Xiang et al. (2010), due to ISS advantages including low cost, simple structure, and environmental friendliness, ISS is used widely in civil engineering projects. Also in 1977, ISS was listed as major technology in a science popularization project by the Ministry of Water Conservancy, although there is little research on soil improvement by ionic soil stabilizers (Lu and Xia, 2015).

Using cation exchange, ionization mechanism, and small size particles are three remedies that have been suggested in case of ISS mechanism (Faisal and Lee). In an ionic exchange mechanism, since the predominant electrical charge of all clays is negative, attraction of cations for clay minerals is common. As the authors mentioned, chemical components can be added to alter the clay's original surface and reduce its susceptibility to water. If positive molecules are supplied, the negative charge of clay can be neutralized and the charge will balance out. At the same time, weaker cations such as H^+ (water) can easily become dissociated and replaced as they cannot fit easily into these sites. As a result, the clay molecules stay inert to water.

In addition, Faisal and Lee explained using the ionization mechanism as an addition of chemical components with numerous potential ionic exchange capacities into the water. They activate the ion H^+ and OH^-, ionize the water and dramatically exchange its electrical changes with the soil particles. As a result of this ionization, the pellicular water breaks its electrochemical bond with the soil particles and becomes free water before it is finally drained out of soil through evaporation or gravity after which, the soil particles settle and attract each other. Moreover, Xiang et al. (2010) asserted ISS can exchange with cations of clay particle surfaces and electrolyze cations $[X]^{n+}$ and anions $[Y]^{n-}$. Therefore, the cations of the clay particle surface are exchanged with the cations electrolyzed from the ISS and thus, anions are able to reduce the surface tension of the water film and transform adsorbed water into free water as shown in Figure 2.12. Xiang et al. (2010) mentioned ISS ionizing when diluted, which causes a reduction in the charge of the soil particle surface and an emergence of the repulsive force between the soil and water leading to the release of the adsorbed water into the double layer with its high electrical conductivity. They showed this procedure using following equation.

$$[\text{Soil Colloid}]^{n-}[M]^{n+} + [X]^{n+} \longrightarrow [\text{Soil Colloid}]^{n-}[X]^{n+} + [M]^{n+}$$

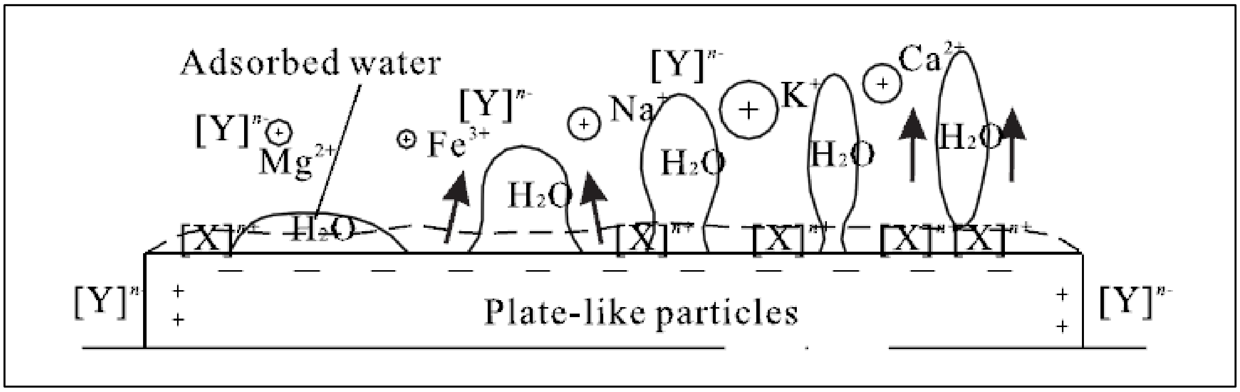


Figure 2.12 Reduction of water film by assistance of ISS. (Xiang et al., 2010)

Tingle et al. (2007) and Katz et al. (2001) demonstrated the mechanism effect of ISS on clay soil particles. Tingle et al. stated the stabilization mechanism would be particularly substantial for smaller clay minerals such as montmorillonite where the double-layer water is remarkably larger than the particle sheet as shown in Figure 2.13. The molecular structure of soil is modified due to adsorption of ions by soil particles, ionic reaction with soil constituents, and ion exchange interactions (Tingle et al.). This yields reduction of plasticity, swell potential, and particle size. Also, the authors added the effects of change in the electrolyte pore fluid from alkali to acidic or vice versa on molecular structure, which usually occurs over long period of time. Katz et al. conducted

X-ray fraction of five different samples including montmorillonite, kaolinite, illite, Bryan soil, and Mesquite soil with four different soil stabilizers to investigate the effect of different stabilizer mechanisms on montmorillonite. They found changes in clay layers associated with the ionic soil stabilizer treatment for montmorillonite to be much more pronounced than the changes to the other soil samples under the same X-ray fraction analysis. Tingle et al. (2007) found the ionic soil stabilizer suitable for fine-grained soils, silts, and clays where the electrical charge of the soil particles and pore fluid have considerable effects on the soil behavior. Thus, the cation exchange capacity plays an important role for evaluating the suitability of ionic additives for specific soils.

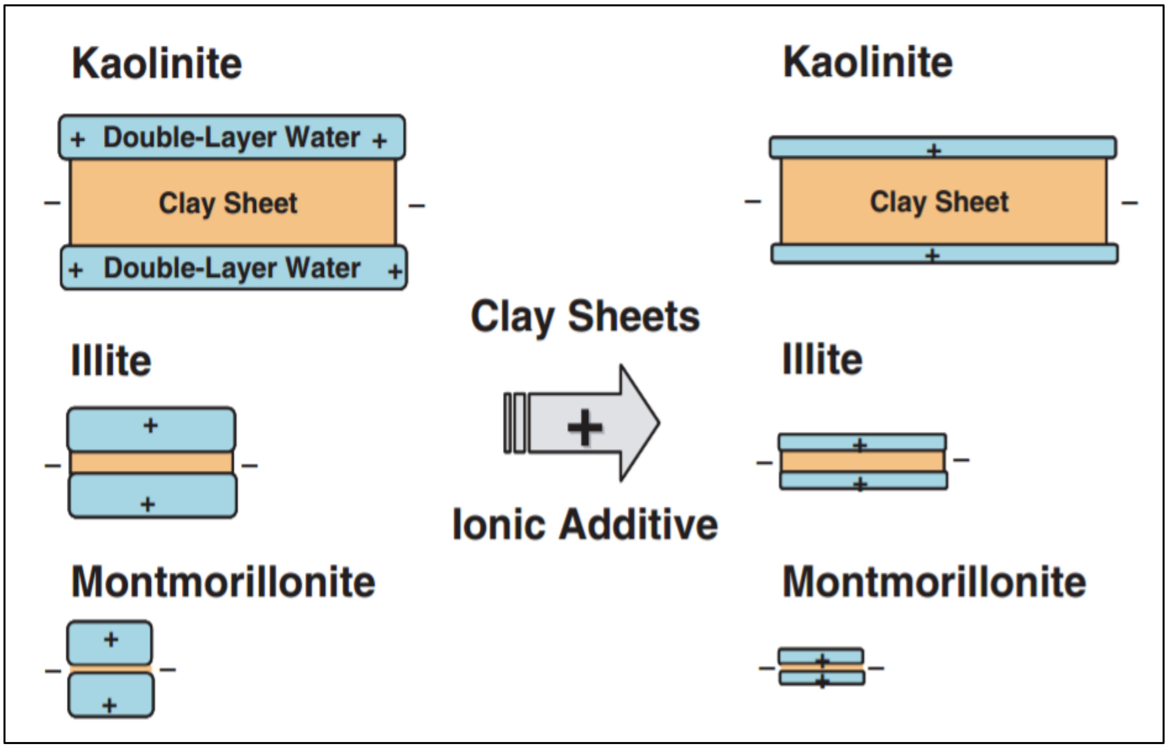


Figure 2.13 Mechanism of ionic exchange for purpose of soil stabilization with ionic stabilizer (Tingle et al., 1989)

2.6 Effect of ISS on Soil Properties

2.6.1 Atterberg Limits

Reduction in size of the diffused double layer and increase in inter-particle contact due to soil treatment with liquid stabilizer was expected to increase in the plastic limit and reduce the liquid limit (Dhakal, 2012). However, some research cases were not observed to consistently increase in plastic limit or decrease in liquid limit (Abadjieva, 2001; Raunch et al., 2002; Alhassan & Olaniyi, 2013; Zhao et al., 2014). They found out ionic stabilizers cause reduction in the plasticity index.

2.6.2 Moisture- Density Relationship

Stabilization with lime and cement yield as dry density decreases and optimum moisture increases content due to change in chemical composition of the soil (Puppala et al., 1996; Jagannath et al., 2004). Zhao et al. (2014) observed the same results for stabilized soil with varied ISS. However, Lu and Xia (2015) and Ali and Tatt (2003) found different types of results for ionic stabilized soil. They reported an increase in maximum dry density with reduction in optimum moisture content with respect to increasing ISS content, whereas Abadjieva (2001) indicated optimum moisture content and maximum dry density increase after treatment. Alhassan and Olaniyi (2013) found out maximum dry density increases suddenly upon to the addition of ISS stabilizer whereas it gradually decreases to a lower value for high ISS content.

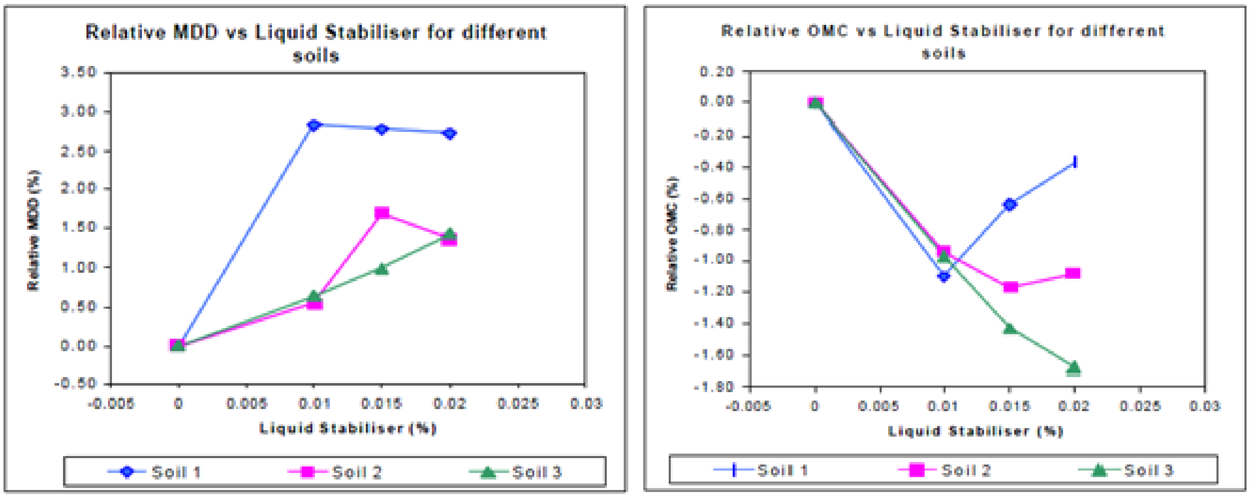


Figure 2. 14 Moisture density relation of soil with ISS (Ali and Tatt, 2003)

2.6.3 Unconfined Compressive Strength (UCS)

Some research indicates that unconfined compressive strength (UCS) of soil increases drastically with the increase of stabilizer content (Ali & Tatt, 2003; Agarwal & Kaur, 2014). Agarwal and Kaur (2014) performed UCS tests on treated soil with different dosages of a bio-enzyme stabilizer. They concluded soil strength was enhanced due to addition of the bio-enzyme stabilizer and a longer curing period. Ali & Tatt (2003), Arrabani et al., Chen and Tan (2012), and Wang et al. (2015) indicated the influence of a longer curing time period on soil strength parameters. Arabani et al. (2012) conducted UCS on three different of types of soil with PI 31%, 16% and 9.1%. They used CBR SUPER 4+ as the stabilizer (Arabani et al., 2013, p. 747) and reported high strength value for treated soil with high plasticity index, and the soil strength significantly increased after 28 days of curing. However, Rauch et al. (2002) reported a significant reduction in soil strength. They tested stabilized soils with three different stabilizers selected according to type (ionic, polymer and enzyme stabilizers), and all results demonstrated reduced soil strength of treated soil compared to untreated soil.

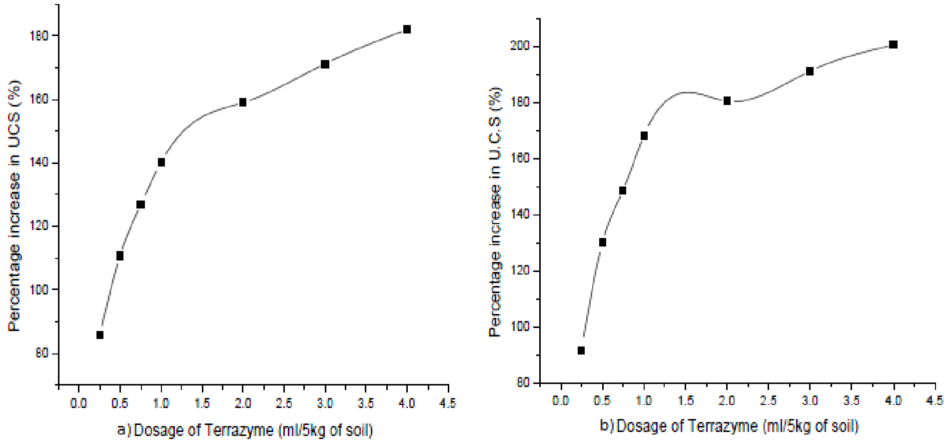


Figure 2.15 percentage increase in UCS with various stabilizers after a) 1 day curing b)7 days curing (Agarwal & Kaur, 2014)

2.6.4 Swelling Behavior of Expansive Soil

Evaluation of swelling characteristics of expansive soil, namely, swell pressure and swell potential, is substantial for foundation design success. Some factors influence swell potential and swell pressure, such as stress history, temperature, type and the amount of clay, nature of pore fluid, volume change permitted during swell pressure measurements, and time (Nayak and Christensen, 1971). The definition of swell pressure for undisturbed soils is the pressure required to keep the volume of a soil constant at its natural dry density. For remolded soils, the swell pressure is the pressure that is required to keep the volume of a soil at its maximum proctor density constant (Fedol and Zhang, 2004). The swell potential definition introduced by Seed and Lundgren (1962) is the percentage of swell of a laterally confined sample after soaking under one psi surcharge and being compacted to maximum density at optimum water content in the standard ASTM compaction test.

2.6.4.1 Methods Used to Predict the Amount of Swell

Dif and Bluemel (1991) stated:

> "Soil scientists recognize that shrink–swell behavior can best be predicted by examining a combination of physical, chemical and mineralogical soil properties. While the shrinkage characteristics of a soil depend on the grain-size distribution, and type of clay mineral. Swelling is caused by a number of additional phenomena including the elastic rebound of the soil grains, the attraction of the clay minerals for water, the electrical repulsion of the clay particles and their adsorbed cations, and the expansion of air trapped in the soil voids"—A. E. Dif and W. F. Bluemel (1991 *Geotechnical Testing Journal,* ASTM, ISSN 0149-6115).

Many investigations have been carried out to propose proper methods for prediction of swell. There are empirical and analytical methods, such as the oedometer free swell method, which is the most common and is designed to measure swell potential of expansive soil. Dakshanamurthy and Raman (1973) classified swell potential of expansive soil with respect to variation of liquid limit.

Table 2. 2 Swell Potential Classification Based on Lquid Limit (Dakshanamurthy and Raman, 1973)

Liquid Limit	Classification
0–20	Non Swelling
20–35	Low Swelling
35–50	Medium Swelling
50–70	High Swelling
70–90	Very High Swelling
> 90	Extra High Swelling

Research has been performed using odeometer tests to measure swell potential with stabilized soil treated with ISS (Rauch et al., 2002; Radhakrishnan, Kumar & Raju, 2014; Zhao et al., 2014; Wang et al., 2015). Although they tested different types of expansive soils, they all concluded the swell potential reduction occurs by adding ISS to the soil sample. Zhao et al. performed free vertical swell tests on 12 chemical-stabilized Texas clay samples. The vertical swell after 7 days of curing indicated that the swell potential was reduced by about 75% for the treated soil with ISS.

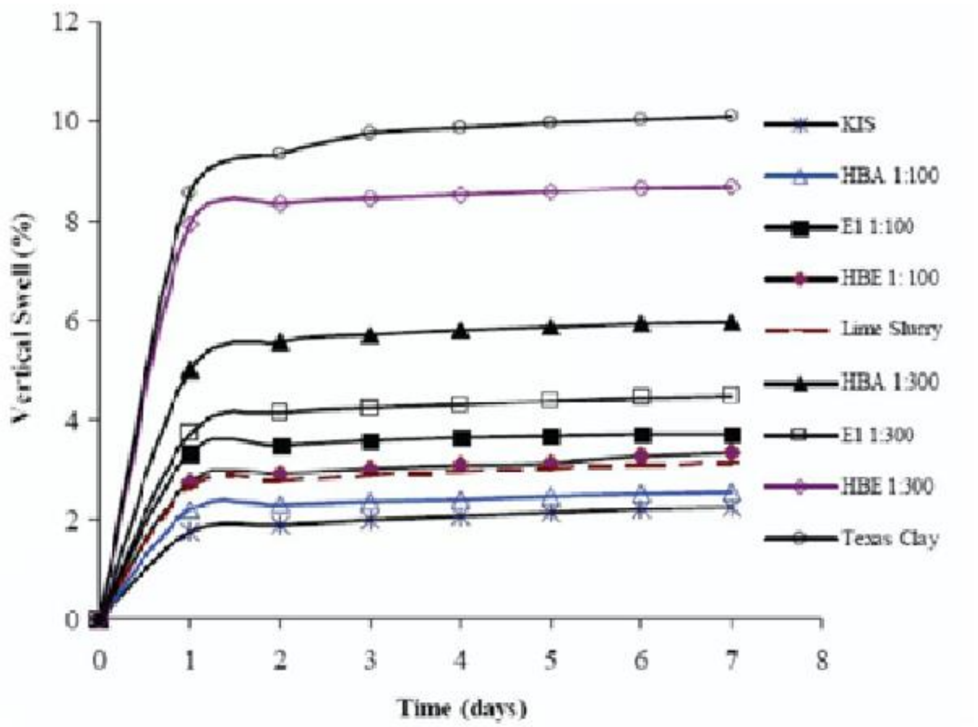


Figure 2.16 Free Vertical Swelling Data of Chemical stabilized Texas Clay Zhao et al. (2014)

2.6.5 Soil pH

PH of stabilized soil with lime and cement has been shown to increase by adding more stabilizer to the soil sample (INDOT, 2015). Whereas, Alhassan and Fadeyi (2013) reported pH of soil reduced as the stabilizer content increased. Moreover, Luo et al. (2016) showed the effect of ISS on pH of the soil is not remarkable.

2.7 Effect of Curing Time on Soil Properties

Curing time has effects on unconfined compressive strength (UCS) and swell potential of the stabilized soil with ionic soil stabilizers. UCS value increases with the curing period (Agarwal & Kaur, 2014; Arabani et al. 2012; Chen and Tan, 2012; Wang et al., 2015). However, they indicated that when the soil samples were maintained for a specific period, either 28 days or 7 days, the UC strength did not have any obvious increase. On the other hand, Zhao et al. (2014) reported a percentage of vertical swell increase with respect to time, although less swell change was recorded after one day of curing.

2.8 Effect of Different Dosage of ISS on Soil Properties

Various dosages of ISS play an important role in properties of stabilized soil. Agarwal & Kaur (2014) and Ali and Tatt (2003) found UC strength value was increased by adding liquid stabilizer. In contrast, plasticity index and optimum moisture content reduced significantly. Radhakrishnan et al. (2014) also investigated the effect of varying stabilizer content on swell potential. They concluded swell potential was reduced by the addition of stabilizer content.

2.9 Effect of Different Dosage of ISS on CEC

There is some available research on CEC for stabilized soil with ISS. As Cui et al (2011) stated, CEC is reduced for red clay soil which has 42% quartz and 18.4 PI. They carried out the test on five different dosages and concluded the addition of stabilizer yields a low CEC. Another study by Rauch et al. (2003) demonstrated CEC cannot change significantly by adding more stabilizer. The authors performed three different application mass ratios to study the effect of stabilizer over a wide range of concentrations. They summarized CEC mean values remain equal for all different dosages. However, Honghua et al. (2014) investigated the effect of different dosages and different ISS stabilizers on Texas clay with 44% plasticity index. As their results show, the CEC value varied for each ISS and reduced when they added stabilizer to natural Texas clay. Moreover, Xiang et al (2010) explored the reduction of cation exchange capacity in stabilized soil with ISS. They carried out mineralogy tests on red clay with 18% plasticity index and 53% swell free rate, and they revealed CEC reduction due to the addition of stabilizer.

Chapter 3

Methodology

This chapter will present the procedures of all the laboratory tests conducted to achieve the objective of this research. The disturbed soil samples were collected from 6373 I-30, Royse City, TX 75189, and all samples used in this study were molded in the laboratory with respect to available standard procedures by the American Society of Testing and Materials (ASTM) or based on literature review. For the laboratory testing program, the TX ProChem soil stabilizer was considered as a candidate to treat and stabilize Texas soil which is known as a type of expansive soil.

3.1 Material Used

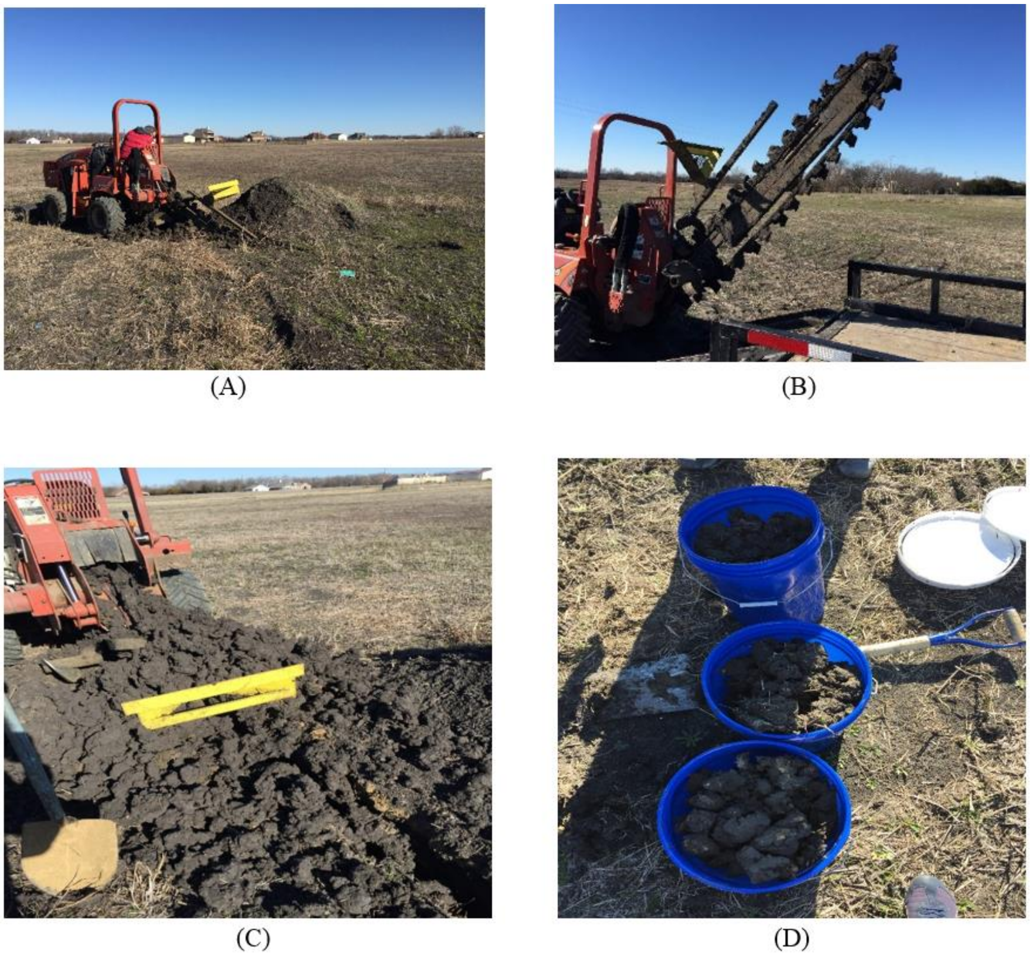
Soil sampling for this project was completed two different times. The first sampling was implemented by machine digging. In the first soil sampling, the exact depth of excavated soil was not clarified. The first soil was collected with a small emplacement excavator machine as shown in Figure 3.1-B. The machine cut the surface soil and carried soil from an uncertain depth to the surface. All basic tests were performed on all five different buckets from the first soil sampling.

The second soil collection used for this research was accomplished from exactly 3ft below the ground surface (Figure 3.2). In the first soil sampling, the contents of each bucket had different soil properties; therefore, the first soil sampling was discarded. All tests and results shown for this study are related to the second soil sampling. The results of sieve analysis for the untreated soil is shown in Table 3.1.

Table 3. 1 Properties of Soil Used in This Study

Black Cotton Soil	
Gravel	0%
Sand	23%
Clay	77%
OMC*	31%
MDD(pcf)*	85.7

*According to Standard Proctor test


(A) (B)

(C) (D)

Figure 3. 1 First soil sampling: (A) project location; (B) machine for curing the soil to get sample; (C) disturbed soil, and (D) different buckets of soil from different depths.

Figure 3. 2 Second soil sampling: 3 ft below ground surface

According to type of liquid ionic stabilizers, agencies define specific patterns to make expansive soil stable. TX ProChemical is a company has been utilizing the chemical to perform soil stabilization for 23 years. They introduced a new liquid ionic soil stabilizer to control and prevent soil expansion. In this case, the concentrate acids and surfactant were both used to make a stabilizer mixture as shown in Fig 3.3. TX ProChem is an ionic liquid stabilizer composed of sulfuric acid, phosphoric acid, citric acid, and water. The chemical is utilized during the water/chemical injection process of soil stabilization. The product is mixed in a concentrated 250-gallon batch. At soil injection, the chemical is further mixed with water at a ratio of 1 gallon to 750 gallons. The final product meets safety standards (ASTM Standard) for introduction into city sewer systems.

Figure 3. 3 A) Concentrate B) Surfactant

3.2 Field Application

In the field, soil stabilization is performed in two different steps: A) pre-saturation and B) chemical injection. In pre-saturation, the soil is injected with the water for 100% saturation by using a hydraulic system to force perforated steel rods into the soil. This injection is performed at high pressure between 250-300 psi into 12-15 feet below ground surface. Based on Atterberg limits, the amount of time per interval stop has been determined, and the average between stops is 10-18 seconds per 6 inches stop to maximum injection depth outlined in the geotechnical report for the first past. In this case, soil cannot retain more water due to presence of so much water. The saturated soil must be at rest 48 to 72 hours before chemical injection. Figure 3.4 shows the pre-saturation.

Figure 3. 4 Water injection equipment after completing 100% soil saturation.

In chemical injection, after soil saturation is complete, TX ProChem and surfactant mixture is injected into the saturated soil at high pressure. Application of high pressure causes the greatest volume of stabilizer to penetrate into the ground and makes the smaller fractures wider to allow stabilizers to penetrate. The fractures occur as part of the last step. As clays begin to swell, the mixture of surfactant and TX ProChem reduces the surface tension of the water and increase permeability.

3.3 Soil Test

Engineering soil tests were carried out on the studied soil in accordance with ASTM (American Society for Testing and Materials) standards (ASTM International, West Conshohocken, PA). In each test, a number of different samples were prepared, tested, and analyzed as shown in the following table.

Table 3. 2 Soil Test Standards and Number of Soil Samples for Each Test

	Test Name	Test Code	No. Tests
Untreated Soil	Atterberg Limit	ASTM D4318	3 repeats
	Hydrometer	ASTM D422	2 repeats
	Specific Gravity	ASTM D854	2 repeats
	Standard Compaction	ASTM D1557	One set - 5 Different Moistures
	Unconfined Compressive Strength	ASTM D2166	3 Compacted Specimens
	Swell Potential	ASTM D4546-14	3 Compacted Specimens
	Swell Pressure	ASTM D4546-14	3 Compacted Specimens
	Cation Exchange Capacity	-	2 repeats
	Specific Surface Area	-	2 repeats
	Total Potassium	-	2 repeats
Treated Soil (3 dosage)	Atterberg Limit	ASTM D4318	2 repeats
	Standard Compaction	ASTM D1557	One set - 5 Different Moistures
	Unconfined Compressive Strength	ASTM D2166	3 Compacted Specimens
	Swell Potential	ASTM D4546-14	3 Compacted Specimens
	Swell Pressure	ASTM D4546-14	3 Compacted Specimens
	Cation Exchange Capacity	-	2 repeat
	Specific Surface Area	-	-
	Total Potassium	-	-

According to the table, atterberg limits test were conducted three times to check the repeatability. Also, in Hydrometer and Specific Gravity test, repeatability was checked. Standard Compaction test was experimented once and 5 different moisture soil samples were compacted to find the compaction curve. The untreated soil was mixed with distilled water in optimum moisture content and 95% dry density and 3 ideal soil specimens were prepared for UCS and Swell test for repeatability. As explained in chapter 2, the specific surface area and total potassium were conducted on untreated soil sample. However, cation exchange capacity was carried out for both treated and untreated soil and the CEC was carried out two time and the average results were chosen as CEC value. The treated soil defines as three different dosage which explained in 3.4 treatment plan. For each different dosage, UCS and Swell test were tested three times and the average value was shown in results and conclusion.

3.3.1 Soil Basic Test

3.3.1.1 Atterberg Limits

The Atterberg Limit tests reveal soil properties related to soil consistency, which include liquid limit (LL), plastic limit (PL) and shrinkage limit (SL) which are essential to identify the shrink-swell potential of the soil with respect to the plasticity index. The plasticity index is defined as the range of water content where the soil is plastic.

The consistency limit tests were conducted in accordance with ASTM D4318 “Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.” The soil sample was required to pass through the No. 40 sieve. For the liquid limit testing, distilled water was mixed with 50 g of soil until it had the thickness and consistency of peanut butter or frosting. Then, a groove was cut along the centerline of the soil pat and count the number of blows until the distance between the edges of soil become 0.5 inches to calculate the moisture content. In plastic limit testing, U.S. PATENT No. 5,027,660, a box was used to roll the soil forming a 0.125 in diameter soil rod without crumbling to test moisture content (Fig 3.4).

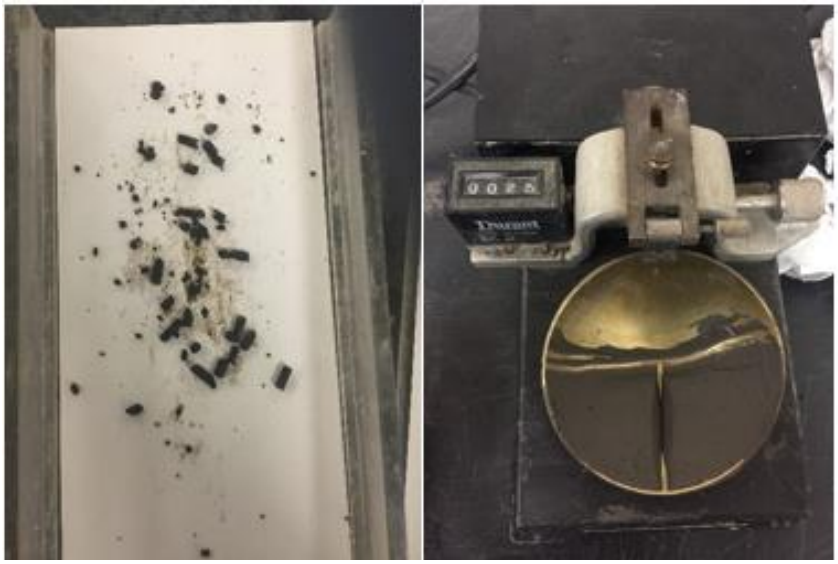

(A) (B)

Figure 3. 5 Atterberg limit-untreated soil sample: (A) liquid limit test and (B) plastic limit test

3.3.1.2 Gradation Curve (Hydrometer Test)

The hydrometer test was conducted by ASTM D422 “Standard Test Method for Particle-Size Analysis of Soils.” Sodium hexametaphosphate was mixed with deionized water as the solute for chemical dispersion (Kalinski, 2011). In general, the 50 g of soil was sieved using a No. 40 sieve and then combined with 125 ml of sodium hexametaphosphate solution in a 250-ml glass beaker. The mixture was then left to soak for at least 16 hours. A mechanical stirring device was used to mix the sample suspensions at a rate of 10,000 rpm and an ASTM 152H hydrometer was utilized for the suspended soil readings (Fig 3.5). Considering an error occurred in the meniscus, the constant temperature coefficient K was introduced to calibrate the data to get the grain size distribution (Rauch et al., 1993).

(A) (B)

Figure 3. 6 Hydrometer test: (A) reading the hydrometer and (B) mixing the mixture of soil and sodium hexametaphosphate (NaHMP).

The soil used in this study was classified in accordance with Unified Soil Classification System (USCS). The soil classification is based on consistency limit and particle-size analysis. Therefore, the soil is classified as high plastic clay as the result of the Atterberg limit tests as well as the USCS classification as presented in Table 3.3 and Fig. 3.6.

Table 3. 3 Soil classification—untreated soil properties

Soil Name	Black Cotton
Soil type	High PI
Liquid Limit (%)	76%
Plastic Limit (%)	18%
Plasticity Index (%)	58
USCS Classification	CH

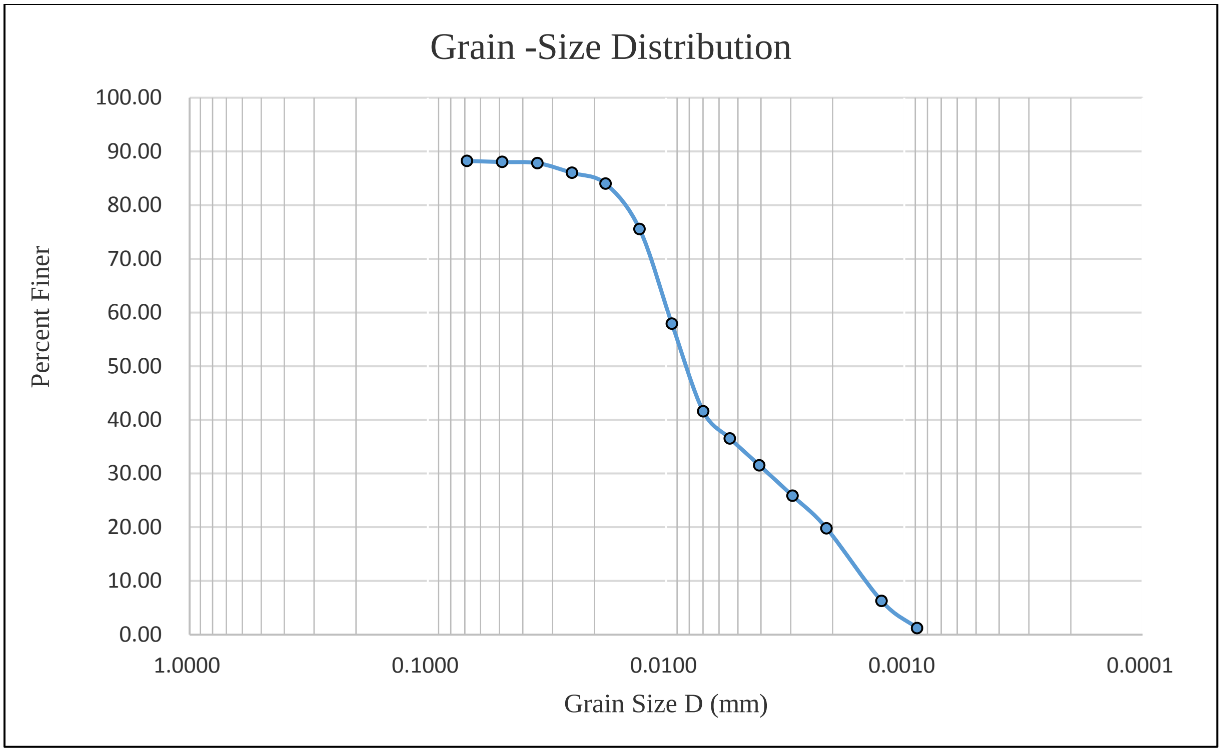


Figure 3. 7 Particle size analysis—hydrometer test

3.3.1.3 Standard Compaction Test

The laboratory soil compaction test was conducted in accordance with ASTM D1557 “Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort” (56,000 ft-lb/ft^3 (2,700KN-m/m^3)). In order to determine the compaction moisture content and dry density relationship of the soil in the present research program curve, at least five compacted soil samples were put in the oven. A 4-inch diameter mold and a mechanical hammer were used for this purpose (Das, 2012). The compaction energy of 12.4 ft.lb/ft^3 was applied by dropping a 5.5 pound hammer from a height of 12 inches on three different layers with 25 blows per layer. The compacted soil was extruded with a hydraulic ram after trimming the excess soil off the top of the mold. Figure 3.8 displays the compacted soil sample.

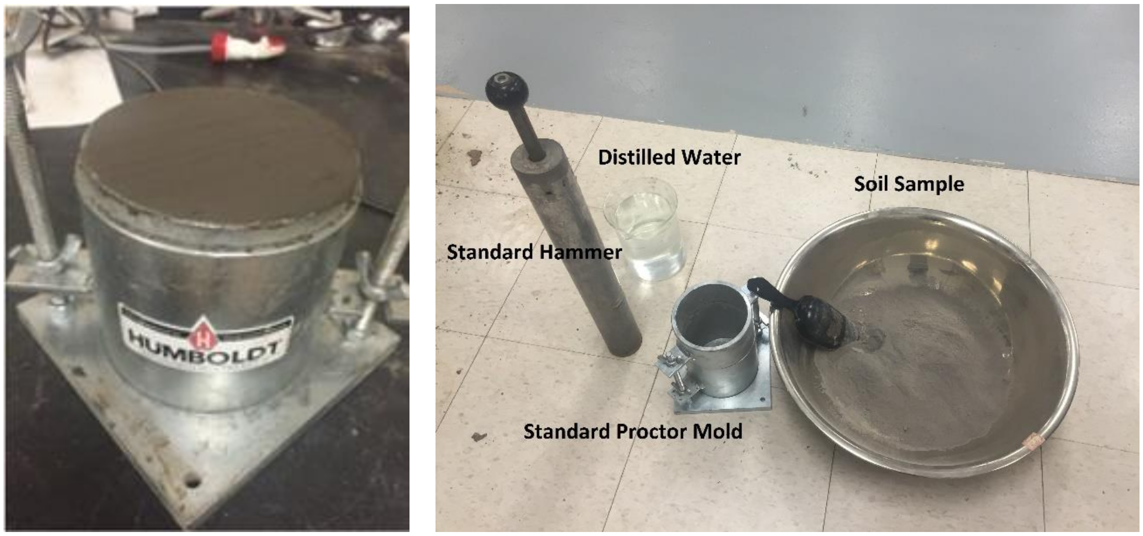


Figure 3. 8 Standard Proctor test

3.3.1.4 Specific Gravity (G_s)

The laboratory soil compaction tests were conducted by ASTM D854 “Standard Test Method for Specific Gravity of Soils.” In general, the specific gravity of clay is 2.65 while it ranges from 2.70 to 2.90 for clay according to the mineral content. Fifty grams of dried soil sample was placed in a volumetric flask which was filled with distilled water. The flask was filled about one- half full of distilled water. Low vacuum was applied to the flask and gradually increased to cause the inside water in the flask to boil for approximately 10 to 20 minutes. The flask should be filled with distilled water to the graduation mark, poured in a pan, and placed in an oven. Figure 3.8 shows the mixture of soil sample and distilled water in flask vacuum.


Figure 3. 9 Soil sample in vacuum flask

3.4 Treatment Plan

The company recommended 5 mls and 0.057 g of surfactant should be diluted in 1 g (3.78 liter) of distilled water. Therefore, in this thesis, this dosage is designated as the first and standard dosage. Two different dosages were monitored in this research program to finalize and define an efficient dosage to restrain soil expansion. Table 3.4 shows the three different dosages used in this study.

Table 3. 4 Different Dosage Rate Mixtures

Dosage Unit	**First (A)**	**Second (B)**	**Third (C)**
Concentrate (ml)	5	5	10
Surfactant (g)	0.057	0.057	0.114
Distilled water (Gallon)	1	2	1

The second dosage was defined as double the recommended value of distilled water which is 1 gallon. In this case, the concentration of liquid stabilizer was reduced. Moreover, in the third dosage definition, the concentrate and surfactant were doubled.

A stabilizer was injected differently for each test, and for each test, a different curing time was defined to find the optimum and sufficient time for conducting a basic soil test and an engineering soil test. In addition, several research regimens were perused to determine a treatment plan. The treatment plan for each test is represented in the following tables.

Table 3. 5 Sample Preparation for Atterberg Limit Test

Sample Preparation- Atterberg Limit Test	
Step	Action
1	Dry the soil sample (100g) in a 60± 5°C (140±9°F) oven and allow it to cool.
2	After drying, crush and pulverize to obtain approximately 50 g representative sample that passes the 4.75 mm (No.40) sieve.
3	Prepare the stabilizer dosage as mentioned in Table 3.4.
4	Spray the mixture to oven-dried soil and mix it with spatula.
5	Wait one hour to let stabilizer components react with soil particles before running the test.

Table 3. 6 Sample Preparation for Standard Proctor Test

Sample Preparation-Standard Proctor Test	
Step	Action
1	Dry the soil sample (2kg) in a 60± 5°C (140±9°F) oven and allow it to cool.
2	After drying, crush, grind, and split the sample to obtain five 300 g representative samples.
3	Using Atterberg limit results, assume five different moisture contents and mix the soil sample with prepared stabilizer (using special gloves).
4	Put the samples in humidity room and keep for 24 hours.
5	Perform the compaction test on each soil sample separately.

Table 3. 7 Sample Preparation for Unconfined Compressive Strength Test

Sample Preparation-Unconfined Compressive Strength Test	
Step	Action
1	Dry the soil sample (200g) in a 60± 5°C (140±9°F) oven and allow it to cool.
2	After drying, crush and pulverize to obtain an approximately 150 g representative sample that passed thorough the 4.75 mm (No.40) sieve.
3	According to compaction test results, add stabilizer to the soil sample to 95% of maximum dry density (MDD) and optimum moisture content (OMC). Use special gloves.
4	Keep the prepared soil for three hours in moist room and cover it to avoid any moisture lost.
5	Make the soil sample with respect to required soil for each sample (Details explained in Section 3.5).
6	Cure the prepared samples in moist room.

Table 3. 8 Sample Preparation for One-Dimensional Swell Test

Sample Preparation for One-Dimensional Swell Test	
Step	Action
1	Dry the soil sample (100g) in a 60± 5°C (140±9°F) oven and allow it to cool.
2	After drying, crush and pulverize to obtain approximately 150 g representative sample that passed through 4.75 mm (No.40) sieve.
3	According to compaction test results, mix the soil sample with stabilizer in order to obtain 95% of maximum dry density (MDD) and optimum moisture content (OMC) (Use special gloves).
4	Prepare the soil sample in accordance with required soil characteristics for each sample (Details explained in Section 3.6).
5	Cure the prepared samples in moist room

3.5 Moisture-Density of Treated/ Stabilized Soil

A standard Proctor test was performed in accordance with ASTM D698 to evaluate the maximum dry density and the optimum moisture content associated with that density. The treated soil was compacted according to the standard proctor density and mixed for 24 hours. It was then left to allow for a mellowing period identical to that required for lime-treated soil. However, cement treated specimens were compacted immediately after mixing. After 24 hours of the soil resting, compaction was conducted for each pan to find five different points which represent the compaction curve for treated soil. Two samples, one from the top and one from the bottom, were put in the oven for 48 hours. The detailed results of the standard compaction tests will be presented in Chapter 4.

Figure 3. 10 Prepared stabilized soil

Compaction test was conducted for each different dosage and in each dosage rate at least four pans of mixed soil with prepared solution were compacted. Thus 14 standard compaction tests were carried out.

3.6 Unconfined Compressive Strength (UCS) Test

An unconfined compressive strength test was used to determine the unconfined compressive strength (qu) of the fine soil. This is a quick test to obtain the shear strength parameters of the fine-grained soils (cohesive) either in undisturbed or remolded samples. When the soil sample is loaded rapidly, the excess pore pressure that emerges does not have enough time to dissipate, and the test is strain controlled. Therefore, the test represents soil behavior in a construction site where the rate of construction is such that the pore water does not have enough time to dissipate.

An unconfined compressive strength test (UCS) was conducted to determine the strength value of untreated soil and evaluate the suitability of the TX ProChem for the tested soil in accordance with ASTM D2166. The test procedure started with placing the specimen in the load frame and lifting it at a strain rate between 0.5 mm/minute readings of displacement and loads taken from external LVDT (to measure the sample displacement) and load cell (Fig 3.12). In general, for stiff clays, q_u is defined as the peak of the curve while it is at the strain level of 15% for soft clays. The ideal water content for a UCS test should be around optimum water content. However, for the sake of water evaporation during mixing, it is hard to control the water content.

The test was performed on the untreated soil sample, which was prepared based on optimum moisture content and 95% maximum dry density. The soil sample was prepared in three compacted layers to make samples 2.8 inches in diameter and 5.7 inches in height. The UCS results for untreated soil was reported at 15 psi.

The soils were mixed with various stabilizer dosages (described in Table 3.4) and compacted at three layers with moisture content selected based on the standard proctor optimum moisture content. The UCS tests of treated soil were performed at different dosage rates to evaluate the effect of stabilizer content on soil strength.

The untreated soil samples were tested 24 hours after compaction, whereas the stabilized soil samples were cured in a moist room for 1, 7, 14, and 28 days prior to testing. Standard proctor tests for measured maximum dry density (MDD) and optimum moisture content (OMC) were used to determine the amount of required soil for preparation of 5.7" × 2.8" soil samples. The equation (3.1) indicates the amount of soil required for each sample.

$$\text{Required weight of solid} = (95\%\ \gamma_{d\text{-max}})*(1+\omega)*V \tag{3.1}$$

$\gamma_{d\text{-max}}$= maximum dry density of soil (pcf)

ω= optimum moisture content (%)

V= volume of the mold in^3

The dynamic compaction device, which is utilized in this research, applies constant compaction energy to the small volume of confined soil which does not represent the field condition. Based on several field and laboratory studies, it has been proven that field compacted soil behavior is different from laboratory compacted soils. Therefore, for required soil calculation, 95% of maximum dry density should be used to simulate field conditions. Table 3.9 shows the required soil in each dosage.

Table 3. 9 Required Soil for Each UCS Sample

Soil Type	**V (in^3)**	**$\gamma_{d\text{-}max}$ (pcf)**	**ω (%)**	**Required weight of solid (lb)**
Untreated	35.1	85.7	31	2.16
First Ratio		82.5	34	2.13
Second Ratio		83.4	30	2.09
Third Ratio		83.8	32.5	2.14

Stabilized soils were put into the metal mold in which the inside surface was lubricated to minimize friction while extruding the sample. Each sample was prepared in three different layers, and compacted with two cylindrical blocks which were placed on the top and the bottom of a dynamic compaction machine. The applied load rate to each specimen was 2.7 mm/ min as shown in Fig 3.11. Also in Figure 3.12 shows an extruded sample curing in the moist room.

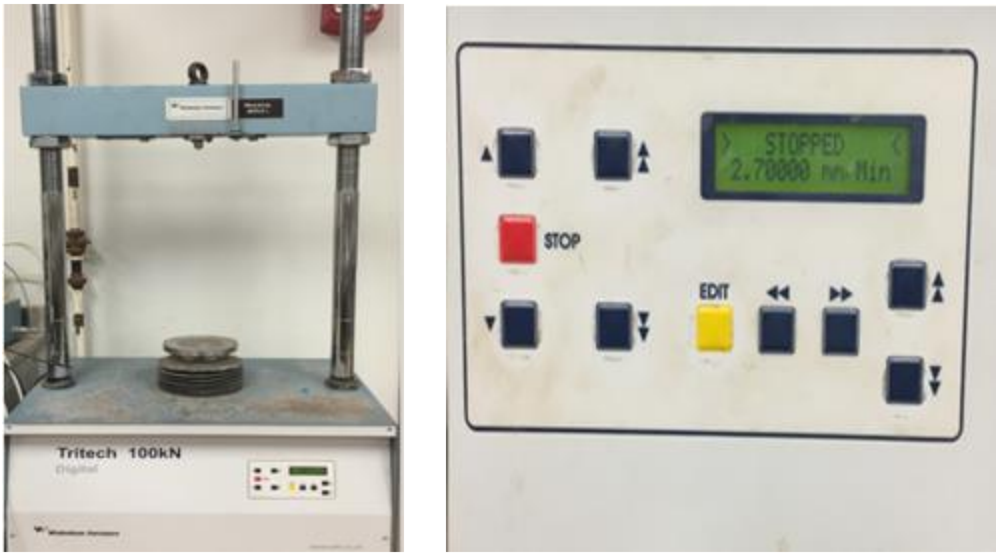


Figure 3. 11 Dynamic compaction machine

After samples were extruded from a metal mold, samples were covered and kept in moist room.

Figure 3. 12 Extruded and cured samples

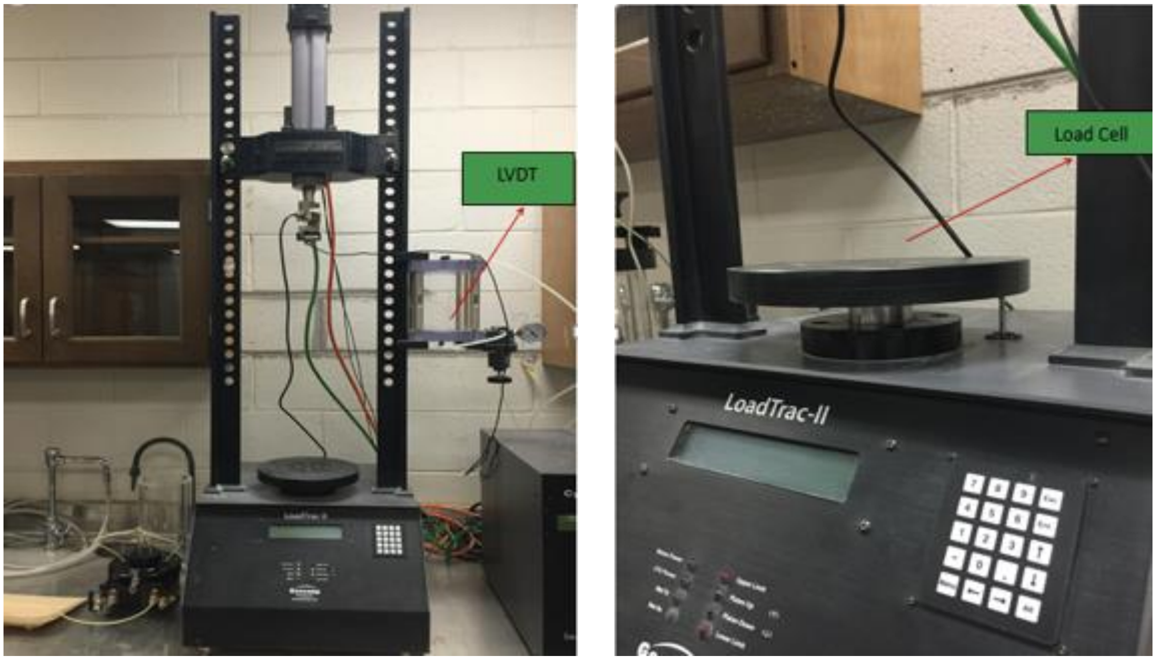


Figure 3. 13 Unconfined compressive strength testing equipment

Figure 3. 14 Soil sample a) before failure b) failure plane

3.7 One-Dimensional Swell Test

3.7.1 Swell Potential

In this study the effect of TX ProChem on the swell potential was investigated by using the free swell method in accordance with ASTM D4546-14. The stabilizer was added to soil as described earlier and the stabilized soil was placed into the consolidation ring. Required soil for sample preparation was calculated using the UCS procedure. Soil samples were placed directly into the ring without any guide rings. In the preliminary research, the samples were compacted in the guide rings, but during transfer of samples from guide rings to consolidation rings, specimens were terribly disturbed. Therefore, the free swell tests were conducted by making specimen 2.5 inches in diameter and at least 0.9 inches in height which is the size of the consolidation ring. The sample was compacted and confined in the consolidation ring that was placed in the oedometer under a small surcharge. Water was then added to the sample and allowed to swell freely. As the sample swelled, the dial gauge readings were recorded. At some point the sample had no further tendency to swell and the maximum swell recorded was used for the determination of swell potential. The percent of swell potential can be measured as shows in following equation 3.2:

$$\text{Swell Potential} = \Delta H/H \times 100 \quad (3.2)$$

where

ΔH= Change in initial height (H) of the specimen

H= initial height of the specimen

After compacting sample in the consolidation ring, dry filter papers were placed on the top and the bottom of the sample. The consolidation ring was assembled in the oedometer and the air-dry porous stone was placed on top the specimen (another porous stone was already in place at the bottom) as illustrated in Figure 3.15. After the oedometer consolidation ring with specimen was mounted on the loading device, the dial gauges were adjusted to zero reading (or the initial reading before adding water). The sample was inundated by pouring water directly from the top of the oedometer. The specimen started swelling the moment it began to be covered with water. The first part of the test was finished when the dial gauge reached a steady point and stopped changing.

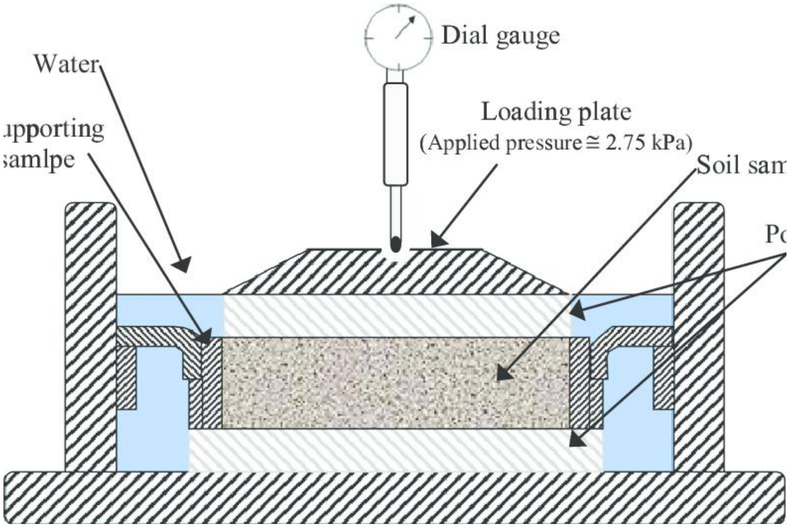


Figure 3. 15 Experimental setup for free swell test (Aldaood, Bouasker & Al-Mukhtar, 2014)

3.7.2 Swell Pressure

When dial gauge achieved a constant reading, a load increment was applied to find the swell pressure. For this purpose, more load was applied to the sample to make the dial gauge zero. When the dial gauge reached zero, the sample was removed from the oedometer, weighed, and placed in oven to determine the height of solid (H_s). Swell pressure was measured based on load and void ratios which are calculated based on each dial gauge record.

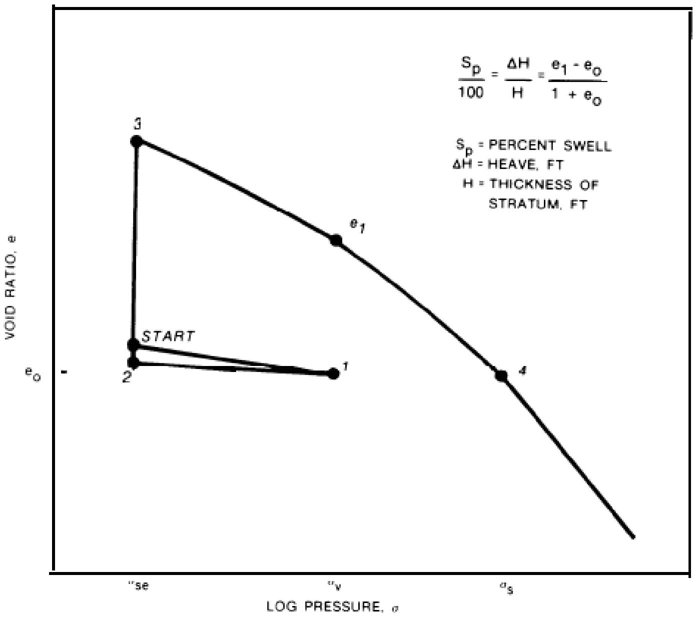


Figure 3. 16 Swell pressure

Figure 3. 17 Consolidometer setup

3.8 Soil pH

The soil sample pH was initially determined based on experiments with three different solutions, DI, 0.01 M, $CaCl_2$, and 1M KCL, and followed the methods of Tan (2005). In this study, soil pH was performed in accordance with ASTM D4972; thus, 0.10 g air-dried sieved soil was poured through a 2-mm (No.10) sieve, mixed thoroughly in 10 mL of distilled water, and then left for an hour; the pH was then measured with a Beckman φ350 pH meter.


Figure 3. 18 pH test


Figure 3. 19 Soil samples being shaken on shaking table

3.9 Mineralogical Study

Cation exchange capacity (CEC), specific surface area (SSA), and total Potassium (TP) are the three chemical properties of the soil used to determine the dominating clay mineralogy.

3.9.1 Cation Exchange Capacity (CEC)

Cation exchange capacity or CEC was used to determine the mineral composition of the soil specimen. High CEC value indicates a high amount of expansiveness due to the presence of the clay mineral montmorillonite; however, a low CEC shows the presence of non-expansive clay minerals such as kaolinite and illite. The CEC of a soil is defined as the capacity or the ability of the soil to exchange free cations that are available in the exchange locations. One of the earliest methods proposed by Chapman (1965) is the most commonly used method in the field and this method was selected for this thesis research. The method involves adding a saturating solution and then removing the adsorbed cations using an extracting solution. Procedural steps of this method are shown in Figure 3.21.

The saturating solution used here is ammonium acetate (NH_4OAc) at pH 7. This solution was prepared by diluting 57 milliliters glacial acetic acid (99.5%) and 68 milliliters of concentrated ammonium hydroxide (NH_4 OH) with one liter of distilled water in a one-liter volumetric flask. Then the solution was added to 25 g of prepared soil specimen and set aside for 16 hrs after shaking for 30 m, to ensure that all the exchange locations were occupied by the ammonium ion (NH_4^+). Then the solution was filtered through a Buchner funnel using retentive filter paper #40 and washed with four different 25 mL additions of NH_4OAc. The purpose of this step is to bring out all the cations from the soil sample solution that had been replaced by ammonium ions. Excess NH_4OAc was removed by eight different 10 mL additions of 2-propanol as shown in Figure 3.20. Therefore, all the cation places were replaced by the ammonium ions and excess ammonium was also removed. The CEC of the soil sample can be obtained if we can measure the amount of ammonium ions by taking them out. This is done by leaching the sample with eight different 25 mL additions of 1M potassium chloride (KCl) solution which is shown in Figure 3.20. Although the potassium ion (K^+) has similar electro negativity, it has a higher molecular weight and the ability to substitute the NH_4^+ ion. The concentration NH_4^+ in the KCl extract gives the CEC of the soil. The detailed step-by-step procedure of how the test is conducted is given in a Figure 3.21 flowchart.

(A) (B)

Figure 3. 20 Cation exchange capacity: (A) washing the soil with 10 ml of propanol and (B) leaching the soil with 25ml of KCl

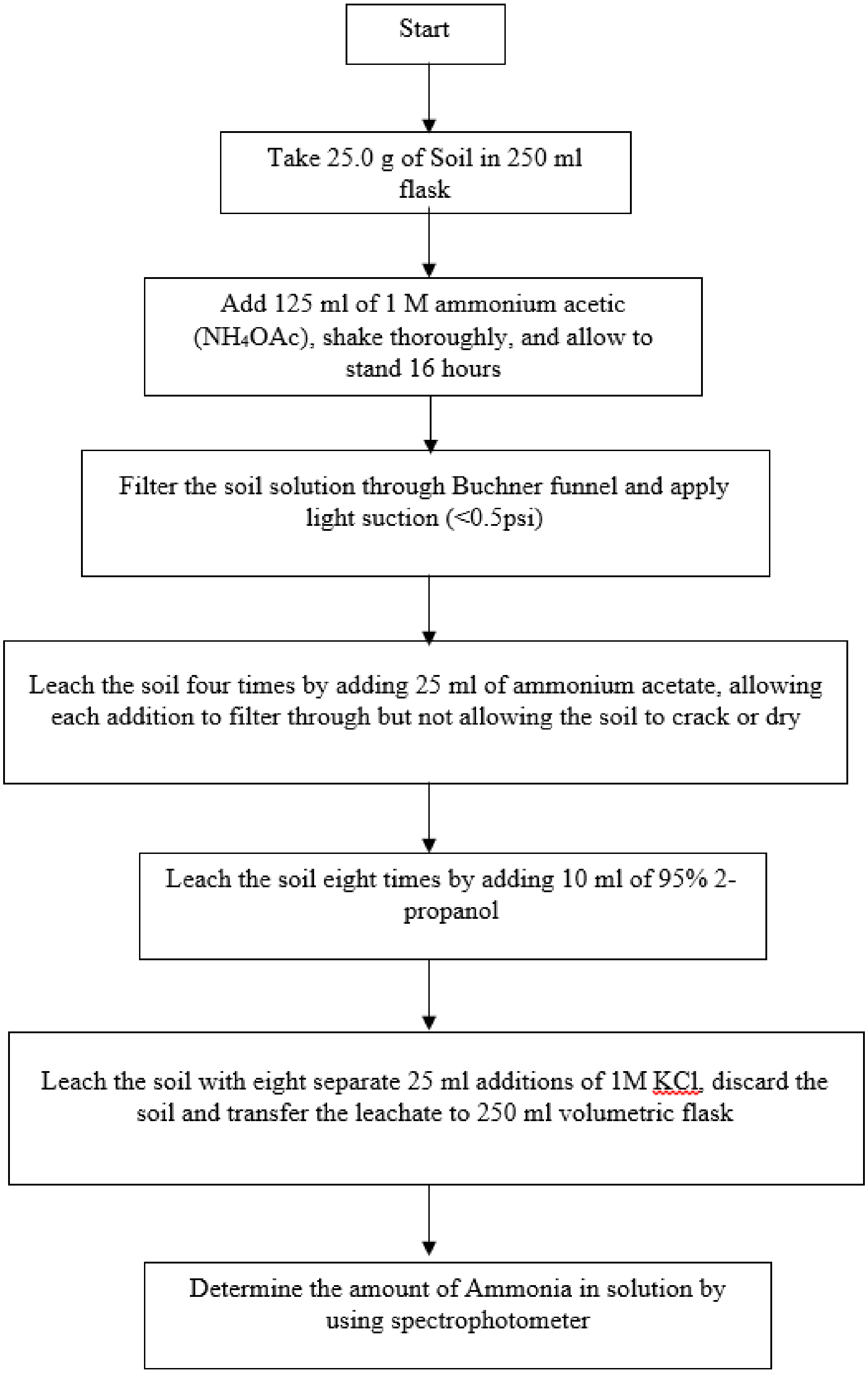


Figure 3. 21 Flowchart illustrating the step-by- step procedure for determination of CEC (Chittoori, 2008)

3.9.2 Specific Surface Area

Specific surface area (SSA) of a soil sample is the total surface area contained in a unit mass of soil. This property of the soil is dependent on the particle size. Soils with a smaller particle size have higher specific surface areas. It should be mentioned here that a soil with high specific surface area has high water holding capacity and greater swell potential.

The most commonly used method for determining SSA in the field of agronomy is the adsorption of ethylene glycol monomethyl ether (EGME) (Carter et al., 1986). This involves saturating oven-dried soil specimens, equilibrating them in vacuum over a calcium chloride–EGME ($CaCl_2$-EGME) solvate, and weighing to determine when there is no further change in weight. Specific surface is calculated from the mass of retained EGME in comparison to the amount retained by pure montmorillonite clay, which is assumed to have a surface area of 810 m^2/g (Carter et al., 1986). The test procedure typically takes a month to complete since the soil particle size is small. This method was fully evaluated for geotechnical usage by Cerato and Lutenegger (2002) who concluded that the method is capable of determining specific surface area for soil samples ranging from 15 to 800 m^2/g. They also pointed that the procedure is iterative and gives reliable results. A detailed procedure for the determination of SSA by EGME method that was followed in the current research is shown in Figure 3.22 and 3.23.

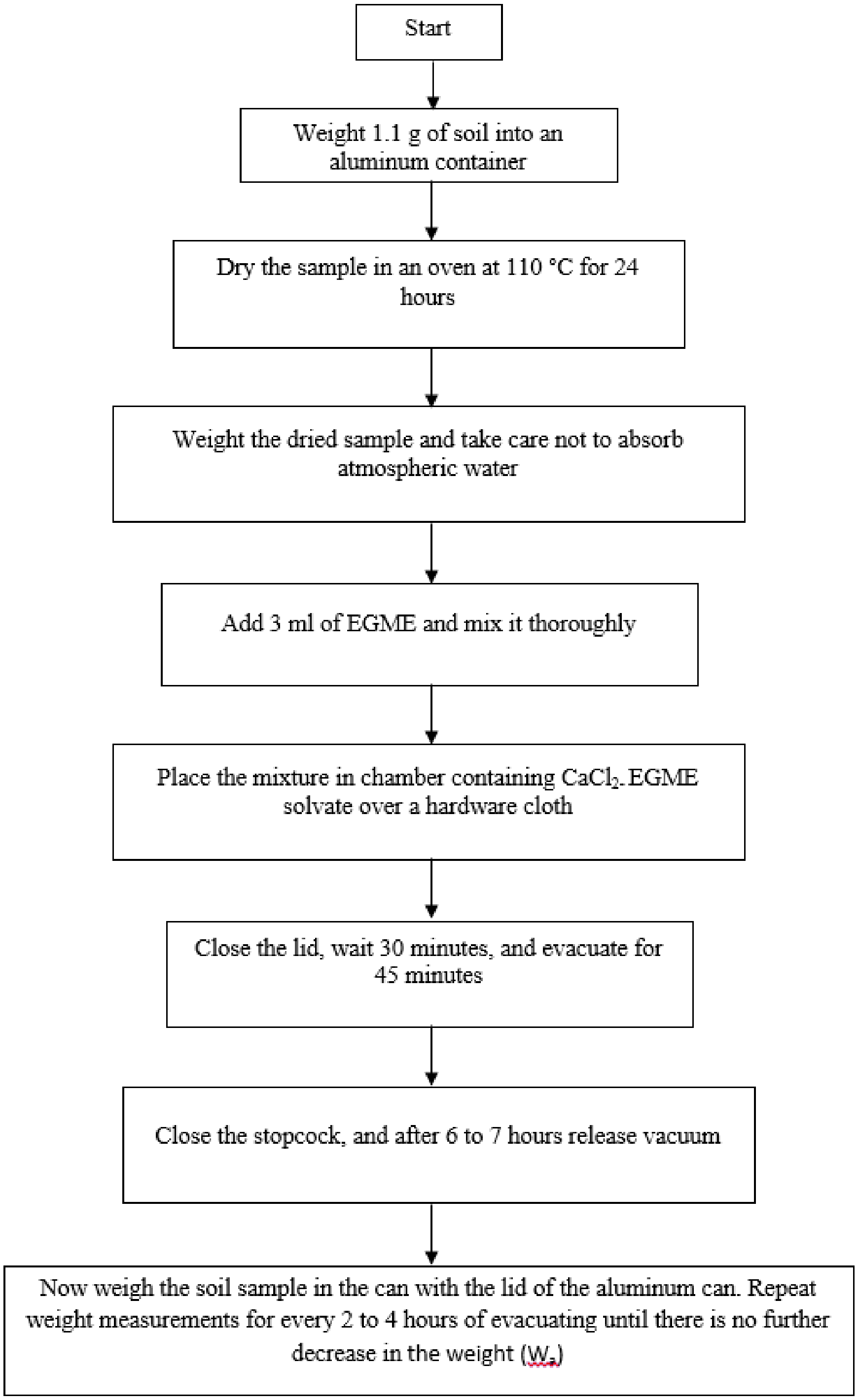
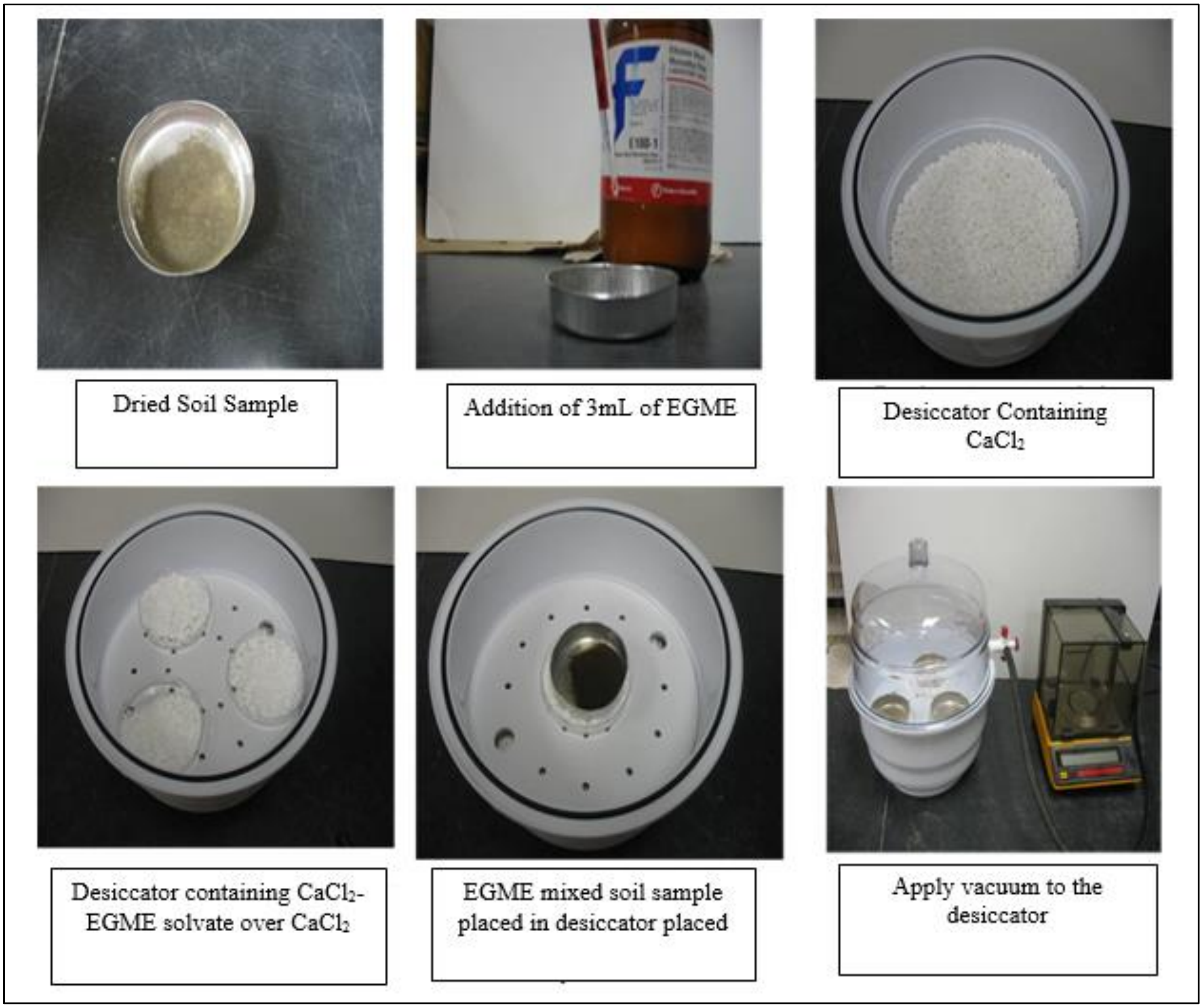


Figure 3. 22 Flowchart illustrating the step-by-step procedure for determination of SSA (Chittoori, 2008)



Dried Soil Sample

Addition of 3mL of EGME

Desiccator Containing $CaCl_2$

Desiccator containing $CaCl_2$-EGME solvate over $CaCl_2$

EGME mixed soil sample placed in desiccator placed

Apply vacuum to the desiccator

Figure 3. 23 Determination of surface specific area

(Specific Surface Area) $A = \frac{W_a}{W_s * 0.000286}\ {m^2}/{gr}$

3.9.3 Total Potassium

Potassium is the interlayer cation in the clay mineral illite and potassium is the only cation that illite has in its structure (Mitchell & Soga, 2003). Therefore, to measure the presence of the mineral illite, the amount of potassium ions in the soil should be measured. Knudsen et al. (1982) formulated the procedure to obtain the amount of total potassium present in the soil. The method involves a double acid digestion technique developed by Jackson (1958) which uses two acids (hydrofluoric acid and perchloric acid) for breaking the mineral structure of the soil and extracting the potassium ions from the structure. With the help of a spectrophotometer or any other suitable device the extracted potassium with any concentration in a solution can be obtained.

The test starts by placing 0.1 g of soil in a Teflon digestion vessel. The original method recommends using platinum vessels as the hydrofluoric acid used has the ability to dissolve silica and glass is 90% silica. However, the use of platinum vessel was not possible due to cost constraints; hence, other possible alternatives were looked at and the Teflon vessel was able to resist the acids used in the current test procedure (hydrofluoric acid (HF), perchloric acid($HClO_4$) and hydrofluoric acid); plus, it has a high temperature tolerance (200 ^{o}C). Hence, with few drops of water wet the soil and then 5 ml of hydrofluoric acid and 0.5 ml of perchloric acid was added to the vessel. The soil-acid mixture was placed in a chemical hood and heated on a hot plate until perchloric acid fumes appeared or heated until the temperature exceeded 200 ˚C. The silicate mineral structure is dissolved by adding Hydrofluoric acid and the interlayer cations released. Perchloric acid was used as an oxidizing agent to oxidize the organic matter in the soil sample. Then the vessel was placed on a hot plate and heated to 200 ^{o}C and then cooled. Another 5 ml of HF and $HClO_4$ was added and reheated on the hot plate. Now the sample is added until it is dry, the process is repeated to make sure all the interlayer cations are released and then finally 6N HCl was added and the amount of potassium in this solution was obtained by using a spectrophotometer. Procedural steps were followed to determine total potassium in this research are outlined in 3.24 and Figure 3.25. The results obtained from all of the above explained tests, and are given in Chapter 4.

Heat soil with 5 ml HF and 0.5 ml of $HClO_4$

Add 5 ml water and 5 ml of 6N HCl

Mixture of dry crystal and potassium indicator

Figure 3. 24 Determination of Total Potassium

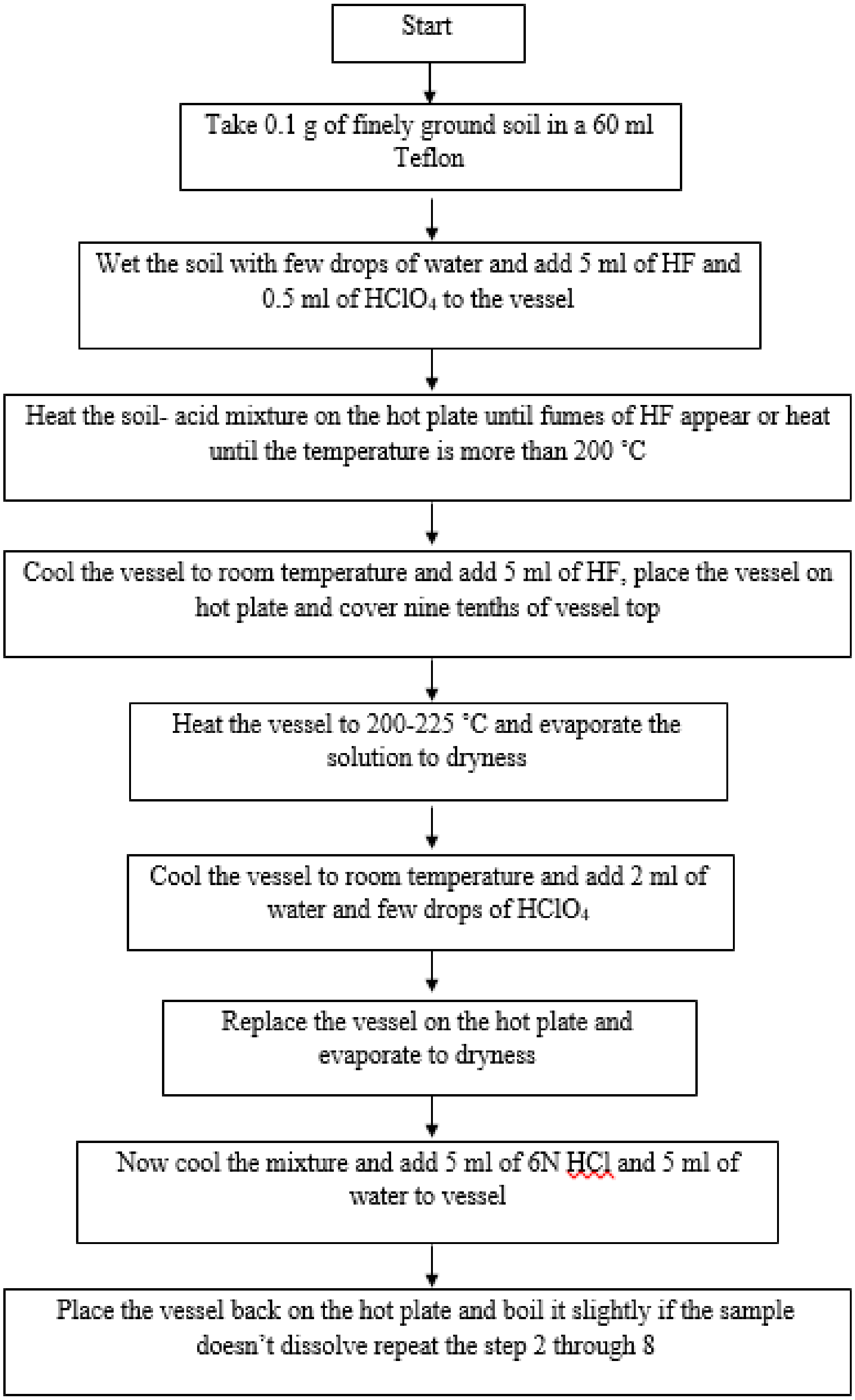


Figure 3. 25 Flowchart illustrating the step-by-step procedure for determination of TP

Chapter 4

Results and Discussion

This chapter presents the results of all experiments that were conducted on the untreated and treated soils described in Chapter 3.

4.1 Atterberg Limits

Atterberg limit tests were performed on untreated soil and treated soil which stabilized with three different dosages as explained in Chapter 3 and as shown below in Table 4.1. Atterberg limit results are presented in Table 4.2.

Table 4.1Different Dosage Properties

Dosage unit	First (A)	Second (B)	Third (C)
Concentrate (ml)	5	5	10
Surfactant (g)	0.057	0.057	0.114
Distilled water (Gallon)	1	2	1

Table 4.2 Atterberg Limit Results of Different Dosages

Atterberg Limit	LL	PL	PI
Untreated	76%	18%	58
First Ratio	72%	15%	57
Second Ratio	79%	29%	50
Third Ratio	69%	43%	26

4.1.1 Effects of Different Dosages on Atterberg Limits

According to results, the liquid limit and plastic limit did not show any consistent change. LL and PL both increased with stabilizer content of 2.5 ml, which applies to second diluted ratio. Addition of stabilizer content causes a reduction in LL, while PL returns to untreated value standard as it increases to 43%. In contrast, PI consistently decreased with addition of stabilizer content from 58 for untreated to 26 for third dosage. Consequently, strength/stiffness of the stabilized soil with ISS improved due to PI reduction.

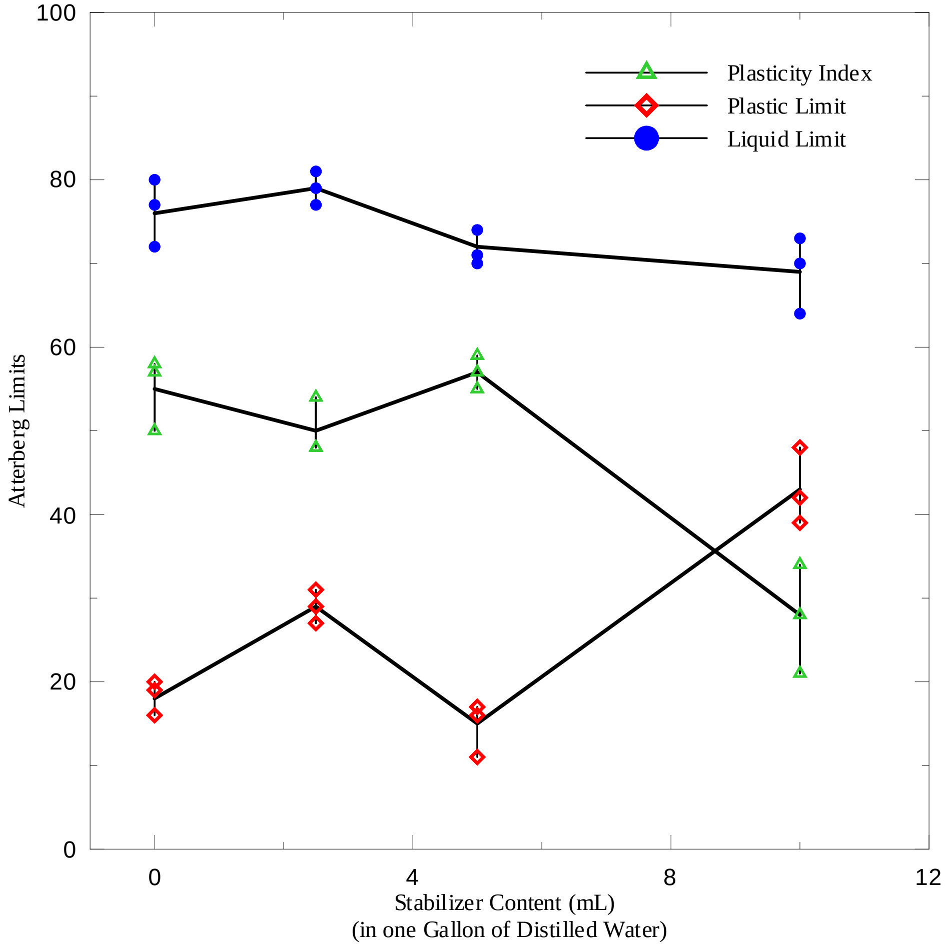
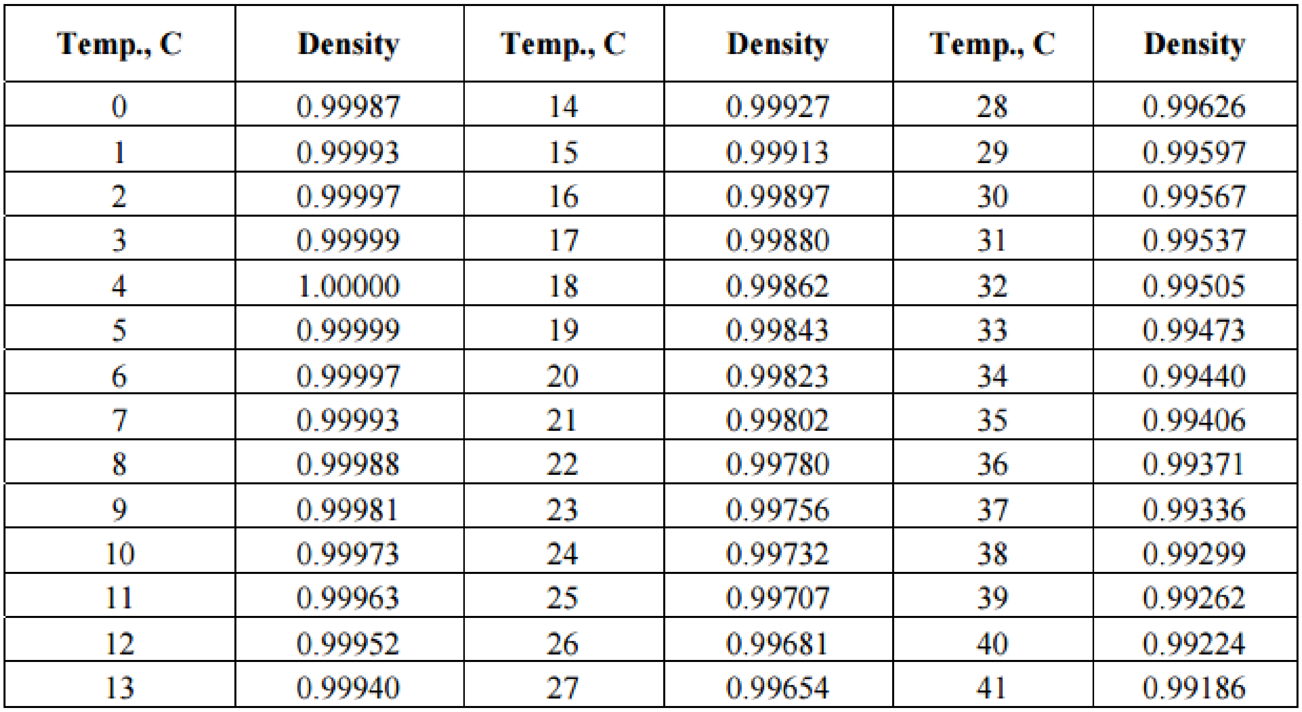


Figure 4. 1 Effects of different dosages under Atterberg limits

4.2 Specific Gravity (G_s)

Specific gravity is the ratio of the mass of unit volume of soil to the mass of the same volume of gas-free distilled water at a stated temperature. Usually, high specific gravity indicates the soil might be expansive clay; however, specific gravity cannot be solely used to determine if soil is expansive. The test was conducted on an untreated soil sample in accordance with ASTM D854 “Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer.” The test was performed at 24 °C, and the density of distilled water was determined from Table 4.3. To calculate specific gravity, Equation 4.1 was used.

Table 4. 3 Density of Distilled Water at Various Centigrade Temperature



Temp., C	Density	Temp., C	Density	Temp., C	Density
0	0.99987	14	0.99927	28	0.99626
1	0.99993	15	0.99913	29	0.99597
2	0.99997	16	0.99897	30	0.99567
3	0.99999	17	0.99880	31	0.99537
4	1.00000	18	0.99862	32	0.99505
5	0.99999	19	0.99843	33	0.99473
6	0.99997	20	0.99823	34	0.99440
7	0.99993	21	0.99802	35	0.99406
8	0.99988	22	0.99780	36	0.99371
9	0.99981	23	0.99756	37	0.99336
10	0.99973	24	0.99732	38	0.99299
11	0.99963	25	0.99707	39	0.99262
12	0.99952	26	0.99681	40	0.99224
13	0.99940	27	0.99654	41	0.99186

$$G = (M * D) / (M + T - L) \quad (4.1)$$

where:

G = specific gravity

M = mass of oven-dried soil, g (See Table 4.4)

T = mass of flask and water to fill at temperature at which flask was calibrated, g (See Table 4.4)

L = mass of flask, soil and water to fill at constant temperature, g (See Table 4.4)

D = density of water at the temperature at which determination was made. (See Table 4.3.)

Table 4. 4 Mass Determination of Soil, Flask and Dried Soil

Specific Gravity	**Sample A**
Mass of flask + water , M_1 (g)	664.5
Mass of flask+ soil + water M_2 (g)	693.8
Mass of dry soil, M_s (g)	47.3
Mass of equal volume of water and soil solids, M_w(g) = $(M_1+M_s)-M_2$	18
G_s	2.63

4.3 Standard Compaction Test

This section presents the compaction characteristics curve determined for the soil used in the experimental work. Standard proctor tests were performed on untreated soil as well as the treated soil as described in Chapter 3. One set of compaction test was conducted on the soil sample and in this one set, five different moisture content were prepared to obtain the compaction curve. Figure 4.2 shows the standard proctor result.

4.3.1 Effect of Different Dosage Rates on OMC and MDD

A summary of the standard proctor test results for untreated and treated soil is shown in Figure 4.3. It indicates the optimum moisture content (OMC) did not reveal a significant change, whereas maximum dry density (MDD) shows a decrease and increase with the addition of liquid stabilizer to untreated soil.

The explanation in the increase in OMC can likely be contributed to soil modification, which means a change in soil texture induced by cation exchange. The result of cation exchange and flocculation of the clay particles is a textural change as the clay particles are rearranged from a parallel alignment to an edge-to-face attraction. This new texture allows for more void space which can accommodate more water during compaction; hence, water occupied most voids and

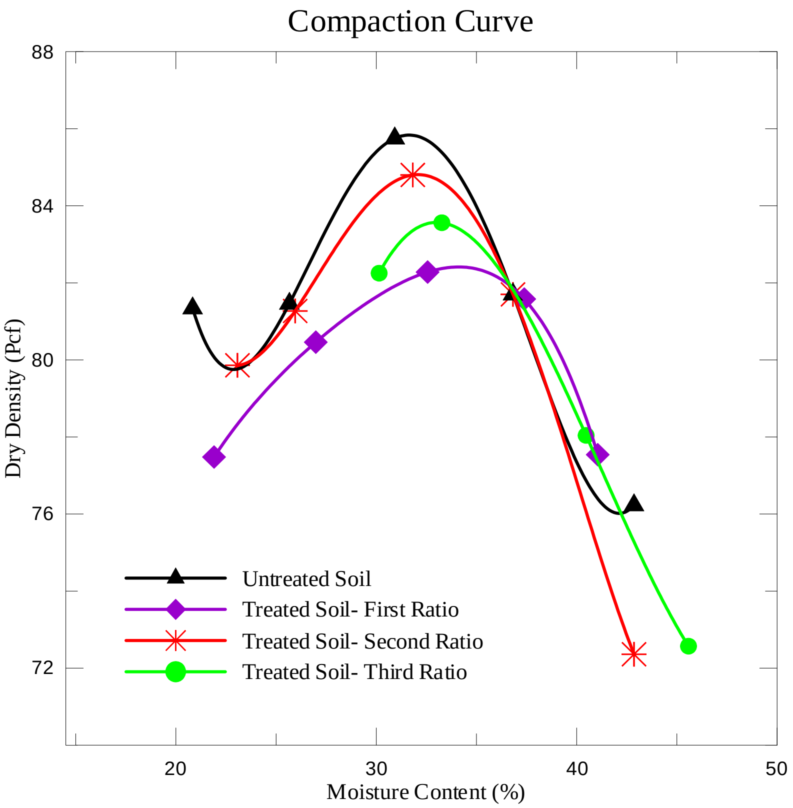


Figure 4. 2 Standard Compaction Curve of Untreated and Treated soil

optimum moisture content increased. As Figures 4.3 and 4.4 shows in third ratio, with more occupancy of voids by stabilizer components, compared to water, optimum moisture content is higher than that found in first ratio analysis. Moreover, to accelerate the reaction of soil and stabilizer components, water plays a remarkable role; therefore, soil absorbed more water to enhance the reaction of silica and alumina inside the soil skeleton with acids component present in stabilizer.

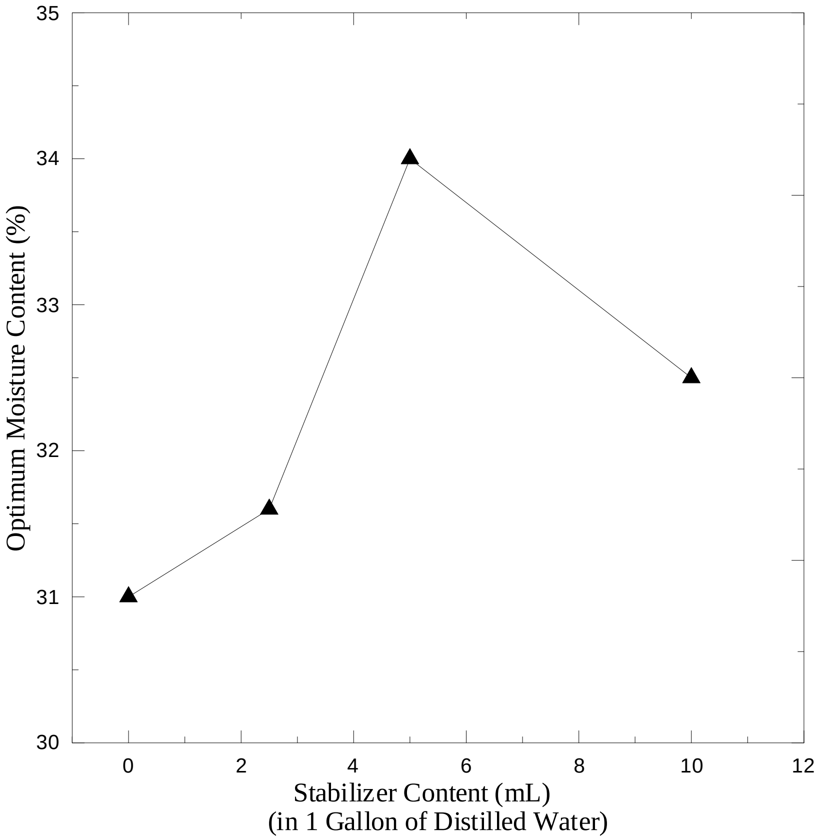


Figure 4. 3 Effect of different dosages on optimum moisture content

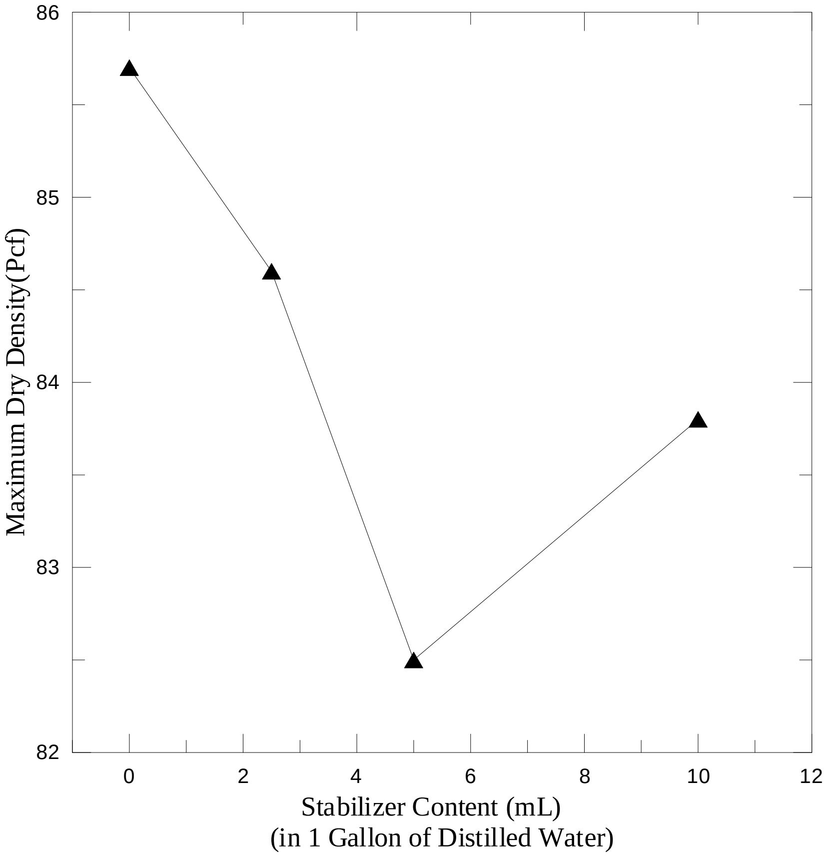


Figure 4. 4 Effect of different dosages on maximum dry density

4.4 Unconfined Compressive Strength (UCS)

The unconfined compressive strength test is a special type of test (unconfined-undrained) that is commonly used to measure the strength of soils under unconfined conditions (Das, 1998). The effectiveness of the liquid ionic soil stabilizer on strength development was evaluated using the unconfined compressive strength (UCS) tests. For this research, unconfined compressive strength testing was conducted on the studied soil, compacted at optimum water content, and 95% of maximum dry density to simulate field conditions. For soil treated at each dosage, 4 identical samples were compacted to test the effect of curing time on UCS strength. The four samples were cured for 1, 7, 14, and 28 days respectively before UCS test. The results of untreated and different curing periods and dosage rates of treated soil samples on unconfined compressive strength are shown in Figures 4.5 through 4.7.

For each dosage rate, three different samples were tested to obtain the unconfined compressive strength which can identify the unconsolidated undrained shear strength of the clay under unconfined conditions.

It has been observed from Figure 4.5 that the peak stress is 16 psi for untreated soil. Figure 4.5 shows the peak stress to range from 15.8 to 17 psi and soil strength. Treated soil had 5 ml of concentrate, 0.057 gr of surfactant, and 1 gallon of distilled water reduced after soil treatment. Figure 4. 6 shows that soil strength for treated soil with 5 ml of concentrate and 0.057 gr of surfactant diluted in 2 gallons of distilled water decreases from 11 to 13 psi after 28 days of curing. The reason for reduction can be found in the compaction curve of treated and untreated soil when the dry density of treated soil has decreased and the optimum moisture content has increased by using liquid stabilizer. Neutral compacted clay is in a less orderly arrangement and thus, the strength of the soil sample decreased due to disarrangement and high moisture content. The figures were obtained based on average value.

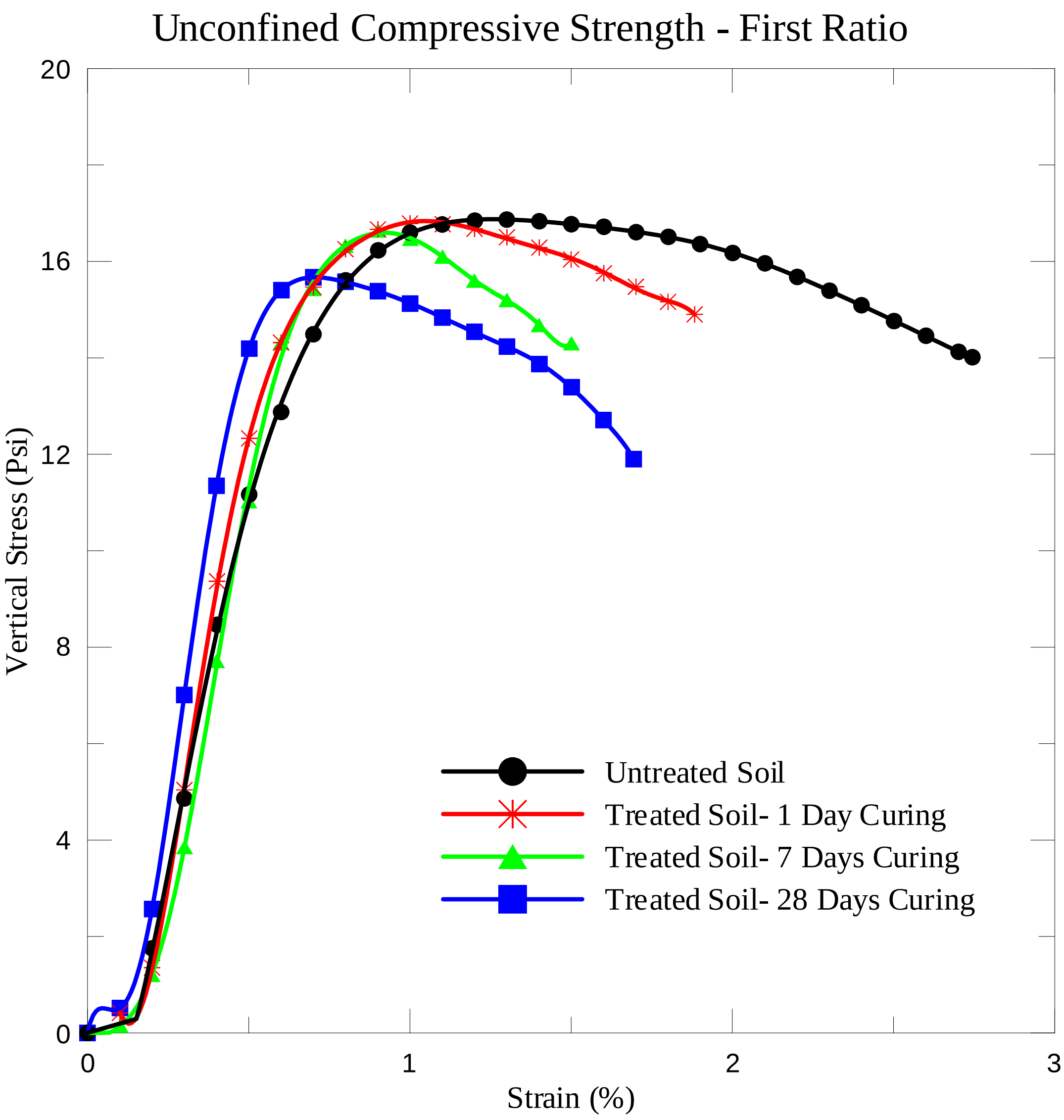


Figure 4. 5 Effects of different curing times on unconfined compressive strength of treated soil

On the other hand, in terms of compressive strength, the liquid stabilizer yielded a prominent enhancement for the untreated soil with 10 ml of concentrate, 0.114 gr of surfactant and one gallon of distilled water from 22 to 28 psi after 28 days curing as shown in Figure 4.7. As seen from Figure 4.8, the soil was strengthened by increasing the amount of stabilizer, especially after seven days of curing, and the soil strength advanced further after 14 days of curing. This was due to during the chemical components of the liquid stabilizer actively reacting with the clay particles during the curing period. The neutralized clay particles were orderly arranged and produced a relatively better interparticle bonding between each molecule. A higher interparticle bonding between each molecule indicates strength improvement. Therefore, the tests showed that a higher concentration of stabilizer component on clay platelets will produce better neutralization, bonding and higher strength compared to a low concentration of stabilizer components.

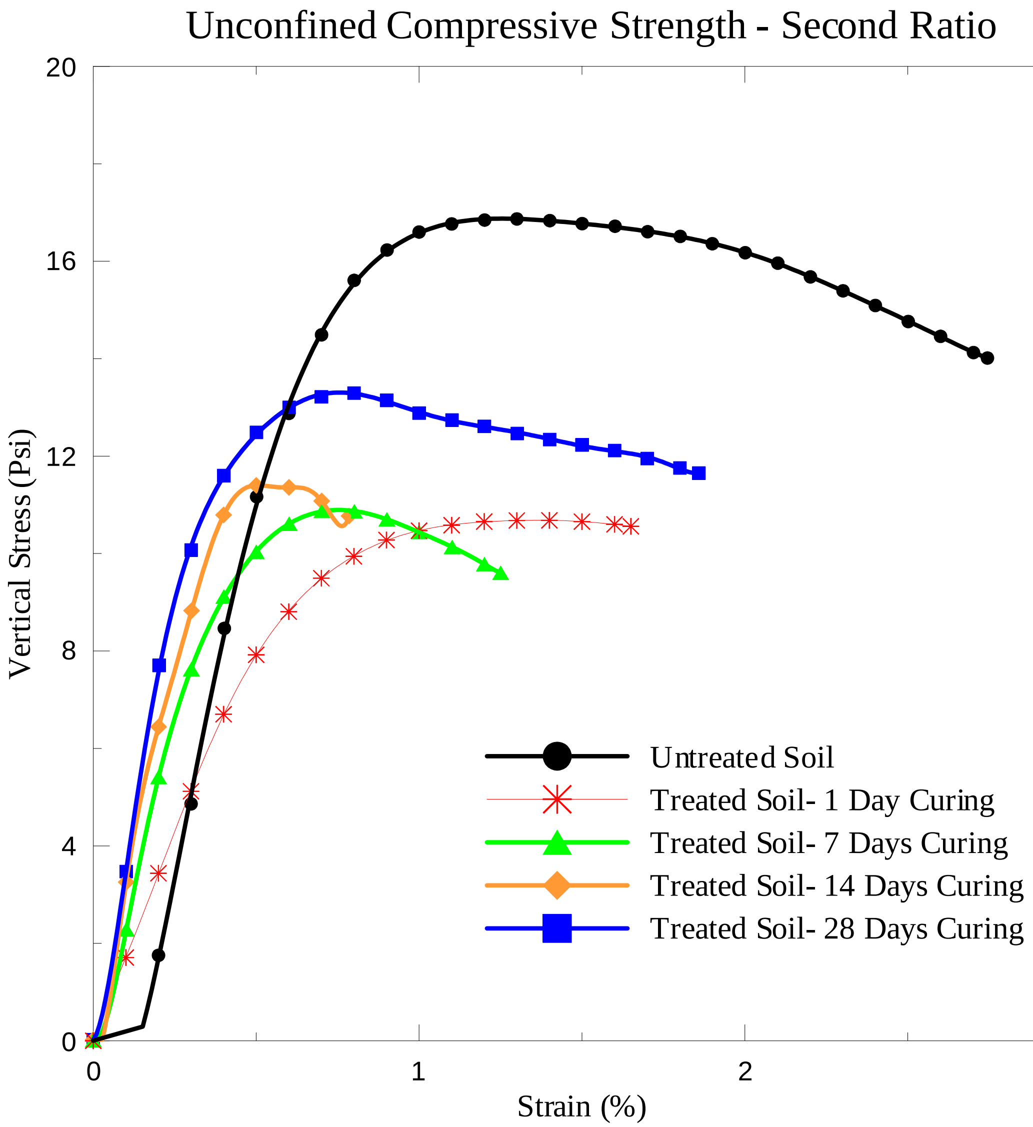


Figure 4. 6 Effects of different curing times on unconfined compressive strength of treated soil

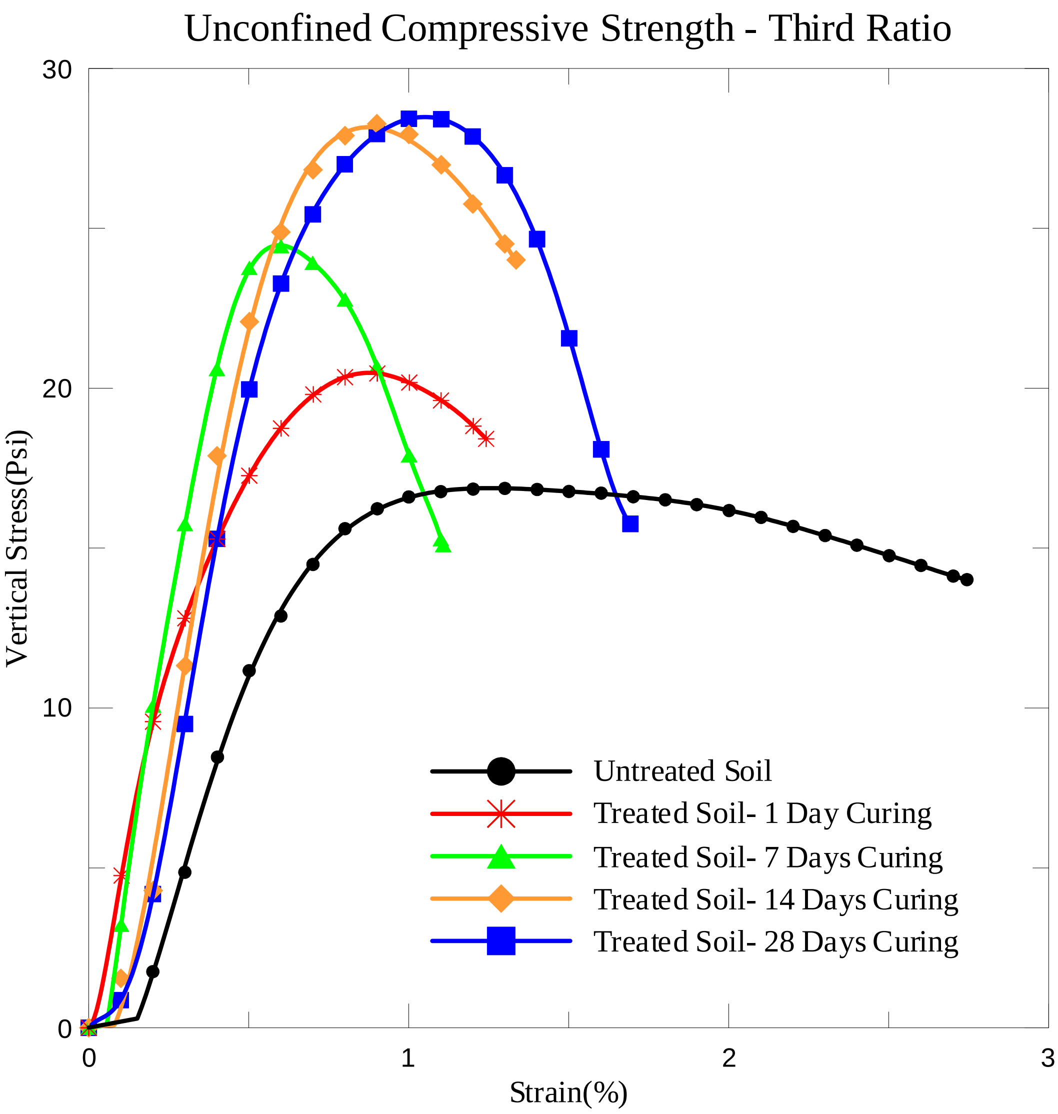


Figure 4. 7 Effects of different curing time on unconfined compressive strength of treated soil

4.4.1 Effects of Different Dosage Rates on UCS

Figure 4.8 shows the effect of different dosages on unconfined compressive strength. When the chemical stabilizer is prepared with the mixture of acid components, the explanation for the reduction of soil strength with low chemical stabilizer is that the chemical was not strong enough to react with all clay particles. However, the soil strength increased significantly in the third ratio when the concentration was doubled. Also, in the first and second ratio OMC increased which could yield a reduction of soil strength. Lower compacted density and high moisture content for the first and second ratio could be another reason to explain the reduction and constant behavior of soil strength for the first and second ratio. As Rauch et al. (2003) reported, only kaolinite-treated soil showed soil strength improvement with ISS; however, montmorillonite and illite experienced strength reduction in ISS stabilized soil due to high moisture content and low compacted density after soil treatment.

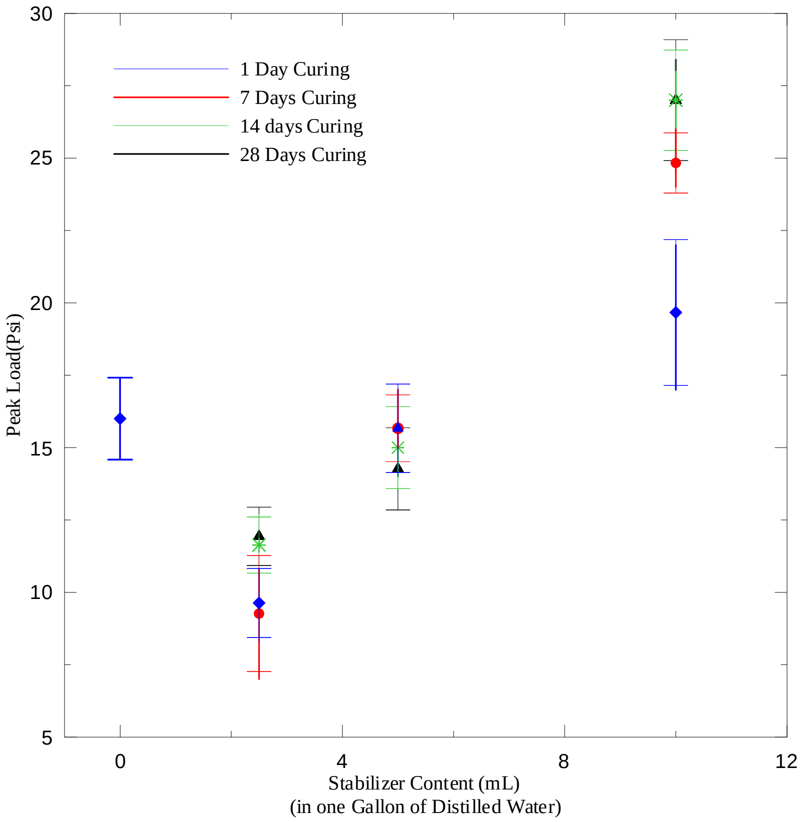


Figure 4. 8 Effect of different dosage rates on unconfined compressive strength of soil

4.4.2 Effects of Different Curing Times on Unconfined Compressive Strength

The effects of different curing time on UCS results are shown in Figures 4.5 through 4.6. According to Figure 4.25, soil strength of untreated soil is 17 psi. After soil stabilization, UCS reduces to 10.5 after one day of curing and reaches 13 psi after 28 days curing. In general, soil strength decreased with the addition of a second dosage to the soil. In comparison, the addition of stabilizer enhances soil strength from 17 psi for untreated soil to 20.5 psi for treated soil with 10 ml of concentration and 0.141 gr of surfactant after one day of curing as shown in Figure 4.6. Therefore, the improvement in UCS of treated soil was observed with the increase in additive content and curing time, and after 14 days curing UCS becomes constant in this ratio.

4.5 One-Dimensional Swell

The test procedure on different dosages of stabilized soil are discussed in Section 3.5 of Chapter 3. Soil samples were prepared based on 95% maximum dry density and optimum moisture content. The test was carried out on three different prepared soil specimen to check the repeatability and the figures demonstrate average value of three specimens.

4.5.1 Effects of Different Curing Time on Swell Potential

Figures 4. 9 through 4.11 show the effects of different curing times on each dosage rate. The soil samples were prepared and kept in a moist room for 1, 7, 14, and 28 days and tested. From the figures, the vertical swell of untreated soil reached 5.5% at the optimum water content. In the first ratio, when treated soil was at the dilution ratio of 5:1000, the swell was reduced by about 65% of the natural soil after one day of curing. After 28 days, swell potential reduced to 2.3%. According to the result of this ratio, the swell decreased after seven days curing and remained constant after seven days. Although the swell potential is reduced in the second and third ratio as well, the swell potential in the third ratio is reduced significantly from 5.5% for untreated soil to 0.9% after soil treatment and curing for 28 days. As can be seen from all figures, the ISS treated soil exhibited a trend of decreasing swell potential by increasing curing time. As ISS can quickly ionize when diluted and decrease the charge property of soil particle surfaces, the swell potential is reduced remarkably after one day of curing. However, after 28 days of curing, the thickness of the absorbed layer of soil particles is reduced, and the strength of the connecting power between soil particles has increased, which yields the reduction of swell potential. However, the specific techniques of curing might have had some influence on the results.

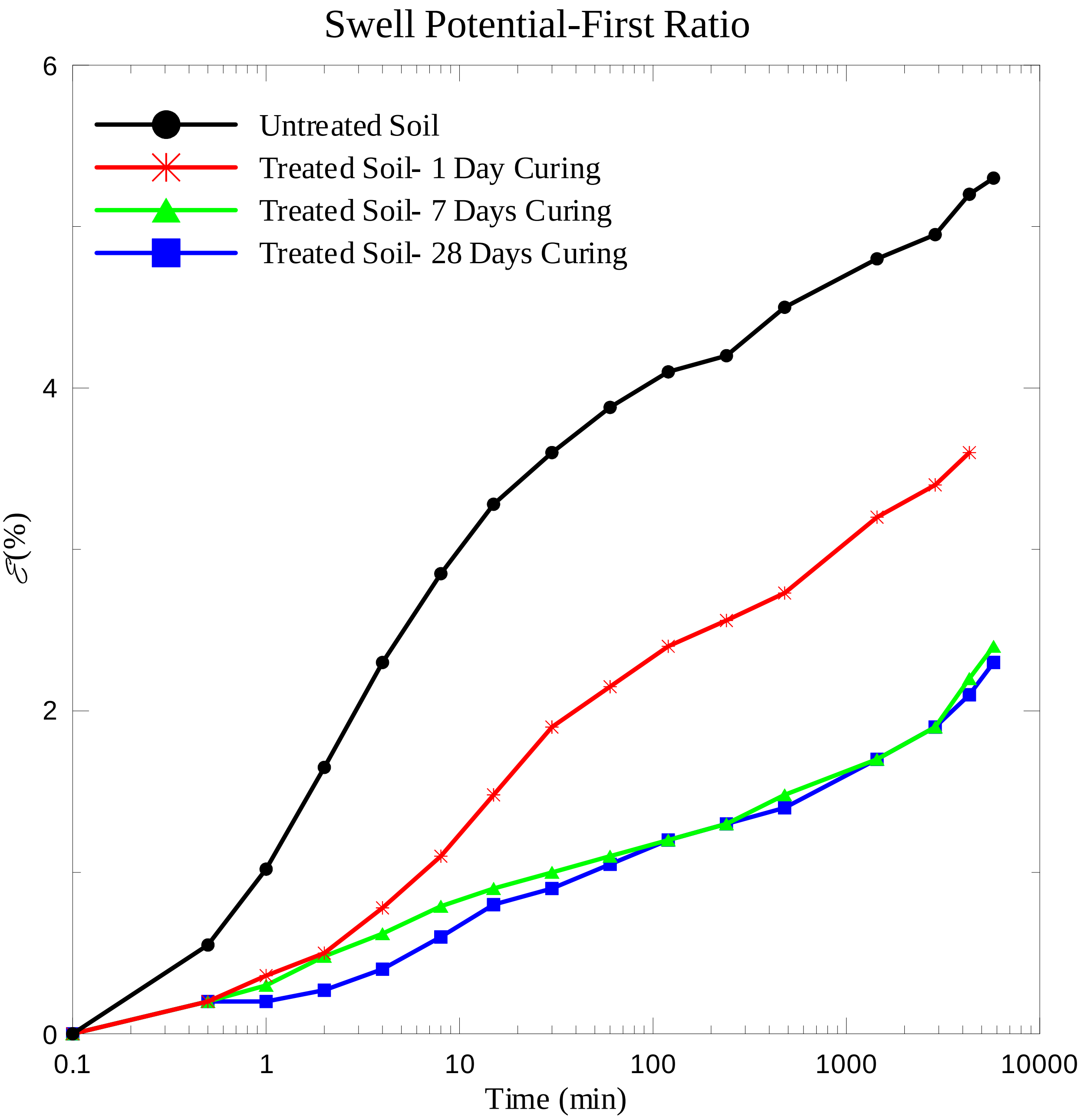


Figure 4. 9 Effects of different curing time on swell potential of treated soil

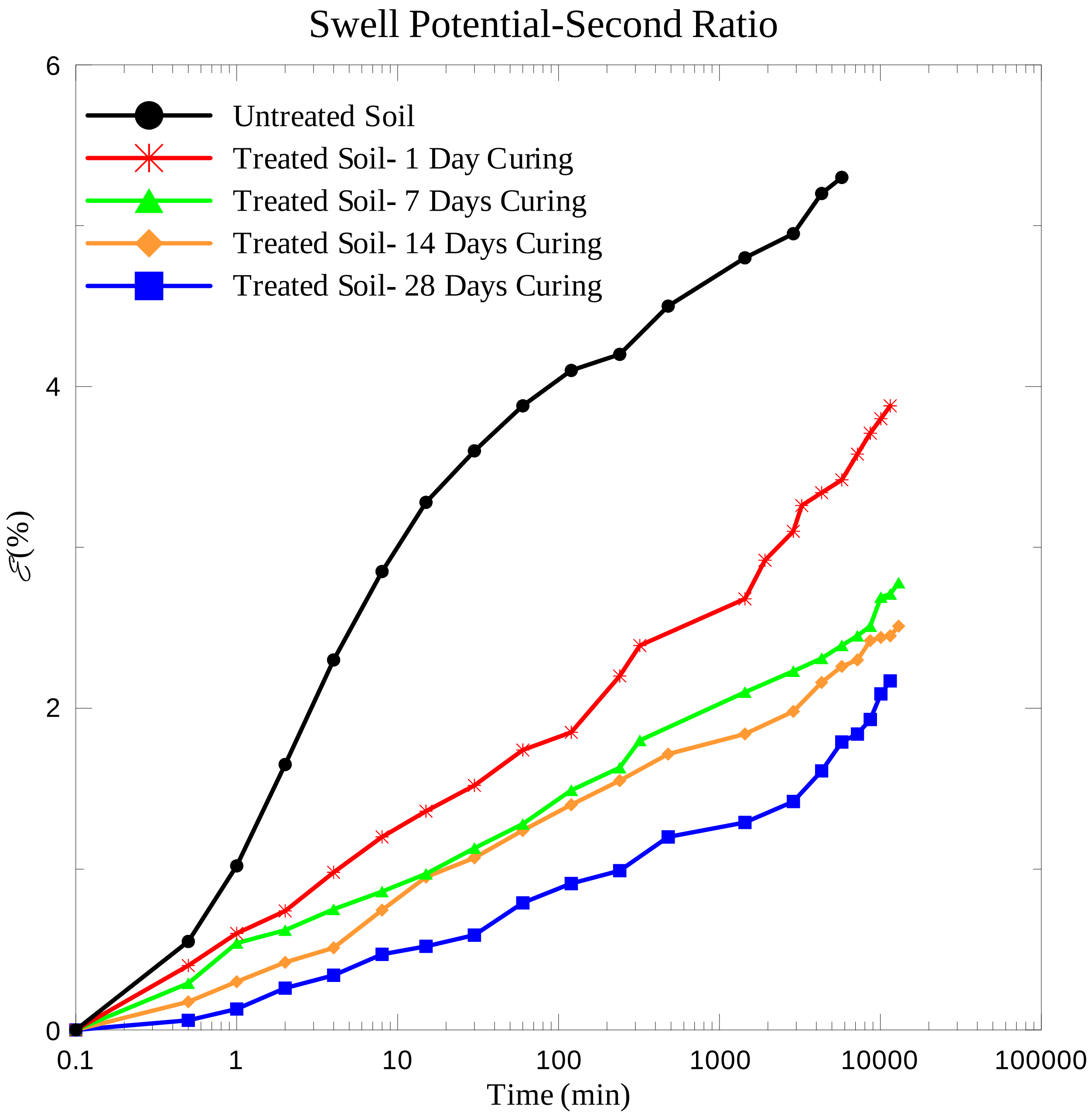


Figure 4. 10 Effects of different curing time on swell potential of treated soil

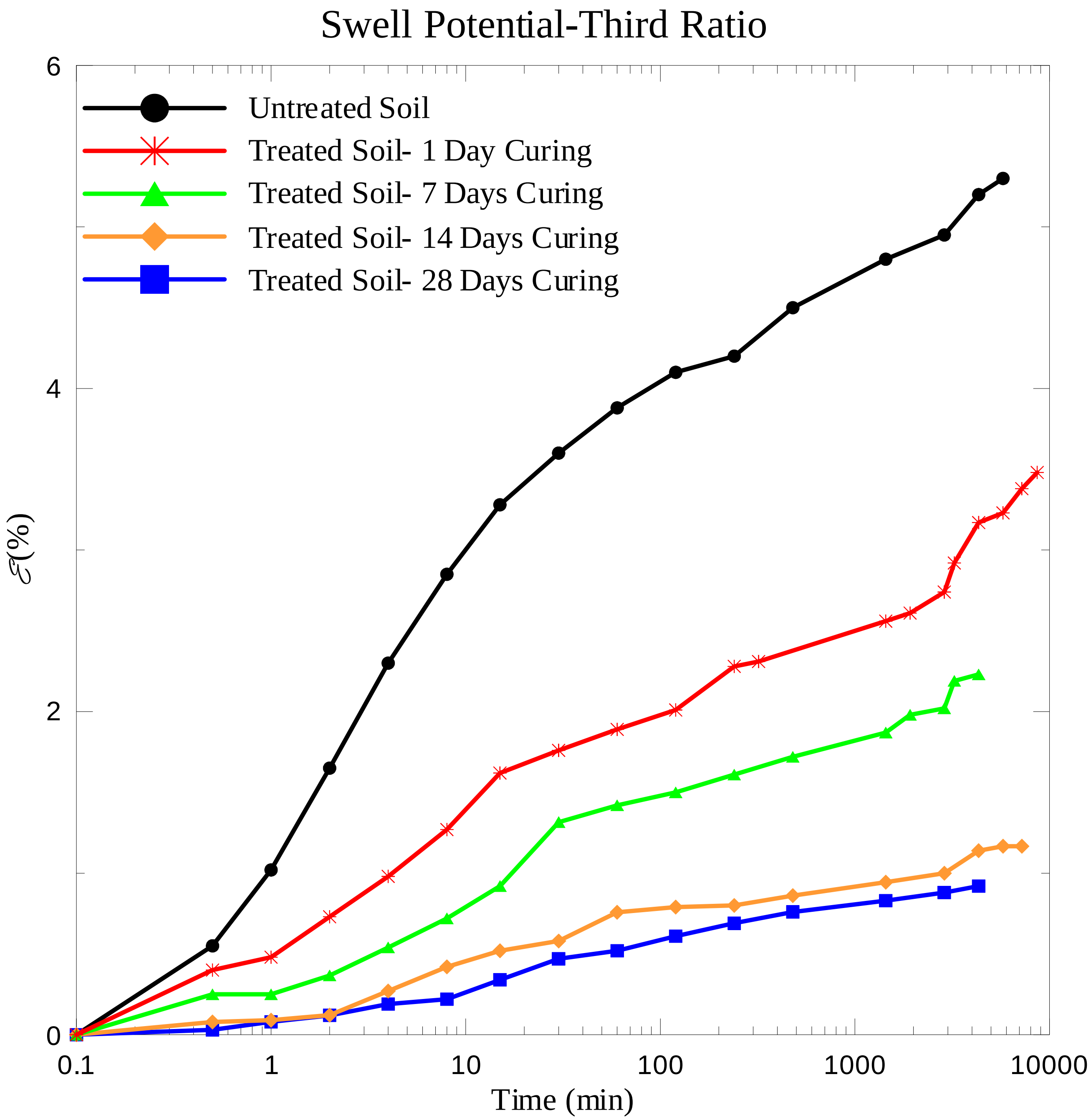


Figure 4. 11 Effects of different curing times on swell potential of treated soil

4.5.2 Effect of Different Dosage Rates on Swell Potential

The effects of dosage rates on swell potential can differ for a few different reasons. The first reason is based on the substantial reduction in soil PI. The PI for the third ratio was reported as 26, which shows a 45% reduction after treatment so the swell potential reduction reached its highest value in the third ratio compared to the first and second ratio. The second reason is the considerable reduction in CEC for the third ratio, which shows that the swell potential for this dosage should be less than other ratios. The quantity of negative charges in treated soil was reduced in CEC, which means the soil absorbed less water compared to treated soil with high CEC. The last reason is the increments of stabilizer usage, which cause a remarkable change in the thickness of the water film as the water doubles into two layers with electrical conductivity, which caused a reduction in the cation exchange capacity. Because as Tingle et al. (2007) explained, the mechanisms of ISS would be substantial for smaller clay minerals such as montmorillonite where the double layer water is significantly larger than montmorillonite particle size, and for this type of soil the main soil mineral is montmorillonite.

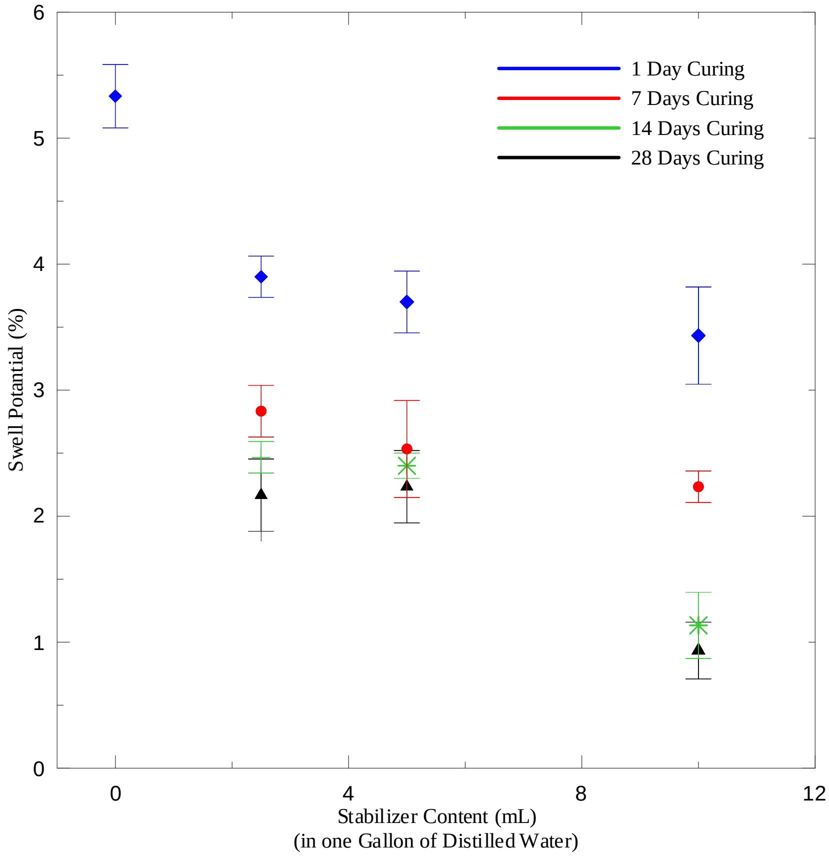


Figure 4. 12 Effect of different dosage rate on swell potential of treated soil

4.5.3 Swell Pressure

Swell pressure is the required pressure to prevent volume change of the sample, or the pressure that requires returning the specimen back to its original state after swelling **(**Som and Das, 2003). A number of studies have tried to developed methods to predict swell pressure either from laboratory tests or field measurements. Several studies argue that swell pressure depends on different factors including type of equipment, density, initial moisture content, and the clay friction (Katti et al., 1994). Therefore, due to the different moisture content and dry density of the prepared soil sample, the swell pressure varies under different ratios. The oedometer test method was performed for this research.

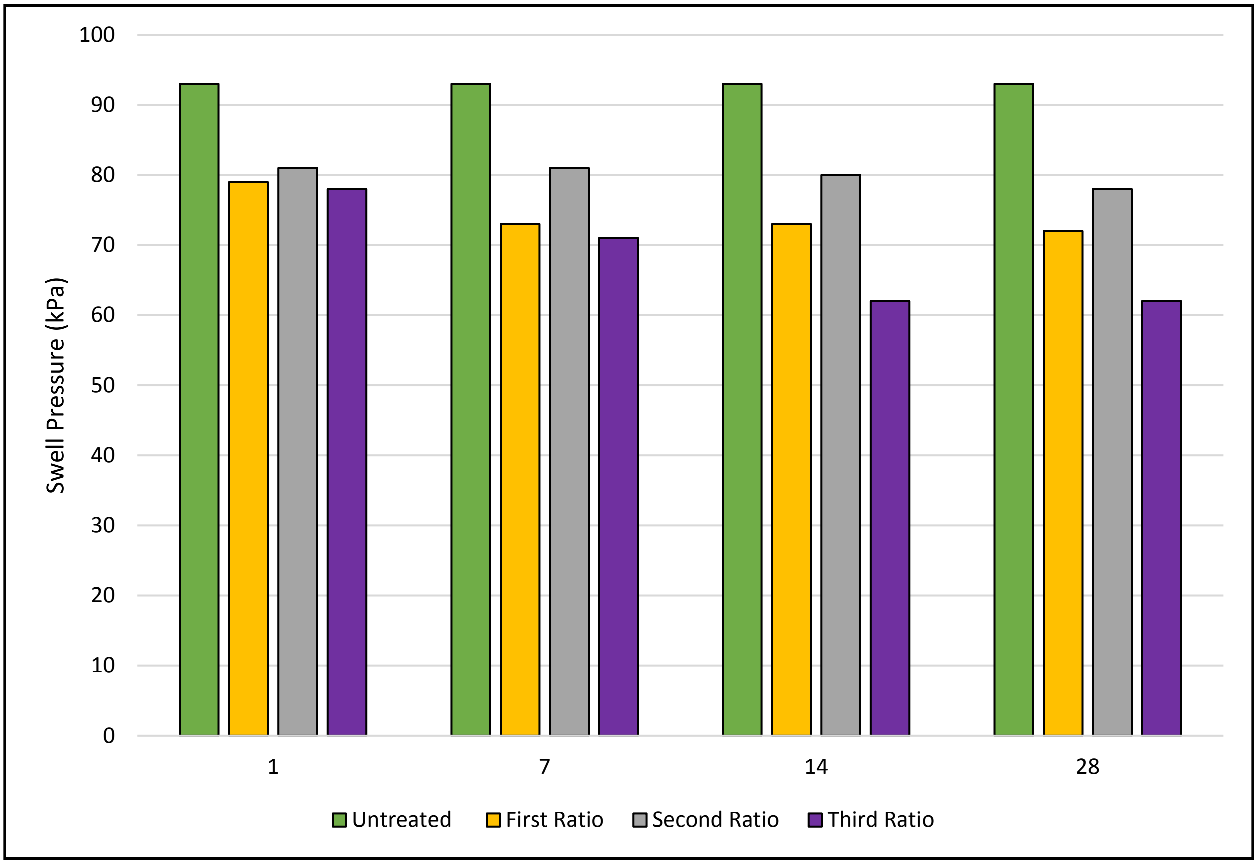


Figure 4. 13 Effect of soil stabilization on swell pressure of treated soil

4.6 Cation Exchange Capacity

Cation exchange capacity (CEC) was measured for untreated and treated soil samples for all three different dosages. As Drama (2005) demonstrated, the CEC is influenced by many factors; therefore, the operation must be strictly controlled to obtain creditable results. Table 4.9 summarizes the results obtained in this research.

Table 4. 5 Cation Exchange Capacity (CEC)

Soil Type	Spectrophotometer	Concentration of NH4-N	Dilution Factor	CEC
	Reading	Calibration curve (mg/L)		meq/100g
Untreated Soil	41.4	1.47	1000	163.5
Treated Soil- First Ratio	49.4	1.18	1000	131.6
Treated Soil- Second Ratio	44	1.38	1000	152.9
Treated Soil- Third Ratio	57.4	0.94	1000	105.0

As Table 4.9 shows, the CEC was reduced by adding stabilizer. And for the third ratio which has a high concentration of CEC is even lower. ISS can electrolyze cations with cations of clay fraction surface and anions with aluminum of clay particle and the anions can decrease the surface tension of water film and transform adsorbed water into free water. As Chittoori et al. (2013) stated, high CEC indicates the presence of clay mineral such as montmorillonite, whereas the low value shows the presence of nonexpansive clay such as kaolinite. Testing results indicate there is a remarkable decrease of cation exchange capacity in the soil pore water for all different dosages. This reduction will depress the double layer thickness, thereby reducing the swelling potential of soil, which forms a more stable clay structure. It is possible that lower cation exchange capacity leads to high shrinkage value due to the loss of water previously held by cations.

4.7 Specific Surface Area

A specific surface area test was performed on untreated soil. The soil sample for determination of SSA should be oven-dried. Treated soil cannot tested for specific surface area due to evaporation of the liquid stabilizer. Per the results, SSA is 197.46 m^2/g.

4.8 Total Potassium

TP testing was conducted on untreated soil to determine illite percentage. Since the concentration includes acids, treated soil mixture with other acids may indicate different results, which are not accurate. After heating the acid-soil mixture with HF and other acids, the dry sample was diluted in distilled water; then, using potassium indicators and a spectrophotometer, the amount of potassium was measured. By using the following equation, the amount of illite inside the soil sample was measured.

$$\%Tp = Concentration\ of\ K * 0.05$$

Table 4. 6 Determination of percentage of potassium

Soil type	**Transmittance**	**Potassium Conc.**	**Dilution factor**	**Potassium Conc.**	**% Potassium**
Untreated	51.8	4.192	5	20.96	1.048

4.9 Quantification Procedure

The following method is used to determine the concentration of laolinite, illite, and montmorillonite minerals within clay material. Direct measurements of the clay mineralogy utilizing X- ray diffraction (XRD) and a scanning electron microscope (SEM) are preferred. However, these tests are not practical for day-to-day use since they are expensive to perform and require advanced instrumentation. A set of simple indirect methods, such as cation exchange capacity (CEC), specific surface area (SSA), and total potassium (TP) are proposed to estimate the dominating clay minerals in the subgrades for day-to-day use. Illite percent is determined by the following equation.

To determine the percent of montmorillonite and percent of kaolinite, cation exchange capacity and specific surface area, Chittoori (2008) proposed the following equations:

$\%M = -2.87 + 0.08 * SSA + 0.26 * CEC$

$\%I = \frac{TP}{6} * 100$

$\%K = 100 - \%I - \%M$

Table 4. 7 Soil Mineralogy Determination

MINERALOGY						
Soil	TP	Percentage Illite	SSA	CEC	Percentage Montmorillonite	Percentage Kaolinite
		I (%)	(m^2/g)	(meq/100g)	M (%)	K (%)
Untreated	1.048	17.47	197.46	163.50	55.44	27.10

4.10 Soil pH Change

The effect of potential hydrogen (pH) ions is presented in Table 4.12 and Figure 4.22. The pH of soil is affected by several factors including nutrient availability, composition of the cation in the exchange complex, the solubility of cations and anions, the weathering of minerals, and microorganisms in the soil (Santoni et al., 2002). The untreated soil pH is measured as 7.25 and with the addition of the TX ProChem, the treated soil pH was reduced to 6.57 for the third ratio. As the table shows, the pH is 6.96 for the second ratio and the first ratio, which has 5 ml of concentration in one gallon of water. The reason for pH reduction is explained by removing cations (Mattsson 2002). According to CEC results, the third ratio has less cation exchange capacity and as a result, it should have less pH compared to others dosages. Therefore, the stabilizer has no considerable effect on pH.

Table 4. 8 Effect of Stabilizer on pH

Soil Type	pH
Untreated	7.25
Treated Soil- First Ratio	6.9
Treated Soil- Second Ratio	6.96
Treated Soil- Third Ratio	6.57

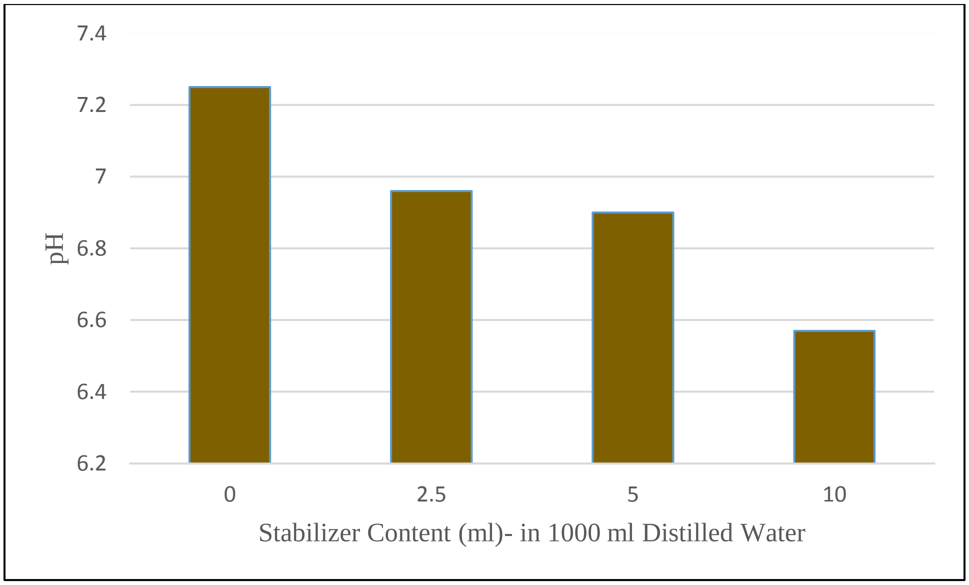


Figure 4. 14 Effect of different dosages on pH of treated soil

4.11 Summary Table of Test Result

The results of all tests performed in this work are summarized in following table.

Table 4. 9 Summary of test results

Test Name		Untreated	Treated		
			First Ratio	Second Ratio	Third Ratio
Liquid Limit (%)		76	72	79	69
Plastic Limit (%)		18	15	29	43
Plasticity Index		58	57	50	26
pH		7.25	6.96	6.9	6.57
Standard Compaction	Optimum Moisture Content (%)	30.9	32.9	31.8	32.60
	Maximum Dry Density (pcf)	85.7	82.5	84.8	83.5
Unconfined Compressive Strength (psi)	1 Day Curing	17	17	10.6	22
	7 Days Curing		17	10.8	26
	14 Days Curing		–	11.4	28
	28 Days Curing		15.8	13.3	28
Swell Potential (%)	1 Day Curing	5.5	3.6	3.88	3.5
	7 Days Curing		2.32	2.78	2.23
	14 Days Curing		2.32	25.0	1.1
	28 Days Curing		2.3	2.10	0.92
Mineralogy	Cation Exchange Capacity (meq/100g)	163.5	131.6	152.9	105
	Specific Surface Area	197.46	–	–	–
	Total Potassium (%)	1.048			

Chapter 5

Conclusions

Throughout this research study, the use of a liquid ionic soil stabilizer to treat expansive soil has been recognized, discussed, and analyzed. The research was focused on selecting a suitable dosage of ProChem based on the soil properties and its use to achieve the maximum strength criteria and minimum swell potential for the expansive soil. These objectives were determined by conducting various laboratory tests on soil specimens at different conditions of testing. The soil to be used in the analysis and designation of appropriate dosage were evaluated by conducting a series of strength and swell tests. Additionally, the mineralogy as well as the plastic characteristics of stabilized soil was studied by cation exchange capacity and Atterberg limit tests

The first task in this study was identified as determination of appropriate dosages of TX ProChem Soil Stabilizer needed to stabilize the expansive soil. For this purpose, three different dosages were identified and several laboratory tests was conducted on all the different dosages. For each ratio, the maximum dry density and optimum water content was obtained and then soil samples were prepared with respect to optimum water content and 95% of maximum dry density to stimulate the field condition. Unconfined compressive strength and one-dimensional swell tests were carried out on specimens from which the sufficient dosages were specified.

The second task was to evaluate the effect of different dosages on clay minerals. To achieve the best results. Mineralogy tests were conducted on the clay portion of the soil to measure cation exchange capacity (CEC), specific surface area (SSA), and total potassium (TP).

These properties were utilized to measure the percentage of montmorillonite, kaolinite, and illite minerals in the soil. It was assumed that the clay friction contained only these three common clay minerals. Therefore, other minerals presented in the clay friction were neglected and assumed to be zero for simplicity. Also, the effect of different dosages on CEC and pH of the different stabilized soil samples were noted in this study.

Finally, the following conclusions were drawn after the completion of the research work:

- Liquid ionic soil stabilizer reduces the plasticity index of expansive soil. The plasticity index had no consistent change in the first and second ratios, but addition of more stabilizer caused 45% reduction in PI.
- Maximum dry density of stabilized soil decreased whereas the optimum moisture content of treated soil increased, which may be attributed to soil modification such as a change in soil texture induced by cation exchange capacity.
- In terms of strength, stabilized soil specimens yielded the high strength. The soil strength decreased for the recommended dosage (5 ml concentrate, 0.057 g surfactant, and 1 Gallon distilled water) and the dosages which were diluted (5 ml concentrate, 0.057 g surfactant, and 2 Gallon distilled water). However, adding more stabilizer increased the strength up to 165% for treated soil after 28 days curing compared to untreated soil strength.
- In case of soil strength, specimens tested after 28 days of curing showed significantly high strength as compared with specimens tested after one day of curing period. As an example, the soil strength in third ratio (10 ml concentrate, 0.114 g surfactant, and 1 Gallon distilled water) obtained 78% increase after 28 days curing.

- The result of treated and untreated soil samples demonstrated a reduced swell potential for soil treated with liquid ionic soil stabilizer. To illustrate, in third ratio, after 28 days curing soil obtained 83% decrease in swell potential.
- The effect of different curing times on swell potential were studied in this research. It was observed that no significant change gained after 28 days of curing compared with one of day curing.
- Low additive dosages in soil could cause a relatively small cation exchange capacity which was evident when the treated soil showed less of a potential to swell.
- In terms of pH, soil specimens with low additive dosages had a high pH whereas adding more stabilizer caused a greater reduction in the pH of soil.

5.1 Recommendation for Future Research

- The method developed to identify the dominating clay mineral assumes that the clay fraction of the soil contains only the three common minerals, kaolinite, illite and montmorillonite, whereas in reality, other non-clay minerals such as quartz and feldspar are also present. Hence, studies should be focused to include one or two more parameters and account for the non-clay minerals.
- Nondestructive tests are recommended like the resonant column tests and resilient modulus tests on the soil specimens to provide more information about dynamic properties and to check the efficiency of the TX ProChem Soil Stabilizer on these properties.

- More tests like X-ray fraction could give us insights into the mineral modifications and serve as a critical technology to determine suitable dosages.
- Different type of soils with different PI must be tested to evaluate the TX ProChem performance

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Appendix A

This appendix presents all the tables created in this thesis research for analysis of standard compaction tests for untreated and treated soil samples.

Standard Compaction Test- Untreated Soil

Set	1	2	3	4	5
Weight of mold and base plate W_1 (lb)	9.354	9.354	9.354	9.354	9.354
Weight of mold and base plate + moist soil, W_2 (lb)	12.63	12.766	13.096	13.08	12.984
Weight of moist soil, W_2-W_1 (lb)	3.276	3.412	3.742	3.726	3.63
Moist unit weight $\gamma=W_2-W_1/(1/30)$ (pcf)	98.28	102.36	112.26	111.78	108.90
Weight can $_1$ (g)	26.4	35.3	35.3	35.2	20.7
Weight can $_1$ + wet soil (g)	119.8	128.3	141.2	146.9	157.9
Weight can $_1$+ dry soil (g)	103.8	109.8	116	116.9	117.4
Weight can $_2$ (g)	35.2	35.5	35.2	35.2	22.6
Weight can $_2$ + wet soil (g)	116.5	121	137.6	136.8	89.2
Weight can $_2$ + dry soil (g)	102.4	103.1	113.6	109.4	68.9
ω_1%	20.67	24.83	31.23	36.72	41.88
ω_2%	20.98	26.48	30.61	36.93	43.84
ω average%	20.83	25.66	30.92	36.82	42.86
γ_d (pcf)	81.34	81.46	85.75	81.70	76.23

Standard Compaction Test- Treated Soil- First Ratio

Set	1	2	3	4	5
Weight of mold and base plate W_1 (lb)	9.354	9.354	9.354	9.354	9.354
Weight of mold and base plate + moist soil, W_2 (lb)	12.63	12.9	13.038	13.076	12.87
Weight of moist soil, W_2-W_1 (lb)	3.276	3.546	3.684	3.722	3.516
Moist unit weight γ=W_2-W_1/ (1/30) (pcf)	98.28	106.38	110.52	111.66	105.48
Weight can $_1$ (g)	26.4	35.3	35.3	34.9	21.4
Weight can $_1$ + wet soil (g)	119.8	128.3	141.2	145	159
Weight can $_1$+ dry soil (g)	103.8	109.8	116	115	120.4
Weight can $_2$ (g)	35.2	35.5	35.2	35	25
Weight can $_2$ + wet soil (g)	116.5	121	137.6	137	90
Weight can $_2$ + dry soil (g)	102.4	101	110.1	110	70.2
ω_1%	20.67	24.83	31.23	37.45	38.99
ω_2%	20.98	30.53	36.72	36.00	43.81
ω average%	20.83	27.68	33.97	36.73	41.40
γ_d (pcf)	81.34	83.32	82.50	81.67	74.60

Standard Compaction Test- Treated Soil- Second Ratio

Set	1	2	3	4	5
Weight of mold and base plate W_1 (lb)	9.354	9.354	9.35	9.354	9.35
Weight of mold and base plate + moist soil, W_2 (lb)	12.63	12.766	13.08	13.08	12.80
Weight of moist soil, W_2-W_1 (lb)	3.276	3.412	3.73	3.726	3.45
Moist unit weight $\gamma=W_2-W_1/(1/30)$ (pcf)	98.28	102.36	111.78	111.78	103.38
Weight can $_1$ (g)	26.4	35.3	31.00	35.2	20.70
Weight can $_1$ + wet soil (g)	119.8	128.3	140.00	146.9	157.90
Weight can $_1$+ dry soil (g)	103.8	109.8	115.00	116.9	117.40
Weight can $_2$ (g)	35.2	35.5	32.00	35.2	22.60
Weight can $_2$ + wet soil (g)	116.5	121.4	140.90	136.8	89.20
Weight can $_2$ + dry soil (g)	100	103.1	113.34	109.4	68.90
ω_1%	20.67	24.83	29.76	36.72	41.88
ω_2%	25.46	27.07	33.88	36.93	43.84
ω average%	23.07	25.95	31.82	36.82	42.86
γd (pcf)	79.86	81.27	84.80	81.70	72.36

Standard Compaction Test- Treated Soil- Third Ratio

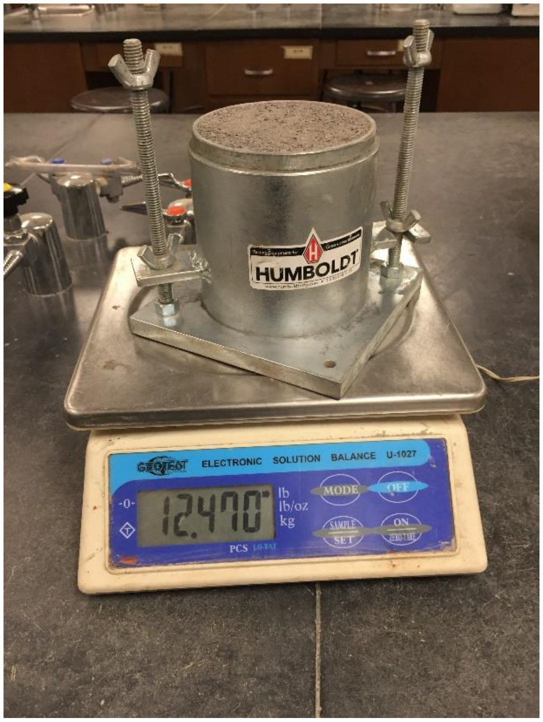
Set	1	2	3	4
Weight of mold and base plate W_1 (lb)	9.348	9.348	9.348	9.348
Weight of mold and base plate + moist soil, W_2 (lb)	12.916	13.06	13.002	12.870
Weight of moist soil, W_2-W_1 (lb)	3.568	3.712	3.654	3.522
Moist unit weight $\gamma=W_2-W_1/1/30$ (pcf)	107.04	111.36	109.62	105.660
Weight can $_1$ (g)	20.6	33.1	28.2	22.000
Weight can $_1$ + wet soil (g)	68.7	67.2	88.3	81.000
Weight can $_1$+ dry soil (g)	57.5	58.7	71.1	63.500
Weight can $_2$ (g)	23.9	17.2	32.8	22.600
Weight can $_2$ + wet soil (g)	56.9	48.8	72.8	69.400
Weight can $_2$ + dry soil (g)	49.3	40.9	61.2	54.010
ω_1%	30.35	33.20	40.09	42.169
ω_2%	29.92	33.33	40.85	48.997
ω average%	30.14	33.27	40.47	45.583
γd (pcf)	82.25	83.56	78.04	72.577

(A)

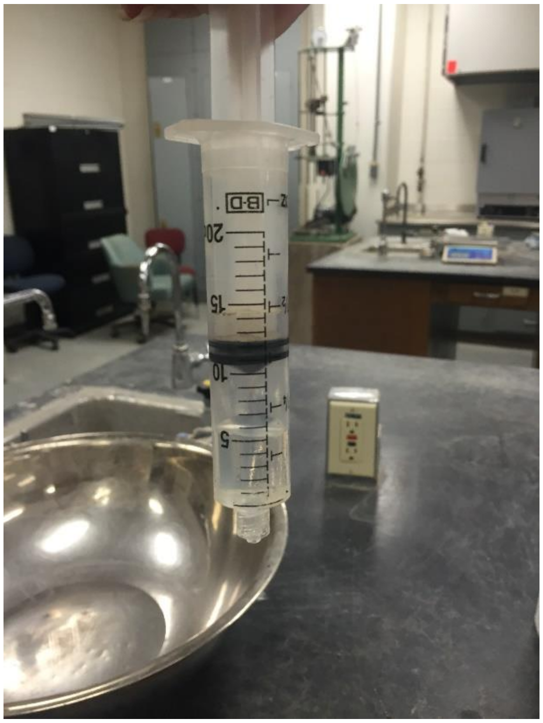
A) Weight 0.057 g of Surfactant

B) Measure 5 mL of Liquid Stabilizer

C) Weight the Mold and Compacted Soil



(C)



(B)

Appendix B

Field Applications

Chemical Application after Water injection

Steel Rod Holes for Chemical and Water Injection

Tank Contains Water and Chemical

Appendix C

Mineralogy

Cation Exchange Capacity- Untreated Soil

Cation Exchange Capacity- First Ratio

Cation Exchange Capacity- Second Ratio

Cation Exchange Capacity- Third Ratio