Geotechnical Investigation on Soil Properties Influencing the Swelling Characteristics of Expansive Soil

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ABSTRACT

Expansive soil which can be found in the semi-arid climates are considered to be one of the natural hazards due to its potential to change in volume when exposed to variations of moisture condition causing wetting and drying of the soil. These volume changes in soils affect the soil's engineering behavior causing serious structural damages for the light-weight structures above. The swelling of expansive soils is mostly affected by the vertical surcharge applied on the soil during saturation. In this experimental study, the effect of soil properties such as initial moisture content, dry density, applied surcharge, and pore fluid chemistry on the swelling behavior of expansive soil were studied and the effect of pore fluid chemistry on soil suction was discussed. In order to examine the one-dimensional swelling behavior of the expansive soil, specimens were compacted at different dry density values (1.18, 1.5, 1.6, and 1.82 g/cm^3) and mixed with different initial moisture contents (12%, 14%, and 16 %) under applied vertical stresses (0, 7, and 15 kPa). Moreover, soil suction test was performed using filter paper method considering different initial moisture contents (5%, 7%, 9%, 12%, 14%, 19%, and 20%). Measurement of soil suction by contact and non-contact filter paper placement method was applied to measure the matric and total suction values, respectively and then the soil-water characteristics curve of the expansive soil were drawn.

This study concluded that the increase of initial moisture content resulted in overall reduction of percent swelling and swelling coefficient in both primary and secondary swelling phases which resulted from the lack of empty pore spaces in the already water filled soil pores. The influence of increasing dry density showed a threshold value of

1.6 g/cm^3. Percent swelling increased at lower water content values below the threshold value and decreased at higher water content and dry density above the threshold value. Applying surcharge pressures restricted the uplift movement and resulted in lower swelling values for all cases. The obtained results indicated that mixing the soil with the seawater caused changes in the diffused double layer (DDL) thickness due to the reaction between the soil particles and the seawater. The compressed double layer generated a soil with a soil texture similar to the coarse texture and caused a significant reduction in soil particles water holding capacity. This resulted in a decrease in the swelling potential. Suction measurements of the soils mixed with distilled water and the seawater indicated a significant increase in the osmotic suction values of the soil mixed with the seawater. The air entry value, AEV of the soil mixed with the seawater had a lower AEV (92.35 kPa) than the soil mixed with distilled water (354.35 kPa) which was due to the weakened water storing capacity of the soil mixed with the seawater. Lower AEV of the soil mixed with the seawater indicated that higher pressure was needed for air to enter into the soil pores of the specimens mixed with distilled water.

Keywords: Air entry value, diffuse double layer, expansive soil, flocculation, suction, swelling.

ÖZ

Yarı kurak iklimlerde bulunan şişen zeminler, zeminin ıslanmasına ve kurumasına neden olan nem koşullarındaki değişikliklere maruz kaldığında hacim değiştirme potansiyeli nedeniyle doğal tehlikelerden biri olarak kabul edilir. Zeminlerdeki bu hacim değişimleri zeminin mühendislik davranışını etkiler ve üstlerindeki hafif yapılar için ciddi yapısal hasarlara neden olur. Islanma esnasında şişen zeminlerin kabarması en çok zemine uygulanan dikey sürşarjdan etkilenir. Bu deneysel çalışmada, başlangıç nem içeriği, kuru yoğunluk, uygulanan sürşarj ve boşluk suyu kimyası gibi zemin özelliklerinin şişen zeminin şişme davranışı üzerindeki etkisi incelenmiş ve boşluk suyu kimyasının zemin emmesi üzerindeki etkisi tartışılmıştır. Şişen zeminin tek boyutlu şişme davranışını incelemek için zemin numuneleri farklı kuru yoğunluk değerlerinde (1.18, 1.5, 1.6 ve 1.82 g/cm^3) sıkıştırılmış ve uygulanan dikey gerilmeler (0, 7 ve 15 kPa) altında farklı başlangıç nem içerikleri (%12, %14 ve %16) değerlerinde karıştırılmıştır. Ayrıca farklı başlangıç nem içerikleri (%5, %7, %9, %12, %14, %19 ve %20) dikkate alınarak filtre kağıdı yöntemi kullanılarak zemin emme testi yapılmıştır. Zemin emme ölçümü matrik ve toplam emme değerlerini ölçmek için sırasıyla temaslı ve temassız filtre kağıdı yerleştirme yöntemi uygulanmış ve ardından şişen zeminin toprak-su karakteristik eğrileri (SWCC) çizilmiştir.

Bu çalışma, başlangıçtaki nem içeriğindeki artışın, halihazırda suyla doldurulmuş zemin gözeneklerindeki boş gözenek boşluklarının olmamasından kaynaklanan, hem birincil hem de ikincil şişme aşamalarında, yüzde şişme ve şişme katsayısında genel bir azalma ile sonuçlandığı sonucuna varmıştır. Artan kuru yoğunluğun etkisi 1.6 g/cm^3'lük bir eşik değeri göstermiştir. Yüzde şişme, eşik değerin altındaki düşük su

içeriği değerlerinde artarken, eşik değerin üzerindeki yüksek su içeriği ve kuru yoğunlukta azaldı. Sürşarj basınçlarının uygulanması kabarma hareketini kısıtlamış ve tüm durumlar için daha düşük şişme değerleri ile sonuçlanmıştır. Elde edilen sonuçlar, toprağın deniz suyu ile karıştırılmasının, zemin partikülleri ve deniz suyu arasındaki reaksiyondan dolayı diffüz çift tabaka (DDL) kalınlığında değişikliklere neden olduğunu göstermiştir. Sıkıştırılmış çift tabaka, kaba daneli zemin dokusuna benzer bir zemin üretti ve toprak parçacıklarının su tutma kapasitesinde önemli bir azalmaya neden oldu. Bu da şişme potansiyelinde bir azalmaya neden oldu. Damıtılmış su ve deniz suyu ile karıştırılmış toprakların emme ölçümleri, deniz suyu ile karıştırılan toprağın ozmotik emme değerlerinde önemli bir artış olduğunu göstermiştir. Deniz suyuyla karıştırılan zeminin hava giriş değeri, AEV, deniz suyuyla karıştırılan zeminin zayıf su depolama kapasitesi nedeniyle, damıtılmış su ile karıştırılmış toprağa göre (354.35 kPa) daha düşük bir AEV (92.35 kPa) değerine sahiptir. Deniz suyuyla karıştırılan zeminin daha düşük AEV değeri, damıtılmış su ile karıştırılmış zemin örneklerinin gözeneklerine havanın girmesi için daha yüksek basınca ihtiyaç olduğunu göstermiştir.

Anahtar kelimeler: Hava giriş değeri, diffüz çift tabaka, şişen zemin, flokülasyon, emme, şişme.

DEDICATION

This achievement is dedicated to

My parents (Majed & Laila)
for their ever-present support

and

In the memory of my Uncle
(Amjad Hashish)

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I want to pay my special regards to Prof. Dr. Zalihe Nalbantoğlu Sezai for her continuous patience and guidance during the experimental and theoretical work to produce this thesis. She convincingly encouraged me to do right thing always and taught me how the professional work should be done. Without her invaluable help and advices the aims of this thesis would not be achieved. I was very fortunate to be one of her students. Also, I wish to acknowledge the invaluable advises and recommendations of my graduate committee, Asst. Prof. Dr. Eriş Uygar and Prof. Dr. Huriye Bilsel, which improved the quality of my research.

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I wish to acknowledge the great and unparalleled love and support of my family. I am forever indebted to my first and last supporter which is my father who gave me the opportunity and experience that have made me reach this stage. Also, I would like to express my deepest gratitude to my mother for her endless love and encouragements. Special thanks and appreciation for my sister, Ahlam who has been always there for me. Finally, I would like to express my love for my youngest brother and sister (Sameeh & Saba'), I hope one day, I can see both of you at this stage.

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LIST OF SYMBOLS AND ABBREVIATIONS

AEV	Air-entry Value
ASTM	American Society for Testing and Materials
A_2	Primary swelling coefficient
A_3	Secondary swelling coefficient
CEC	Cation exchange capacity
DDL	Diffused double layer
G_s	Specific gravity
h	Soil suction
LL	Liquid limit
MDD	Maximum dry density
OMC	Optimum Moisture Content
PI	Plasticity Index
PL	Plastic limit
SWCC	Soil Water Characteristics Curve
USCS	Unified Soil Classification System
w	Gravimetric water content
$H_\circ$	Soil specimen initial height
w_f	Filter paper water content
ΔH	Soil specimen vertical deformation

Chapter 1

INTRODUCTION

1.1 Background

One of the most problematic soils can be found in nature are the expansive soils. This kind of soil can experience volume changes in the presence of water. These volume changes occur as swelling and shrinkage behaviors which lead to noticeable deformations in soil layers (Estabragh et al., 2013). In the areas which are affected by wetting and drying processes, the presence of expansive soil becomes a serious issue due to its ability to cause damages to structures and foundations above. The arid and semi-arid regions go thorough cyclic wetting and drying states which makes these regions' soils tend to change in volume (Zumrawi & Abdelmarouf, 2017). The unique behavior of expansive soils comes from its mineralogical composition has a tendency for ion exchange with pore water (Khorshidi & Lu, 2017). Physical conditions such as moisture content and dry density also has a critical effect on the swelling behavior of expansive soils (Nagaraj et al., 2010).

Every year huge financial losses are reported in various parts of the world due to the presence of expansive soils. Considerable amount of pressure can be generated from the uplift movement of expansive soils which can cause serious structural damages in the form of cracks in structures' foundations, roads, and tunnels (Dhowian, 1990Wang et al., 2017; Ozer et al., 2012). Light structures are more likely affected by the uplift pressures caused by unpreferable volume changes of expansive soil. In the USA, statistics showed that the overall amount of financial losses due to expansive soil behavior on structures can reach millions of Dollars (Gourley et al., 2020).

The danger of the existence of expansive soils was first recognized by geotechnics in 1930. Since that time, different countries from all over the world are giving a huge attention to the undesirable movement of the ground caused by expansive soils. Countries like United States, Canada, and India work together to find out the best techniques to reduce the effect of expansive soils which the nearby structures and utilities cannot withstand (Chen, 1975). Many conferences were made to share knowledge and to achieve the best model which can identify the behavior of expansive soils.

Continuous investigations and studies are required to understand the unusual behavior of expansive soil in order to avoid or reduce the effect of swelling or shrinkage. These soils need to be tested appropriately to understand the factors affecting the volume change potentials which can lead to better view on how to treat these geotechnical and structural issues. Investigating expansive soils properties and classifications can produce more accurate predictions of the volume change potential (Puppala et al., 2013). Therefore, reducing the expected damages in terms of costs and time.

The mineralogical aspect is critical and must be taken into consideration while studying the unique behavior of expansive soils. The crystal lattice layers arrangement of clay particles which contains a significant amount of dissolved ions has a strong influence on the behavior of soil. In the case of expansive soils, these crystal layers have the ability to attract and retain water forming electrochemical attractions which can be termed as absorption (Panjaitan et al., 2013). Clay minerals such as montmorillonite has the ability of absorbing significant amount of water molecules which results in increasing the shrink-swell potential of the soil. When saturating the expansive soil, more water is retained between the clay sheets causing an increase in the bulk volume of the soil which called swelling. However, when water is released because of temperature change or drainage, the volume of the soil decreases which called shrinkage (Soltani et al., 2017; Viswanadham et al., 2009).

1.2 Objective of the thesis

The main objective of this study is to investigate the soil properties which may influence the geotechnical behavior of natural expansive soil. The laboratory investigations were done focusing on four main soil properties which are initial moisture content, dry density, applied surcharge, and pore fluid chemistry. Multiple amounts of soil specimens were prepared at different initial conditions considering a wide range of possibilities while measuring one-dimensional swelling and suction of the expansive soil. The main aim of the experimental work is to identify swelling behavior and soil-water characteristic curves for the expansive soil under investigation.

1.3 Thesis outline

This thesis includes five chapters. Chapter 1 contains the background information and the main objectives of this experimental investigation. Chapter 2 displays a literature review about the expansive soils main characteristics and represents the previous studies done on the factors affecting the behavior of expansive soils. Chapter 3 summarizes the followed methodology while testing the inspected soil in the laboratory and it shows the geotechnical classification of the tested soil. Chapter 4 contains the outcomes of the experimental work implemented on the inspected soil and the discussions of the results. Chapter 5 highlights the conclusions of this investigation and recommendations for further investigations can be done.

Chapter 2

LITERATURE REVIEW

2.1 General review of expansive soil

Expansive soils were categorized to be one of the problematic soils due to heave or settlement movements caused by changes in water content (Huang et al., 2019). These movements in expansive soils can generate an excessive amount of pressure and result in critical damages to the structures constructed on expansive soils. Expansive clays can be found in various parts of the world specially in arid and semi-arid regions which makes it a serious issue and the main concern of many researchers in the last eight decades (Alibrahim & Uygar, 2021; Bilsel & Tuncer, 1998; Nalbantoglu & Gucbilmez, 2001; Nalbantoglu & Tuncer, 2001).

Expansive soils are generally formed from rocks which contains expansive materials such as bentonitic mudstones, marls, argillaceous dolomitic limestones, and altered conglomerates (Al-Rawas & Qamaruddin, 1998). These expansive soils and rocks go into a noticeable amount of volume change when induced to wetting or drying conditions. Wetting and drying can take place several times due to seasonal changes during the year and a continuous volume change is expected in terms of expansive soils (Al-Mahbashi et al., 2021). Expansion and shrinkage in the soil layers can result in massive damages to the nearby manmade structures or naturally existing slopes (Yang et al., 2019). Many damages were noticed due to expansive soils in different countries such as (1) structural damages to buildings due to heave up movement (2) damage to underground pipelines (3) structural damages to retaining walls and foundations due to excessive pressures generated by expansive soils (4) reduction in slope stability due to reduction in shear strength (Patel, 2019).

Expansive soil was considered as a serious issue in terms of its ability to damage the nearby structures, especially the light weight structures (Nusier & Alawneh, 2004). These damages are mainly developed under the effect of the uplift forces generated in the expansive soil layers (Rogers et al., 1993). When soil expansion occurs it is difficult to predict the cracking pattern will occur on the structure. Figure 2.1 displays an example of cracking patterns due to soil expansion. Moreover, the damages can take place within a long-time range not just immediately (Shi et al., 2014). In some cases, damages start to be noticeable after 5 years unless the soil does not experience a significant change in moisture content (Zumrawi & Abdelmarouf, 2017). Figure 2.2 shows the effect of the pressure on buildings generated due to heave of expansive soils.

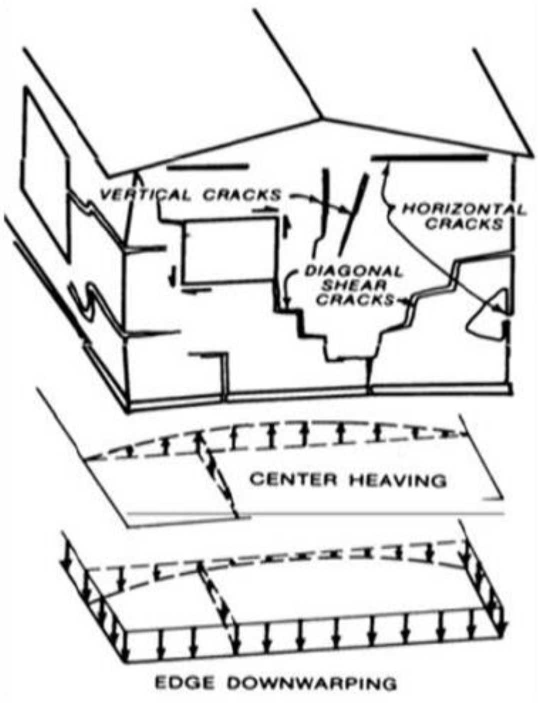

Figure 2.1: Cracking patterns developed on walls due to soil heaving (Delandro & Wickham, 1983).

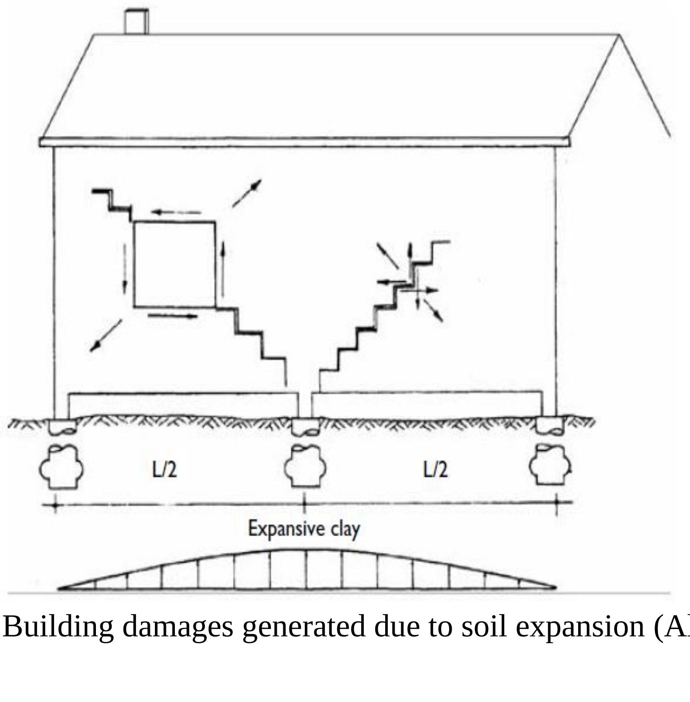

Figure 2.2: Building damages generated due to soil expansion (Al-Rawas, 1999).

2.2 Expansive soil mineralogy

The unique behavior of the expansive clay is highly related to the clay minerology and the amount of clay minerals which are sensitive to variations of moisture (Zhang et al., 2017). It was proven that the presence of montmorillonite is the main reason of the volume change in expansive soils after mineralogical studies (Al-Rawas, 1999). Studying expansive clays requires deep understanding of clay mineralogy and swelling mechanism in order to expect its swelling potential. Expansive clays contain the most common clay minerals such as kaolinite, illite, and montmorillonite. Among those the montmorillonite clay minerals cause swelling and shrinkage of soils through any change in water content. Expansion and shrinkage behaviors depend on the chemical structure of clay minerals which are sensitive to water content variations. The main factors considered in order to categorize clay minerals were inner structure and cation exchange capacity (Mitchell & Soga, 2005).

Clay minerals are formed of atoms arranged into tetrahedral and octahedral units (Mitchell & Soga, 2005). These units are bonded together to form sheet like structures as shown in Figure 2.3. The combination of these sheet like structures creates various kinds of clay minerals. Hence, clay minerals can also be categorized considering the layering pattern because minerals of the same layering pattern showed similar engineering characteristics (Maina et al., 2016). Clay minerals can be found in the form of two layers, three layers, or mixed layers.

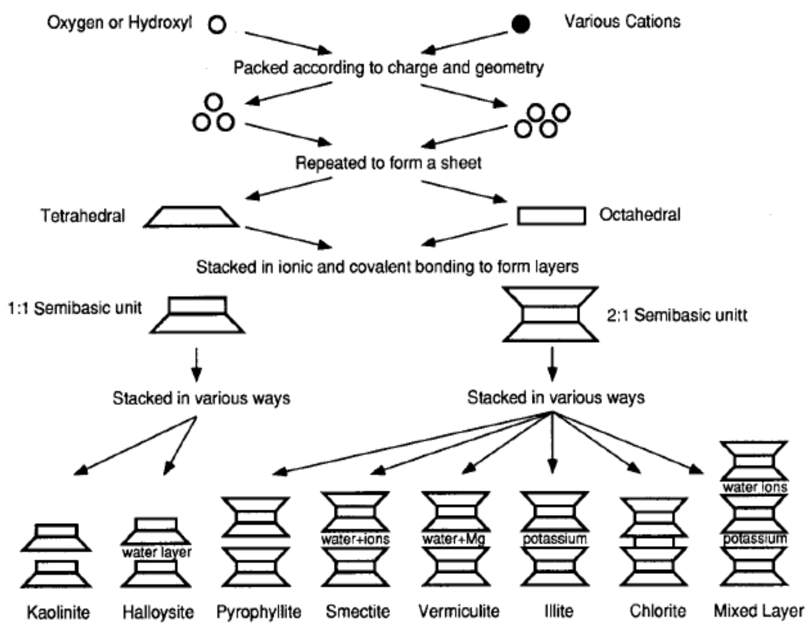

Figure 2.3: Clay minerals composition (Mitchell & Soga, 2005).

The smectite group in Figure 2.3 has a significantly high capacity of exchange cations which can generate an unstable mineralogical condition. Hence, soil swelling is expected in such clays. The expansion mechanism of expansive clays is associated with the existence of free cations which tend to be exchanged (Mehta & Sachan, 2017). However, different clay minerals have different amount of negatively charged particles which can be expressed as the cation exchange capacity CEC (Khorshidi & Lu, 2017). Table 2.1 summarizes CEC values of clay minerals (Drever, 1982).

Table 2.1: Cation exchange capacity of clay minerals (Drever, 1982).

Clay Minerals	Cation Exchange Capacities (meq/100g)
Smectities	80-150
Vermiculites	120-200
Illites	10-40
Kaolinite	1-10
Chlorite	<10

Clay particles sensitivity to water can be explained by the existence of exchangeable ions on the surface of clay particles (Keren & O'Connor, 1982). Das (2008) stated that the swelling of expansive clays can be explained by the concept of diffuse double layer, which explains the effect of the floating cations and anions around the clay particles as displayed in Figure 2.4. Water molecules are electrically acting like a rod which is charged with both negative and positive charges resulting from the unsymmetrical arrangement of hydrogen atoms around the oxygen atoms as Figure 2.5 shows the dipolar nature of water molecules.

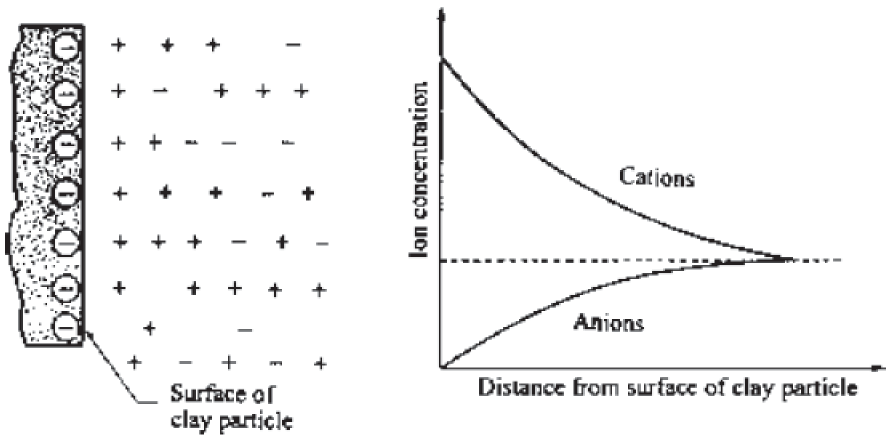

Figure 2.4: Diffuse double layer (Das, 2008).

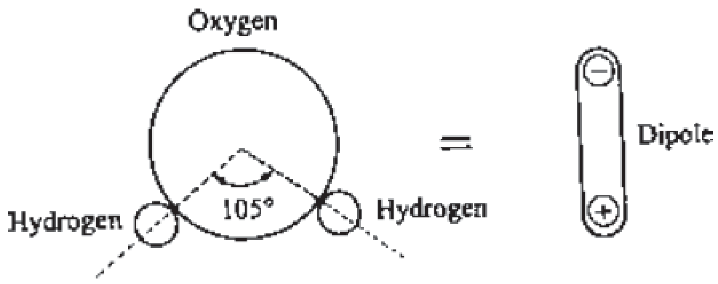

Figure 2.5: Dipolar nature of water molecules (Das, 2008).

The attraction forces between the water molecules and the charged surface of clay particles create a water layer which surrounds the clay particle called double-layer water (Das, 2008). The existence of double-layer water is the reason of the plastic nature of clayey soils and the thickness of water layer significantly affects the characteristics of expansive soil.

2.3 Classification of expansive soils

Expansive soils can be categorized using clay size fraction percentage which is determined by performing sedimentation analysis (Asuri & Keshavamurthy, 2016). Clay fraction percentage can be defined as the percentage of the amount of fine grains (i.e., < 0.002 mm size) to the whole soil mass. Table 2.2 classifies expansive soils based on clay size fraction.

Table 2.2: Expansivity due to clay size fraction (Asuri & Keshavamurthy, 2016).

Degree of expansivity	Clay size fraction (%)
Very high	>95
High	61-94
medium	30-60
low	< 30

2.4 Factors affecting expansive soils properties

Chen (1988) stated that the process of monitoring swelling of expansive soils is highly affected by different physical and environmental factors. These factors are significantly important to be taken into consideration while assessing the behavior of expansive soils. Various factors can impact the expansivity or shrinkage of expansive clays which can be grouped as (1) factors influencing the internal stress state of the soil, (2) surrounding environmental effects on the soil's internal stress conditions, (3) the applied stress conditions (Elarabi, 2015).

Studying the behavior of expansive soils should be correlated with both the environmental conditions and soil properties such as (1) initial water content, (2) initial dry density, (3) applied axial stress (surcharge), (4) soil suction and (5) pore fluid chemistry. Taking these factors into consideration can help understanding the behavior of expansive soils during different conditions and scenarios (Mokhtari & Dehghani, 2012).

Initial water content has a significant effect on swell characteristics of expansive soils (Driss et al., 2021; Y. Li et al., 2021; Meshram et al., 2021; Niu et al., 2021). The effect of water content on expansive soils was examined in previous studies and it was proven that soil samples with lower water content tend to experience higher values of expansion (Huang et al., 2019; Karumanchi & Mandal, 2020; Rank et al., 2015). The increase in swelling occurs due to the excessive amount of micropores in dry soil which can absorb water generating tension forces between small areas within soil aggregates (Smucker et al., 2007). Udukumburage et al. (2005) investigated the effect of initial water content on compacted grey vertosol mixed with different water content percentages (15%, 20%, and 25%). Consolidation apparatus was used to detect the vertical deformation of the samples and the swelling was allowed for 48 hours. Results showed a linear relationship between the initial water content and swelling strain for all samples. Highest swelling strain values was recorded for the samples with 15% moisture content and lower swelling strain values were measured for the samples with 20% and 25% moisture content. Those findings can be explained by the impact of initial moisture content on the microstructure of soil. Samples prepared at lower initial moisture content contain more micropores which can be filled with water and lead to higher swelling strain values. At higher water content, small soil particles can be transferred to fill the pores between larger particles which result in densifying the soil and reduction in micropores capacity to retain water (Yin et al., 2018).

Soil dry density illustrates the ratio between mass of dry soil and the total volume of soil. The soil compaction is the main condition which can produce a certain dry density value (Elkady et al., 2017). In terms of expansive soils, dry density has a serious effect on swelling potential due to the variations in volume of voids occurring when soil is being compacted to a different dry density value. Huang (2019) studied the influence of dry density on total swelling strain of expansive clays collected from Hubei city in China. Soil samples were mixed with different moisture contents (10.10%, 12.85%, 15.8%, 18.3 and 22.19%), and then compacted using a specially designed mold to reach three different dry density values (0.14, 0.15, and 0.16 kN/m^3). The compacted soils at different density values were installed into the oedometer ring allowing the samples to deform vertically. In the oedometer apparatus, the vertical deformation values were recorded using a dial gauge and samples were allowed to swell and reach the maximum possible vertical deformation. The graphical relationship between dry density and total swelling strain for each initial water content was conducted using the vertical deformation values from the oedometer. Samples with initial water content less than 18.3% showed a slight expansion when compacted to lower dry density, but more expansion was noticed when compacted to higher dry density. At lower initial water contents, swelling strain was significantly affected by the dry density. This can be explained by the increment of the amount of soil particles per unit volume when increasing the dry density result in more swelling deformation for samples mixed at identical moisture content (Nagaraj et al., 2010). It was found that the increase in initial water content limits the vertical deformation of expansive soils (Villar & Lloret, 2008).

In nature, expansive soils can exist in layers which have been affected by external pressure. This pressure can significantly affect the expansion characteristics of expansive soils (Bensallam et al., 2014; Udukumburage et al., 2005; Zou et al., 2020). Zou et al. (2020) suggested that the swelling pressure generated in expansive soils due to wetting must reach a certain level to exceed the external applied pressure and cause in volumetric changes. Moreover, the applied vertical stress on soil has the ability to restrict swelling if it reaches larger value than the expansion pressure produced between the soil particles. On the other hand, the excessive increase in the externally applied vertical stress can lead to soil collapse (Pedarla et al., 2012).

2.5 Soil suction

Soil suction values show the negative pore pressure generated inside the soil pores happening between the saturated and unsaturated soil layers (Lu, 2016). Water is drawn up through the empty pores of the soil due to the capillary action (Likos, 2010). Soil suction measurements provide an indication of hydraulic conductivity of the expansive soils, where the volume changes is depending on the attraction forces between the clay minerals and pore fluid generating due to the presence of dissolved salts (Fattah & Ali, 2014). The appearance of soil cracking under drying conditions was known to be resulted by soil suction (Auvray et al., 2014; Fredlund et al., 1993; Rosenbalm & Zapata, 2017). Different researchers proposed the idea of relating soil suction measurements with the expansive characteristics of soils (Thyagaraj & Rao, 2010).

Tahasildar et al. (2018) attempted to develop a model to specify the relationship between swelling characteristics with other soil properties which are plasticity index, moisture content, dry density, and soil suction. Oedometer test was used to measure swelling of the soil at different initial conditions of water content and dry density. Suction measurements were found using a dew point potentiometer (WP4) which can measure suction values up to 300 MPa. This device collects different data from the sensors and translate it to a pressure value which is suction in MPa. Different trails were done on a wide range of initial water contents and dry densities in order to have enough data to construct an artificial neural network (ANN) model (Park & Lee, 2011). Findings of the study showed a linear relationship between suction values and swelling potential. Low dry density samples which have a higher volume of voids have the ability to expand more than high dry density samples (Komine & Ogata, 1999). In general, soil swelling happens when water is being absorbed and filled between soil particles. However, when the soil pores are already filled with water, limited swelling values are attained (Rank et al., 2015). This explains the increment in swelling potential when soil suction increases as a decrease in moisture content.

Expansive soils are sensitive to moisture variations. However, the nature of the moisture induced is a serious issue in terms of suction and swelling investigations. Yukselen-Aksoy et al. (2008) stated that pore fluid chemistry directly affects the absorption process occurring in clay soil by decreasing the layers thickness of clay particles which consequently reduces the fluid retaining capacity of the soil particles (Estabragh & Moghadas, 2013). It was found that high ionic concentration fluids such as seawater can result in a significant settlement of expansive soils by affecting the diffused double layer thickness around the clay particles which reduces the hydraulic conductivity of the soil particles (Pulat et al., 2014).

2.5.1 Measurement of soil suction by filter paper method

Filter paper method has the widest possible range of measuring suction pressures (0 to 30,000 kPa) comparing to other methods such as tensiometer or pressure plate apparatus (Fondjo et al., 2020). Filter paper method allows the measurement of both matric and total suction values of the soil at the same time with different location of filter paper installations. The contact filter paper technique was applied for the measurement of matric suction whereas the non-contact filter paper technique was used for total suction measurements as shown in Figure 2.6.

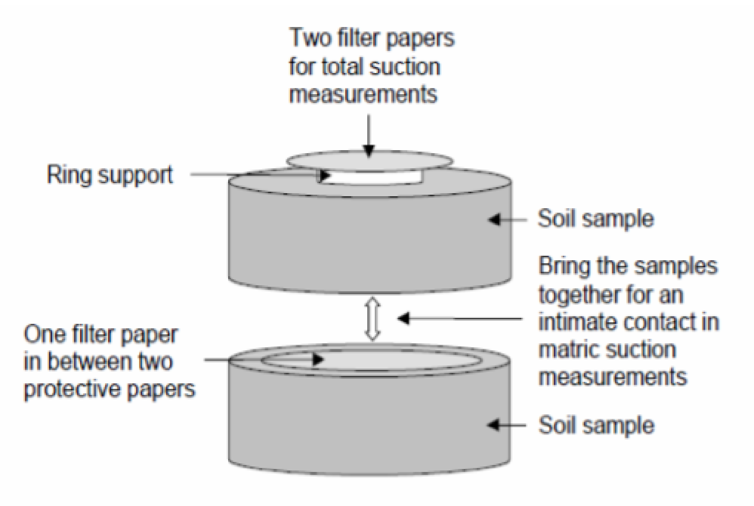

Figure 2.6: Total and matric suction measurements (Bulut et al., 2001).

There are number of ash-less filter papers available but only Whatman 42 filter paper and Sleicher and Schuell 59s are commonly used for the measurement of soil suction. When using Whatman No.42 filter papers for measuring soil suction, soil suction can be calculated by using Equation 2.1 and Equation 2.2 according to (ASTM D5298-16) standard.

For $w_f < 45.3$ $\qquad h = 5.327 - 0.0779\, w_f \qquad$ (2.1)

For $w_f > 45.3$ $\qquad h = 2.412 - 0.0135\, w_f \qquad$ (2.2)

Where:

h: Suction, pF

w_f : moisture content of filter paper, g.

Figure 2.7 shows the preparation of soil samples for mesuring soil suction (Figure 2.7 a, b and c). Measurement of soil suction by contact filter paper placement (for measuring matric suction) and non-contact filter paper placement (for measuring total suction) was shown in Figure 2.7 (d) and (e).

(a) *(b)* *(c)* *(d)* *(e)*

Figure 2.7: Soil suction measurements using filter paper method. Measurement of filter paper mass using sensitive scale. *(b)* Containers sealing using electrical tape *(c)* Styrofoam boxes used for storing. *(d)* Contact filter paper placement. *(e)* Non-contact filter paper placement.

Soil suction is considered as a valuable parameter which can describe the moisture condition of unsaturated soils (Gray & Graham, 2015; Fattah et al., 2017; Dong & Lu, 2021). Total soil suction is a general term which is the summation of matric and osmotic suctions. In terms of matric suction, the controlling factor is the variation of the capillarity action and the surface absorption forces of the soil, but osmotic suction depends on the amount of dissolved salts in the pore fluid (Fredlund et al., 1993).

Pulat et al. (2014) investigated the effect of pore fluid on swelling and suction of clay soils. Six different clay types were used for testing and mixed with two different fluids which were distilled water and seawater. Soil suction estimation was done following filter paper method with two different techniques (contact and non-contact) to find out the matric and total suction values. The study indicated that matric suction values for both fluids were the same which means that matric suction does not depend on the ion concentration of the used fluid.

2.5.2 Soil water characteristic curve (SWCC) and the air entry value (AEV) of soil

SWCC is commonly used to describe the water reserving capability of soil under different soil suction values, which is used to predict different soil characteristics such as shear strength, volume change potentials, hydraulic conductivity, and soil compressibility (Saha et al., 2016). Soil water characteristics curve, SWCC can provide a simulation of both wetting and drying paths of soil when moisture content increases (adsorption) and decreases (desorption), respectively. The slope of SWCC and air-entry value (AEV) were the main studied parameters which can describe the suction properties of the inspected soil. Air-entry value can be defined as the suction value where air starts entering into soil pores, and it is the point where the desaturation starts (Li et al., 2020). SWCC slope identification can illustrate the sensitivity of the inspected soil to moisture content variations (Zhang et al., 2018).

This study concentrates on one-dimensional swelling measurement for compacted specimens with varying initial water content, dry density, and vertical applied stress using oedometer apparatus. Also, soil suction is measured using filer paper method (contact and non-contact). The study also investigates the impact of chemical nature of pore fluid on swelling and suction measurements. Distilled water and seawater will be used, and a comparison will be made between the effect of both fluids.

Chapter 3

MATERIALS AND METHODS

3.1 Introduction

This experimental study aims to investigate the soil properties which may have an impact on the volume change properties of expansive soils. Different geotechnical properties were examined using diverse values of initial conditions in order to investigate the effect of initial moisture content, dry density, applied surcharge, and pore fluid chemistry on the swelling properties of soils. The aforementioned soil properties were studied considering various wetting, compaction, and applied stress conditions in different patterns in order to have a wider understanding of expansive soil behavior. Swelling measurements were done using three different moisture contents (12%, 14%, and 16%) which represent the dry portion of the compaction curve obtained in the modified Proctor compaction test. The dry density values corresponding to these water content values were also chosen from the dry portion of the compaction curve obtained from the modified Proctor compaction test, which were (1.18, 1.60, and 1.82 g/cm^3). The prepared soil specimens were put under different stress conditions to test the impact of putting specimen under applied surcharge on soil swelling. The chosen surcharge values were (0, 7, and 15 kPa). Moreover, soil suction measurements were done in order to analyze the soil-water characteristics of the tested expansive soil. The effect of pore fluid by using distilled and seawater on the swelling properties of the expansive soil was also investigated.

3.2 Expansive soil

The tested expansive soil was obtained from the South Campus of Eastern Mediterranean University in Famagusta, North Cyprus. In order avoid the organic soil such as the tree toots or any artificial materials, the top soil was removed, and the test soil was taken from a depth of approximately 2 m from the ground surface. Figure 3.1 displays the soil extraction from the chosen location. The obtained soil sample was dried using oven with 50°C for three days and then pulverized and stored in the oven. Physical and chemical tests were performed in order to classify the selected soil. Referring to the Unified Soil Classification System (USCS) and, considering the soil properties stated in Table 3.1, the tested soil was classified as highly plastic silty clay, MH-CH. The in-situ moisture content, *w* and the dry density of the obtained expansive soil was determined to be 22% and 1.61 g/cm^3, respectively.

Table 3.1:Inspected soil's physical and chemical properties.

Properties	Inspected soil
Clay size fraction content (< 2 µm) (%)	56.82
Silt size fraction content (2 µm – 74 µm) (%)	43.04
Sand size fraction (> 74 µm) (%)	0.14
Specific gravity, (Gs)	2.79
Liquid limit, LL (%)	61
Plastic limit, PL (%)	31.8
Plasticity Index, PI (%)	29.2
Linear shrinkage, LS (%)	15
Soil Classification	CH-MH
pH	7.05
In-situ moisture content, w (%)	22
In-situ dry density, (g/cm^3)	1.61

Figure 3.1: The extraction of expansive soil from selected location in South Campus (35°08’51.2” N, 33°54’14.0” E).

3.3 Experimental methods

This experimental research was done in order to investigate the effect of different initial soil conditions on the swelling characteristics of expansive soils. Different tests were performed following the American Society for Testing and Materials (ASTM) standards except the linear shrinkage test which was performed by using the British Standard BS-1377; 75. Modified Proctor compaction test was performed in order to determine the moisture contents and the corresponding dry density values on the dry side of optimum moisture content of the compaction curve under which soil swelling tests were performed. One-dimensional swelling test by using the oedometer test apparatus was done to measure the percent swell of soil specimens with various initial conditions and applied stress values. Moreover, soil suction measurements were performed to evaluate the impact of initial soil conditions on the inspected soil suction and generate soil water characteristics curves (SWCC) under these conditions. In total, 1 compaction test, 39 one-dimensional swell tests, and 14 soil suction tests were performed.

3.3.1 Modified Proctor compaction test

For obtaining the compaction characteristics of the inspected soil, Proctor compaction test using modified effort was performed in accordance with ASTM D1557-12. The modified compaction test was done with the modified compaction effort of $2700\ kN - m/m^3$, and the applied compaction energy was 2693.3 kJ/m^3. The compaction hammer weight used was 4.54 kg and dropped from 45.7 cm height. The main advantage of using modified compaction effort which is considered as heavy compaction is the ability of achieving higher dry density values, subsequently higher swelling can be achieved, and the soil behavior can be better analyzed. Many researchers adopted this method specially for studying the behavior of low to medium swelling soils (Emarah & Seleem, 2018; Rao et al., 2001; Sridharan & Gurtug, 2004). At higher density values, the amount of soil particles per unit volume is increasing which generates a more sufficient reactions between soil particles and water, also the voids overall volume decreases and expansive strain of soil increases (Du et al., 1999; Huang et al., 2019; Hussain, 2017; Nowamooz & Masrouri, 2010).

Oven-dried soil was sieved using No.4 (4.75 mm) sieve to eliminate the over-sized particles and then the soil particles passing No.4 sieve was mixed with different percentages of distilled water. The soil-water mixtures were then left in a desiccator for 24 hours to establish a homogenous percentage of the added water in all parts of the soil. Five different water contents were tested (12, 15, 17, 18, 20, and 24%). The mixed soil was compacted into five different layers in the compaction mold by applying 25 blows for each layer to ensure the consistency of the compaction process. Masses and volumes of the compacted soil were measured using a scale, and then the corresponding densities were calculated. Figure 3.2 displays the used compaction apparatus.

Figure 3.2: Proctor compaction apparatus used during the experiments.

3.3.2 One-dimensional swell test

A series of one-dimensional swell test performed to measure the swell % of the expansive soil following the experimental procedure provided by ASTM D4546-14. Soil specimens were mixed at three different distilled water contents (12%, 14%, and 16%) and dry densities (1.18, 1.60, and 1.82 g/cm^3) based on the values obtained from the compaction curve which were on the dry side of the compaction curve including the optimum moisture content and maximum dry density. The compacted soil specimens under different water contents and dry densities in the compaction mold were extruded into the consolidation rings. The metal ring dimensions were 50 mm diameter and 20 mm height. All specimens were cut to be 15 mm height in order to allow the swelling to take place freely.

Soil specimens rings were placed in the swelling cells between two porous disks to ensure the consistency on the moisture flow during the tests. Filter papers were used to cover the soil specimens from both sides to avoid clogging the porous discs. Specimens were saturated under three different applied surcharges (0, 7, and 15 kPa). The swelling readings of soil Specimens at different time intervals were detected using one dimensional consolidometer connected to a computer. Specimens were left to swell for 9 days, where the change in the last two readings was 0.01 mm. Percent swell was calculated using Equation 3.1. Figure 3.3 shows the followed test procedure for measuring the percent swell of the examined soil.

$$\text{Swell } \% = \frac{\Delta H}{H_0} * 100 \tag{3.1}$$

Where,

ΔH: Vertical deformation of the soil specimen

H_0 : Initial height of the soil specimen.

Figure 3.3: Specimen preparation for one-dimensional swell test.

3.3.3 Soil suction measurements

Soil suction tests were performed using the filter paper method in accordance with ASTM D5298-16, which allows the measurement of both matric and total suction values of the soil at the same time with different location of filter paper installations.

In the present study, soil samples were mixed with specific water contents (5%, 7%, 9%, 12%, 14%, 19%, and 20%) and then compacted mechanically then the compacted soil specimens were cut into two equal parts and placed in a container and then the filter papers were placed in contact and non-contact conditions in the soil specimens to measure both total and matric suction. For measuring the matric suction, a good close contact was provided between the filter paper and the soil specimens in the container and non-contact filter paper was provided to measure the total suction by placing the filter paper on a plastic ring without any direct contact with the soil specimen. Very good sealing was provided to avoid any vapor effect from the surrounding environment to the soil specimens by using an electrical tape surrounding the whole perimeter of the containers. Containers were stored in Styrofoam boxes to control the temperature deviations. Soil specimens in the containers were left in the Styrofoam boxes to reach equilibrium for at least 14 days.

3.3.4 Pore fluid chemistry testing

The second pore fluid used in this study was the seawater which was collected from the Mediterranean Sea on the coast of Famagusta. Before testing, the seawater was filtered to remove all the contaminants such as sea plants or sea sand from the water. Seawater effect on suction and swelling of the inspected soil was considered in this experimental work. Soil specimens were mixed with three different seawater contents (12%, 14%, and 16%) and the same test procedures were applied using one-dimensional swell apparatus. The same dry density values as with distilled water were used for all soil specimens and percent swell was measured and calculated. Whereas soil suction measurements were conducted using different percentages of seawater such as 12, 15, 17, 18, 20, and 24% mixed with the inspected soil. Filter paper method was used to measure both total and matric suction of the soil specimens. In the present study, swelling and suction results obtained by using both distilled water and seawater were compared and discussed.

Chapter 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter examines the effects of various soil properties on the swelling and soil suction properties of the inspected soil. The detailed testing programs showed the effect of the initial water contents, dry densities, applied surcharge pressure (vertical stresses), and the pore fluid chemistry on the swelling properties of the experimented expansive soil.

4.2 Engineering and index properties of the natural expansive soil

This section presents the results of the engineering properties of the natural expansive soil. The index properties were identified in order to classify the selected soil.

4.2.1 Hydrometer analysis

Figure 4.1 presents the results of the hydrometer test conducted on the expansive soil. As observed from the graph presented, the natural expansive soil comprises < 1% content of sand, 43% content of silt, and 57% content of clay size particles. The test results showed that expansive soil contains fine-grained soil particles of clay and silt greater than 50% by dry weight.

4.2.2 Atterberg limit of the obtained expansive soil

Atterberg limits of the studied soil were found as 61% for the liquid limit (LL) and 31.8% for the plastic limit (PL) and the plasticity index (PI) was calculated as 29.2%, shown in Figure 4.2. The results showed that the expansive soil was located very near below the A-line and it contains more than 50% of clay size particles so, it could be a CH-MH soil; highly plastic silty clay.

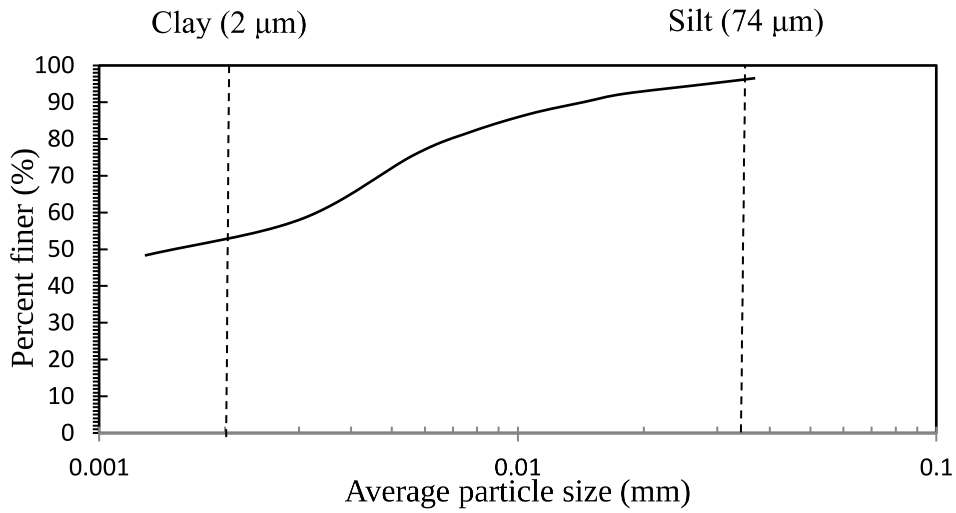

Figure 4.1: The natural expansive soil's hydrometer analysis.

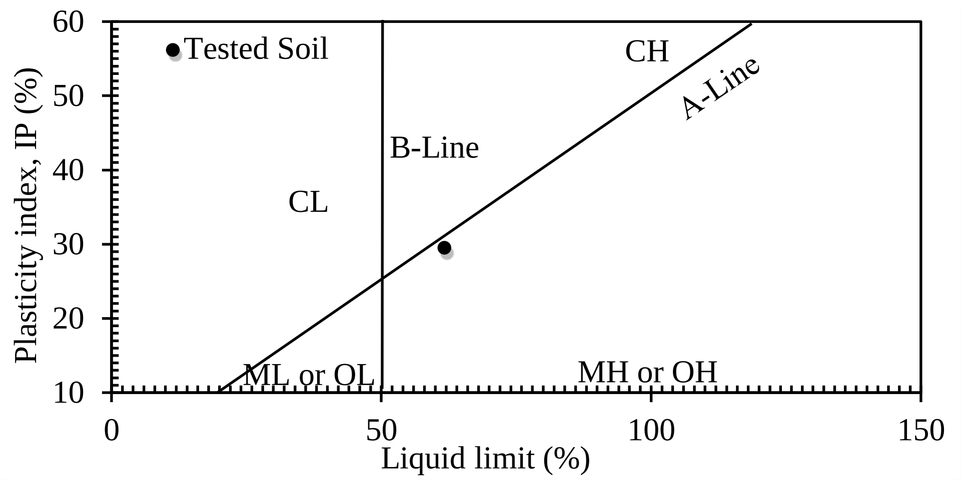

Figure 4.2: Plasticity chart (USCS) of the natural expansive soil.

4.2.3 Modified Proctor compaction test

The test results demonstrated by Figure 4.3 show the expansive soil's compaction characteristics. Based on the modified Proctor compaction test results, the maximum dry density (MDD) and optimum moisture content (OMC) values were found to be 1.82 g/cm^3 and 16%, respectively.

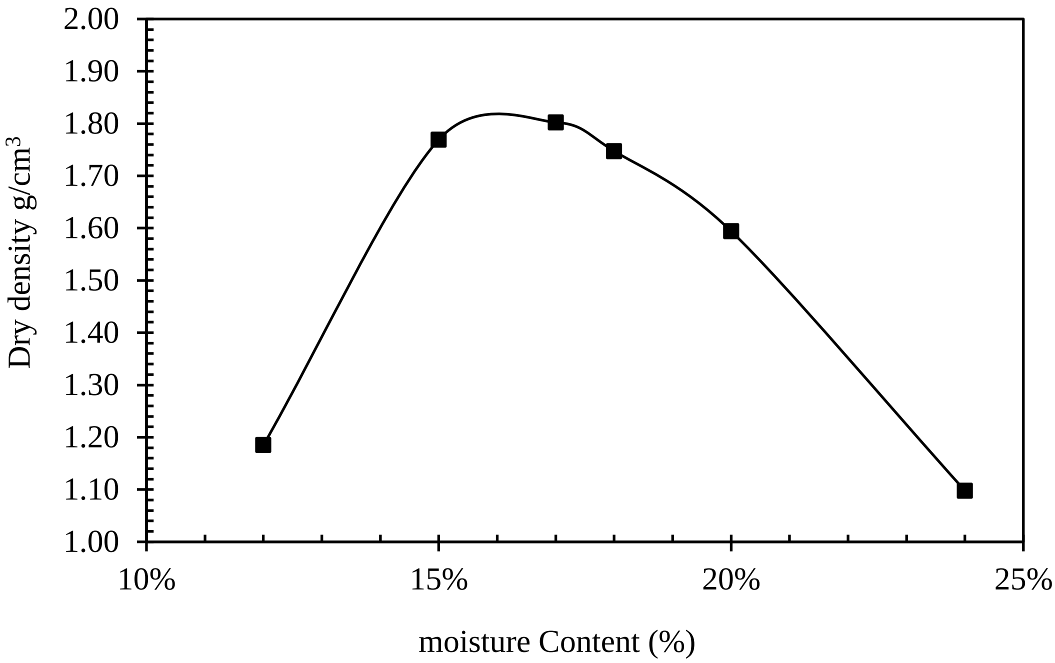

Figure 4.3 : Compaction curve of the natural expansive soil.

4.2.4 Percent swelling of the expansive soil using in-situ conditions

In one dimensional swell test, the vertical deformation readings of the natural in-situ soil were measured. Figure 4.4 presents the swelling curve for the natural expansive soil using the in-situ conditions. It can be seen that the peak value of percent swelling of the natural expansive soil found to be 9.2%.

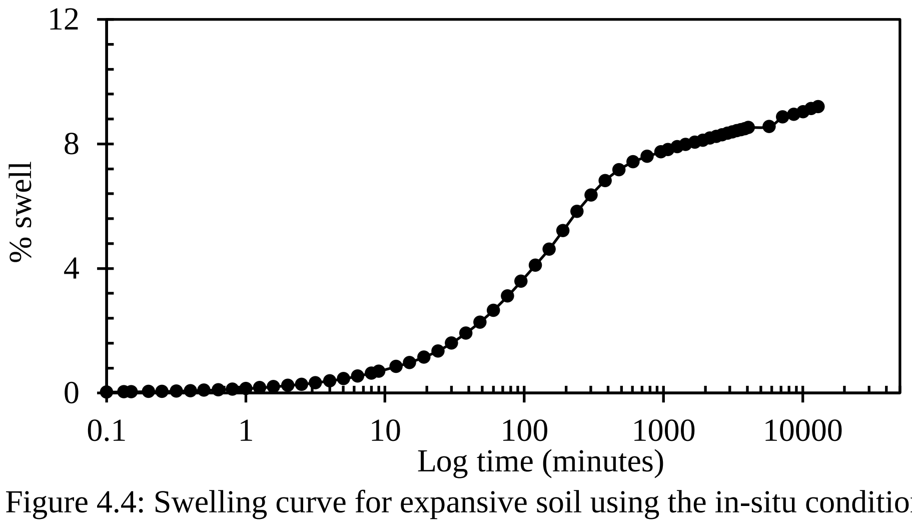

Figure 4.4: Swelling curve for expansive soil using the in-situ conditions.

4.2.5 Percent swelling and swelling coefficients of the expansive soil compacted at maximum dry density and optimum moisture content under different vertical surchare pressures

According to Huang et al. (2019) and Nagaraj et al., (2010), the swell kinematic properties of the expansive soils occurred in separate phases as illustrated in Figure 4.5.

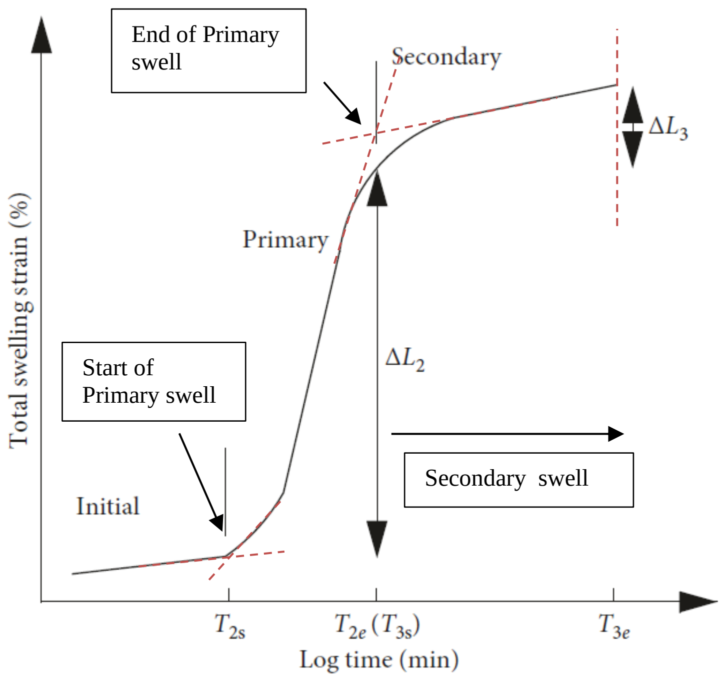

Figure 4.5: The three phases of swelling (Huang et al., 2019).

As it can be seen from Figure 4.5, the considerable amount of swelling takes place in the primary and secondary phases. In the present study, in order to understand the behavior of swelling deformation under different soil placement conditions, the swelling coefficients of two phases: A_2 and A_3 which are the primary and secondary swelling phases of the expansive soil, respectively were considered. The swelling coefficients A_2 and A_3 are defined in the following equations: Equation (4.1) and Equation (4.2) below, also the log-time intervals for both phases are shown in Equation (4.3) and Equation (4.4):

$$A_2 = \frac{\triangle L_2/L_o}{\triangle \log\ T_2} \tag{4.1}$$

$$A_3 = \frac{\triangle L_3/L_o}{\triangle \log\ T_3} \tag{4.2}$$

$$\triangle \log\ T_2 = \log T_{2e} - \log T_{2s} \tag{4.3}$$

$$\triangle \log\ T_3 = \log T_{3e} - \log T_{3s} \tag{4.4}$$

L_o is the specimen height at the beginning of the tests. Also, $\triangle L_2$ and $\triangle L_3$ present the axial strains in the second and third swelling phases, representing the primary and secondary swelling phases of the expansive soil, respectively.

Figure 4.6 gives the swelling curves of expansive soil at MDD and OMC under vertical surcharge pressure values (0, 7 and 15 kPa). The values of the swelling coefficients of the second and third phases of the expansive soil obtained from Figure 4.6 according to Equations (4.1) and (4.2) are provided in Table 4.1.

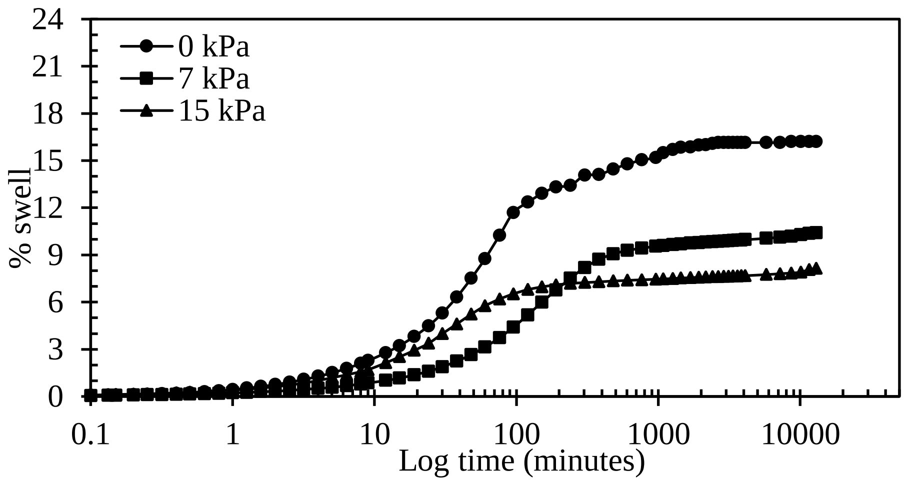

Figure 4.6: Swelling curves for expansive soil compacted at maximum dry density and optimum moisture content under different vertical stresses.

According to Figure 4.6 and Table 4.1, the determined percent swelling values of the tested expansive soil at primary and secondary swell phases under vertical stress of 0 kPa were higher than the equivalent values at 7 kPa and 15 kPa. The swelling coefficients values of the expansive soil calculated using the primary and secondary swelling phases under vertical stress of 0 kPa were higher compared to swelling coefficients values under applied 7 kPa and 15 kPa vertical stresses. The found swelling coefficient values are provided in Table 4.1, were consistent with the calculated values of percent swelling.

Table 4.1: The swelling coefficents of inspected soil compacted at MDD and OMC.

Vertical stresses (kPa)	L_o (mm)	$\triangle L_2$ (%)	$\triangle L_3$ (%)	$A_2(10^{-2})$ $(\frac{1}{min})$	$A_3(10^{-4})$ $(\frac{1}{min})$
0	15	10.85	3.8	0.24	0.20
7	15	7.54	1.69	0.14	0.09
15	15	5.22	1.28	0.11	0.07

As it can be seen from the obtained results, the values of the primary swelling coefficients decreased with increasing the vertical stress from 0 kPa to 15 kPa. Higher swelling coefficients values produced higher swell deformation and the peak distance difference between the two swelling phases. Whereas the lower swelling coefficients indicates lower swell deformation and peak difference for the given two primary and secondary swelling phases.

4.3 Factors affecting percent swelling and swelling coefficients of expansive soils compacted at dry density of 1.5 g/cm^3 at different initial moisture contents

In this part of the study, the swelling tests on expansive soil were performed on compacted soil specimens reaching a dry density of 1.5 g/cm^3 at different initial moisture contents (12%, 14% and 16%) and vertical stresses (0 kPa, 7 kPa and 15 kPa) by using different inundating fluid such as distilled water and the seawater.

4.3.1 Swelling of soils compacted at a constant dry density of 1. 5 g/cm^3 at different initial moisture contents using distilled water

In this section, the test specimens inundated with the use of distilled water under different vertical stresses (0 kPa, 7 kPa and 15 kPa) and different moisture contents (12%, 14% and 16%) but without changing the compaction condition (dry density of 1.5 g/cm^3). For these specimens, the swelling coefficients were provided in Tables 4.2 to 4.4 to show the primary and secondary phases of swelling obtained from the swelling curves in Figures 4.7 to 4.9.

4.3.1.1 Swelling of soil prepared at an initial moisture content of 12% using distilled water

Figure 4.7 presents the swelling of expansive soil specimens considering dry density of 1.5 g/cm^3 and 12% moisture content, using distilled water under different vertical stresses. It can be seen that the percent swelling values under 0 kPa surcharge pressure, were higher than the percent swelling values of expansive soils under 7 kPa and 15 kPa. Low surcharge pressure applied on the specimens caused higher swelling deformation in the expansive soil, whereas higher surcharge pressure reduced the percent swelling values of the expansive soil.

In Table 4.2, in the consideration of swelling coefficients of the expansive soil prepared with distilled water under 0 kPa, it was observed that its swelling coefficients were higher than the values obtained under the 7 kPa and 15 kPa. This showed that under the 0 kPa surcharge pressure, there was higher swelling in the expansive soil in both primary and secondary phases.

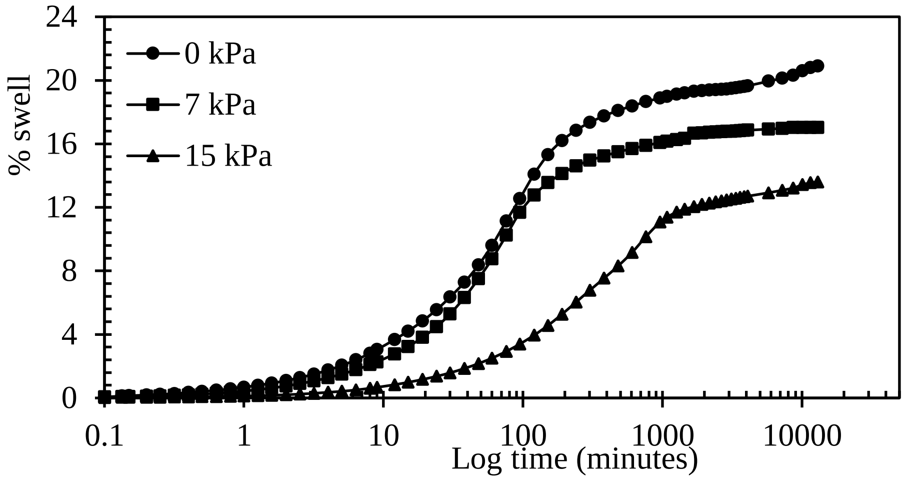

Figure 4.7: Swelling curves for expansive soil prepared using distilled water at a moisture content of 12% under different vertical stresses.

Figure 4.7 shows that higher percent swelling values, led to higher swelling coefficients A_2 and A_3 occurred in the primary and secondary phases under different vertical stresses. There were significant swelling coefficients increment under different vertical stress, as the 0 kPa recorded the highest values of 0.5 in the primary swelling phase and 0.25 in the secondary swelling phase, while 15 kPa vertical stress had the lowest values of 0.12 in the primary swelling phase and 0.11 in the secondary swelling phase as displayed in Table 4.2.

Table 4.2: Swelling coefficients of inspected soil at dry density of 1.5 g/cm3 mixed with distilled water content of 12%.

Vertical stresses (kPa)	L_o (mm)	$\triangle L_2$ (%)	$\triangle L_3$ (%)	$A_2(10^{-2})$ $(\frac{1}{min})$	$A_3(10^{-4})$ $(\frac{1}{min})$
0	15	13.8	4.7	0.5	0.25
7	15	12.35	2.9	0.36	0.15
15	15	10.23	2.21	0.12	0.11

It can be observed that the percent swelling and swelling coefficient in the primary phases (A_2) obtained at MDD and OMC shown in Table 4.1 were lower compared to equivalent values obtained for the soil specimens at dry density of 1.5 g/cm^3 and 12% moisture content. Moreover, the values of secondary swelling (A_3) showed the same behavior but the difference was less than the primary swelling case. The swelling deformation was higher for the specimen prepared at the initial moisture content of 12% and a dry density of 1.5 g/cm^3 compared to the values obtained for the specimen prepared at MDD and OMC. This shows that the initial moisture content and dry density were all significant controlling factors linked to the volume deformation of the expansive soil. This is because of different soil particles arrangement conditions generated with different initial conditions of moisture and compaction. Soils at drier state than the soils at optimum moisture content absorb more water than the soils at optimum moisture content and result in higher swelling. Since, in the compaction test, almost all the pore void spaces of the soil compacted at optimum moisture content were filled with water, soils compacted at the maximum dry density gave less swelling than the soil compacted below of this optimum.

4.3.1.2 Swelling of soil prepared at an initial moisture content of 14% using distilled water

Figure 4.8 presents the swelling percent of expansive soil prepared with the distilled water content of 14% under different vertical stresses compacted at dry density of 1.5 g/cm^3. The swelling values obtained using water content of 14% were consistent with the swelling values obtained with a water content of 12%. As expected, these values under the 0 kPa were higher than the equivalent swelling values of expansive soils under 7 kPa and 15 kPa. The results indicated that, lower vertical stress applied on the specimens allowed higher percent swelling in the expansive soil, whereas the higher vertical stress applied on the specimen prevented the swelling and resulted in reduction in the percent swelling of the soil. As the initial water content increased to 14%, the impact on the percent swelling and swelling coefficients was significant on both primary and secondary phases, as provided in Figure 4.8 and Table 4.3. The soil initial moisture content increment resulted in decrease in the percent swelling. Soil specimen prepared at 14% water content under 0 kPa vertical stress gave 17.4 % vertical swelling, whereas the swelling of the soil prepared at 12% water content resulted in approximately 20.9% of swelling under the same vertical stress value.

In the consideration of swelling coefficients of the expansive soil prepared with distilled water under 0 kPa, it was observed that its swelling coefficients (A_2 and A_3) were higher than the values obtained under the 7 kPa and 15 kPa. These outcomes highlight the impact of applying stress on the swelling deformation of the inspected soil on both primary and secondary swelling phases.

As shown in Table 4.3, the increase in the water content to 14%, reduced the values of both the percent swelling and swelling coefficients of compacted specimen at dry density value of 1.5 g/cm^3. The maximum swelling coefficients values estimated as 0.34 and 0.16 for the primary and secondary phases, respectively. These values obtained were quite higher when compared with the values of percent swelling and swelling coefficients obtained at the MDD and OMC. This could be explained due to the higher amount of water absorbed by the soil specimen prepared at an initial dry density of 1.5 g/cm^3 which had higher pore void spaces to absorb more water and result in higher swelling compared to the specimen at OMC. The macropores of the soil specimens compacted at OMC were almost filled by water and there was almost no empty pore space to allow water to enter into those pore spaces and because of this, the absorption of water for the specimen compacted at OMC was less than the soil specimen prepared at an initial density of 1.5 g/cm^3, which resulted in an increase in percent swelling and swelling coefficients (A_2 and A_3).

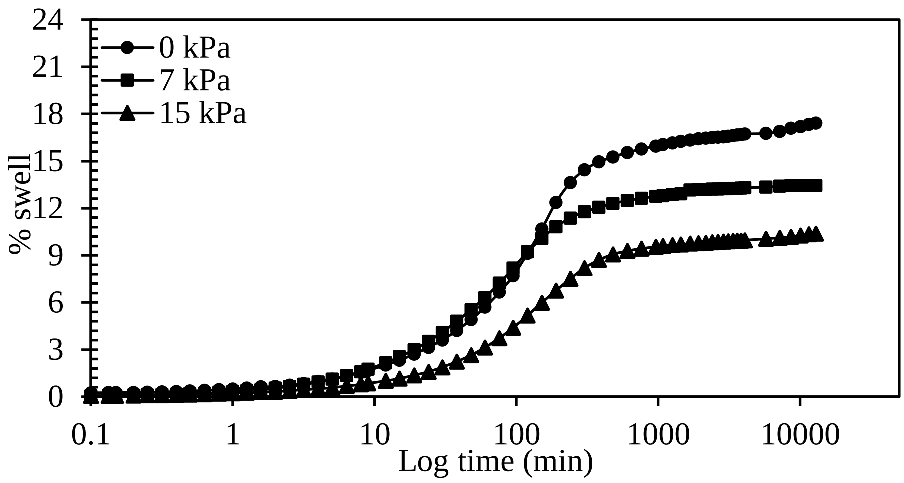

Figure 4.8: Swelling curves for expansive soil prepared using distilled water at a moisture content of 14% under different vertical stresses.

Table 4.3: Swelling coefficients of inspected soil at dry density of 1.5 g/cm3 and mixed with distilled content of 14%.

Vertical stresses (kPa)	L_o (mm)	$\triangle L_2$ (%)	$\triangle L_3$ (%)	$A_2(10^{-2})$ $(\frac{1}{min})$	$A_3(10^{-4})$ $(\frac{1}{min})$
0	15	12.78	3.04	0.34	0.16
7	15	9.23	2.61	0.29	0.14
15	15	7.03	2.2	0.11	0.10

4.3.1.3 Swelling of soil prepared at an initial moisture content of 16% using distilled water

Figure 4.9 presents the percent swelling for expansive soil prepared using the distilled water content of 16% under different vertical stresses which compacted to reach a dry density value of 1.5 g/cm^3. This consistency of findings can be observed by comparing the percent swelling values obtained with a water content of 14% and 12% with that obtained with a water content of 16%. Swelling percent values showed further decrease when increasing the water content to be 16%. Also, the effect of applying vertical stress on percent swelling and swelling coefficients was obvious as shown in Table 4.4. These values under the 0 kPa at the primary and secondary phases (A_2 and A_3) were higher than the equivalent percent swelling values of expansive soils under 7 kPa and 15 kPa. Thus, applying higher vertical stress restricted the swelling of the inspected expansive soil and resulted in lower swell values. In the consideration of swelling coefficients of the expansive soil prepared with distilled water content of 16%, the maximum values were estimated to be 0.27 for the primary phase (A_2) and 0.13 for the secondary phase (A_3) under 0 kPa surcharge pressure. These values were reduced when applied surcharge stresses increased to be 7 kPa and 15 kPa as displayed in Table 4.4.

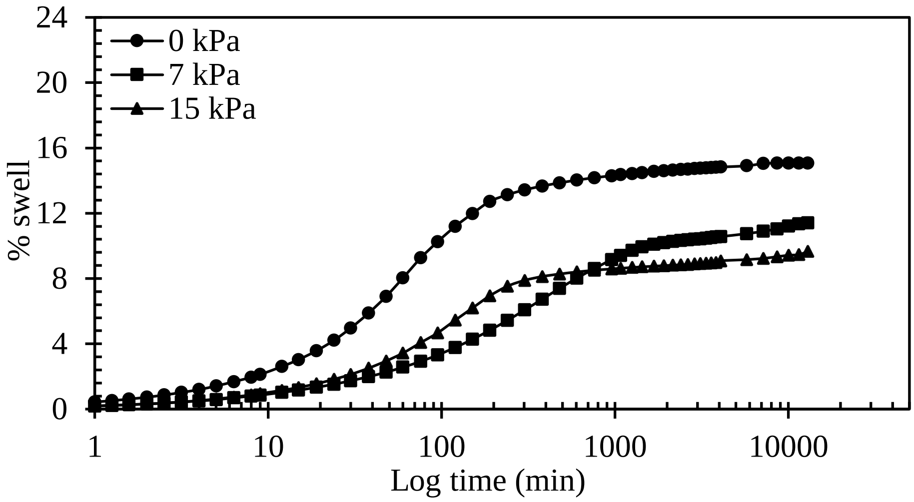

Figure 4.9: Swelling curves for expansive soil prepared using distilled water at a moisture content of 16% under different vertical stresses.

Table 4.4: Swelling coefficients of inspected soil at dry density of 1.5 g/cm3 and mixed with distilled water content of 16%.

Vertical stresses (kPa)	L_o (mm)	$\triangle L_2$ (%)	$\triangle L_3$ (%)	$A_2(10^{-2})$ $(\frac{1}{min})$	$A_3(10^{-4})$ $(\frac{1}{min})$
0	15	10.76	2.36	0.27	0.13
7	15	7.69	1.98	0.15	0.11
15	15	5.8	2.03	0.11	0.10

As presented in Table 4.4, the increase in the water content from 12% to 16%, results in further decrease in the values of both the percent swelling and swell coefficients at constant dry density value of 1.5 g/cm^3. Also, the values obtained in this section by using dry density of 1.5 g/cm^3 were the least when compared with the values of the percent swelling and swelling coefficients obtained at the maximum dry density and optimum moisture content. This could be explained by the critical influence of achieving the maximum dry density condition on soil particles arrangement, where the macropores of expansive soil were filled with water which lead the soil pores to lose their ability to absorb more water and expand.

4.3.2 Swelling of soils compacted at a constant dry density of 1. 5 g/cm^3 at different initial moisture contents using the seawater

In this section, the swelling deformation of the expansive soil was examined using the seawater under different vertical stresses (0, 7 and 15 kPa) and different moisture contents (12, 14 and 16%), but using constant dry density of 1.5 g/cm^3 for all soil specimens. The swelling coefficients (A_2 and A_3) were provided in Tables 4.5 to 4.7 considering primary and secondary phases as obtained from the swell curves given in Figures 4.10 to 4.12.

4.3.2.1 Swelling of soil prepared at an initial moisture content of 12% using the seawater

Using the seawater for soil specimen compacted to reach a dry density value of 1.5 g/cm^3 with water content of 12% reduced the obtained percent swelling values of the soil under all vertical stress conditions. The highest percent swelling of 18.70% was obtained under the vertical stress of the 0 kPa, and the percent swelling at 7 kPa and 15 kPa were 14.50% and 11.47%, respectively as shown in Figure 4.10. Comparing these findings with the soil specimens at the same moisture content of 12%, but using distilled water, it is clear that percent swelling values decreased when mixing the soil with seawater. The reason for the overall decrease in the values of percent swelling of the soil specimens mixed with the seawater, was due to the change in the pore chemistry of clay mineral particles in which reduction in diffused double layer, DDL caused the swelling of the inspected soil to be restricted. The high salinity of seawater has a direct impact on the swelling characteristics of expansive soils. The dissolved salts in seawater react with the free anions and cations around the clay particles cause reduction in the moisture absorption capacity of clays and results in less swelling. According to Olphen (1977) increased salt concentration in clays compresses the diffused double layer and results in restricting the swelling of double layer. As a result of the high ionic concentration of the seawater, causes reduction in the double-layer thickness and consequently causes reduction in the swelling of the soil. The findings in the present study are in good agreements with the previous findings in the literature (Olphen, 1977; Yukselen-Aksoy et al., 2008; Estabragh et al., 2013).

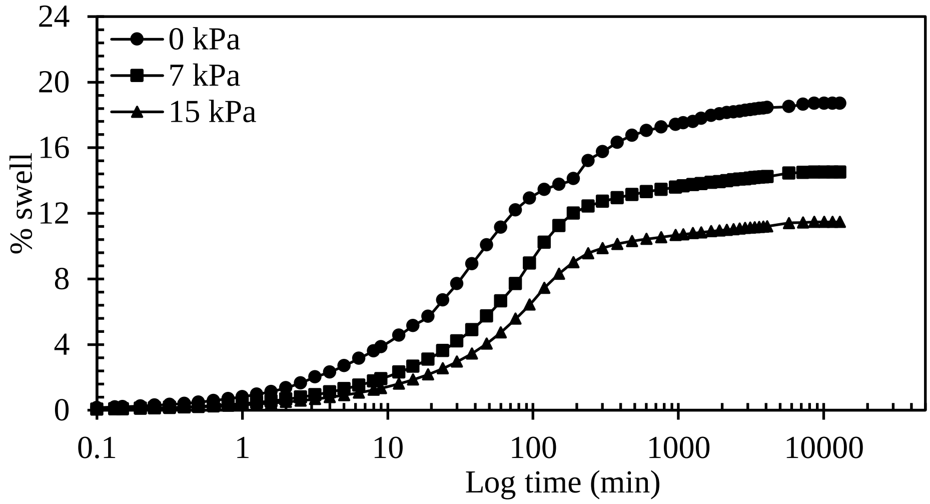

Figure 4.10: Swelling curves for expansive soil prepared using seawater at a moisture content of 12% under different vertical stresses.

Table 4.5: Swelling coefficients of inspected soil at dry density of 1.5 g/cm3 and mixed with seawater content of 12%.

Vertical stresses (kPa)	L_o (mm)	$\triangle L_2$ (%)	$\triangle L_3$ (%)	$A_2(10^{-2})$ $(\frac{1}{min})$	$A_3(10^{-4})$ $(\frac{1}{min})$
0	15	13.05	4.29	0.46	0.22
7	15	10.48	2.51	0.38	0.13
15	15	8.33	1.91	0.11	0.11

Table 4.5 presents swelling coefficients of the soil under dry density of 1.5 g/cm^3 and 12% of seawater content. The swelling coefficients of primary phases (A_2), were slightly lower when compared to soil experimented with distilled water mixed at the same moisture content of 12%. The swelling coefficient value of the primary phases (A_2) were 0.46 and 0.5 for the seawater and distilled water, respectively. The same behavior was noticed for the secondary phases (A_3) which slightly decreased when compared to results using distilled water.

4.3.2.2 Swelling of soil prepared at an initial moisture content of 14% using the seawater

Figure 4.11 presents the percent swelling for the soil using seawater under different vertical stresses compacted at dry density of 1.5 g/cm^3 and moisture content of 14%. As the initial moisture content rose at the same dry density, the values of the percent swelling of the soil at both primary and secondary phases were all reduced. The percent swelling values obtained under the vertical stresses of 0, 7, and 15 kPa were 13.22%, 11.44%, 9.5%, respectively. The calculated swelling coefficients are displayed in Table 4.6.

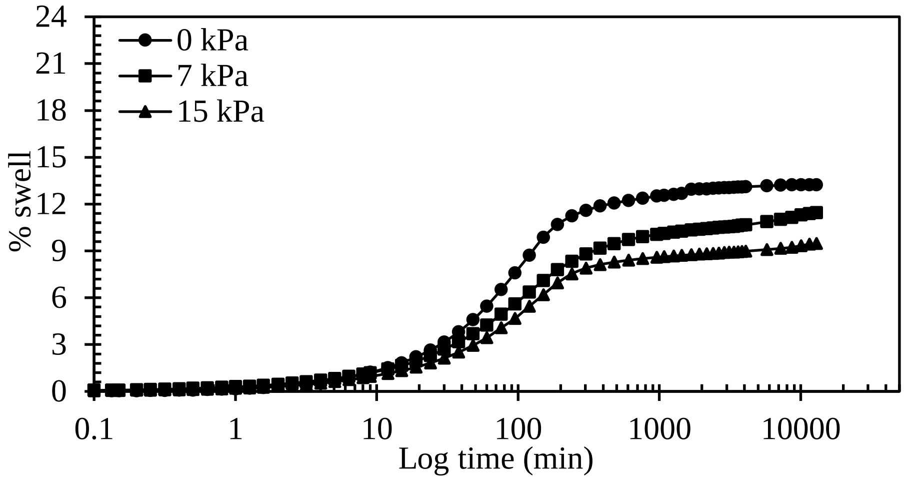

Figure 4.11: Swelling curves for expansive soil prepared using seawater at a moisture content of 14% under different vertical stresses.

Table 4.6: Swelling coefficients of inspected soil at dry density of 1.5 g/cm3 and mixed and seawater content of 14%.

Vertical stresses (kPa)	L_o (mm)	$\triangle L_2$ (%)	$\triangle L_3$ (%)	$A_2(10^{-2})$ $(\frac{1}{min})$	$A_3(10^{-4})$ $(\frac{1}{min})$
0	15	9.73	2.54	0.29	0.16
7	15	7.84	2.65	0.19	0.14
15	15	6.57	1.94	0.10	0.10

The overall values of the percent swelling and swelling coefficients of the soil prepared with seawater content of 14%, were lower than their equivalent values obtained from the soil prepared with distilled water content of 14%. It was observed that the swelling coefficients for both primary and secondary phases (A_2 and A_3) decreased from 0 kPa to 15 kPa as shown in Table 4.6. These findings can be linked to the effect of seawater and its electrochemical effects on the prepared soil specimens. Mixing soil with the seawater resulted in reduction of the needed time to reach the maximum percent swelling. That could be explained due to the flocculation and aggregation resulted from the chemical reactions between the soil particles and the seawater which weakened the diffused double layer of the soil particles and reduced its hydraulic conductivity.

According to the plotted swelling curves, the primary swelling phase of soil specimens prepared using the seawater was finished in shorter time interval than soil specimens prepared using distilled water. For example, in the swelling curves of specimens mixed with 14% of moisture content, the time needed to complete the primary phases was 381 minutes and 190 minutes for the specimens prepared using distilled water and seawater, respectively. These findings were consistent for all tested initial moisture contents (12%, 14%, and 16%).

In the swelling curves displayed in Figure 4.11, it was noticed that the soil specimens resistant to swelling was quite very high at the initial phase of the swelling curves. That was because of the relatively high initial water content and salts concentration of the seawater at the initial stage of the swelling. But over a certain swelling duration, the seawater was diluted and then the swelling deformation increased. Nonetheless, the values of the percent swelling and swelling coefficients were lowered comparing with the equivalent swelling values of the soil prepared using initial seawater content of 12%.

4.3.2.3 Swelling of soil prepared at an initial moisture content of 16% using the seawater

For the initial moisture content of 16% using seawater with the dry density of 1.5 g/cm^3, the values of the percent swelling of the soil at the primary and secondary phases were all further reduced as shown in Figure 4.12. The percent swelling obtained under the vertical stress of the 0, 7, and 15 kPa were 12.64%, 9.19%, and 8.13%, respectively. While applying more vertical stresses, percent swelling was reduced in the given swelling phases. The percent swelling for the 7 kPa and 15 kPa, matched one another during the secondary phases of the soil swelling.

The overall values of the percent swelling and swelling coefficients of the soil prepared with seawater were lower than their equivalent values obtained from the soil prepared with distilled water. It was observed, that the A_2 and A_3 values of the soil specimens prepared with the seawater were the lowest for 0 kPa, 7 kPa and 15 kPa. There has been consistency in the effect of the vertical stresses of 0 kPa to 7 kPa and then to 15 kPa on the outcomes of the swelling deformation. In fact, in comparison to the values of swelling coefficients and percent swelling of the soil obtained under the other considered factors, the values obtained in this section are at the lowest as shown in Table 4.7. The swelling coefficients reduced significantly comparing to soil specimens prepared using lower initial moisture contents (12% and 14%). The maximum A_2 and A_3 values were measured to be 0.18 and 0.12 for the primary and secondary phases, respectively.

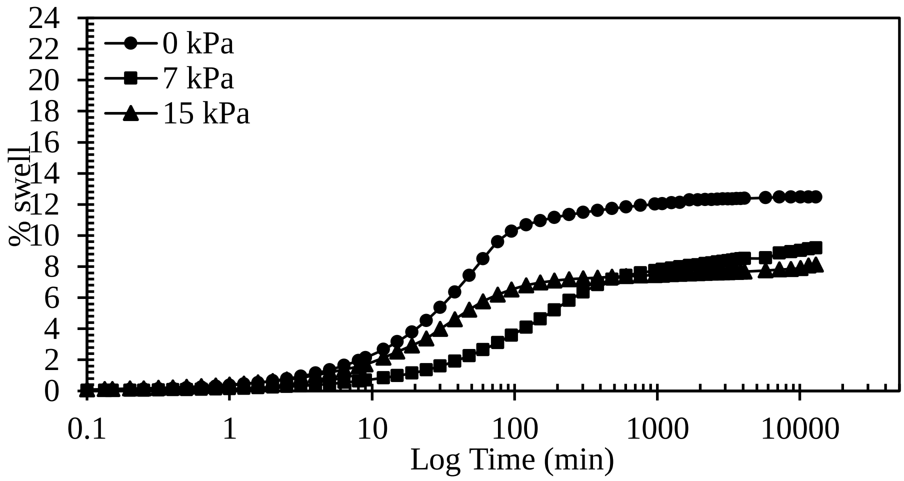

Figure 4.12: Swelling curves for expansive soil prepared suing seawater at a moisture content of 16% under different vertical stresses.

Table 4.7: Swelling coefficients of inspected soil at dry density of 1.5 g/cm3 and mixed with seawater content of 16%.

Vertical stresses (kPa)	L_o (mm)	$\triangle L_2$ (%)	$\triangle L_3$ (%)	$A_2(10^{-2})$ $(\frac{1}{min})$	$A_3(10^{-4})$ $(\frac{1}{min})$
0	15	9.31	2.2	0.18	0.12
7	15	6.33	1.91	0.12	0.10
15	15	5.84	1.34	0.10	0.09

4.3.3 Effect of initial moisture content, dry density, and surcharge pressure on swelling of soil

In this section, the effect of controlling factors such as initial water contents variation, dry density value, and applied surcharges on percent swelling of the inspected soil will be discussed. Different range in the values of the controlling factors will be correlated to observe their influence on the volume deformation characteristics of expansive soils.

4.3.3.1 Effect of initial moisture content and dry density on the swelling properties of expansive soil under zero surcharge pressure

Figure 4.13 illustrates the dry density effect on swelling values of the inspected soil at different initial water contents. Different dry density values caused an increment of percent swelling until a certain dry density value and then after this threshold value, the swelling decreased. The same behaviour was obtained for all different values of initial moisture contents, which reveals that the relationship between dry density and percent swelling is not constant or linear for all dry density values. These findings indicate that, the macropore spaces of the soil become the significant controlling factor because of the arrangement condition of the soil particles which controls the soil swelling. Soil specimens experienced an increase in percent swelling from dry density of 1.18 g/cm^3 to 1.6 g/cm^3 dry density. However, at higher dry density values (>1.6 g/cm^3) the percent swelling decreased steadily. The maximum value of the percent swelling was found to be 16.3% occurred when the initial moisture content was 12% and compacted at a dry density of 1.6 g/cm^3. These findings show a good harmony with what was reported by Çimen et al. (2012), Dafalla, (2012), and Huang et al. (2019), these studies stated that expansive soils compacted at high dry density values tend to deacrease in volume after the initial volume increase occured at low dry density values. Table 4.8 shows the precent swelling values of the soil specimens compacted at different dry density values. The maximum percent swelling values occurred initial moisture content of 12% and the lowest values occurred at initial moisture content of 16%. Soil swelling increased with the increment of dry density until threshold value of 1.6 g/cm^3 then decreased with further increment of dry density.

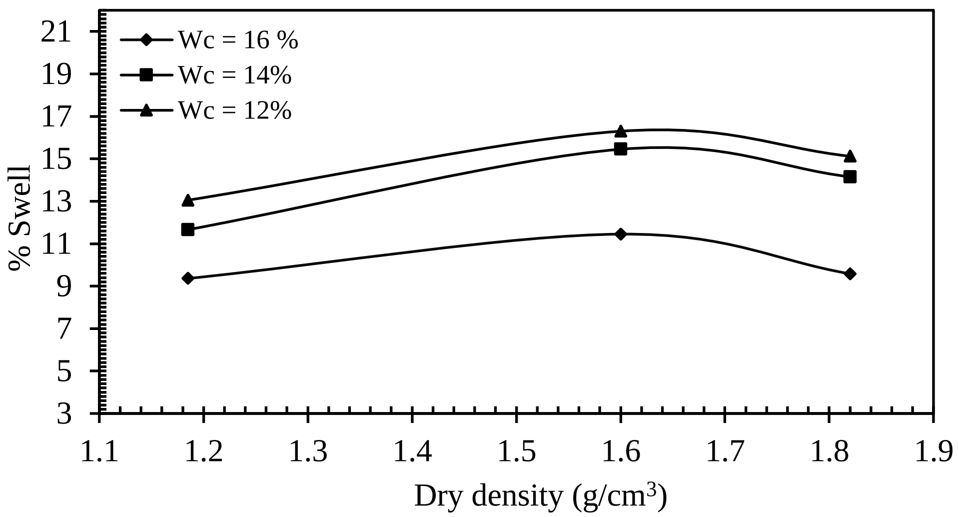

Figure 4.13: Percent swelling versus dry density under zero surcharge pressure.

Table 4.8: Percent swelling values using different initial moisture contents compacted at different dry density values under zero surcharge pressure.

Initial moisture content (%)	Dry density (g/cm^3)	Percent swell (%)
12	1.18	13.05
	1.6	16.3
	1.82	15.12
14	1.18	11.66
	1.6	15.45
	1.82	14.15
16	1.18	9.36
	1.6	11.45
	1.82	9.58

4.3.3.2 Effect of initial moisture content and dry density on the swelling properties of expansive soil under 15 kPa applied vertical stress

Figure 4.14 shows the effect of dry density on the swelling values of the inspected soil at different initial water contents under applying vertical stress of 15 kPa. Similar behaviour was noticed for all different initial moisture content, and the lowest percent swelling values were achieved at moisture content of 16%. In terms of dry density, precent swelling reached its maximum for the soil specimens which compacted at dry density of 1.6 g/cm^3. However, at higher dry density values (>1.6 g/cm^3) the percent swelling decreased steadily, which shows the consistency of these findings with the findings from the previous section, where the same threshold values of 1.6 g/cm^3 was found. The impact of applying vertical stress of 15 kPa on the inspected expansive soil can be seen in Table 4.9. The percent swelling values experienced further decrease with applying vertical stress of 15 kPa for all different dry density values, which declares that swelling of expansive soils is restricted by the applied surcharge pressure. These findings were consistent regardless to the soil specimen initial conditions, where the generated swelling pressure between the soil particles and moisture cannot overcome the applied high vertical stress (Zou et al., 2020). By comparing precent swelling values in Table 4.8 and Table 4.9, the maximum percent swelling values reached were 16.3% and 12.8%, under vertical stresses of 0 kPa and 15 kPa, respectively. However, the minimum percent swelling values recorded were 9.36% and 4.29%, under applied vertical stress of 0 kPa and 15 kPa, respectively.

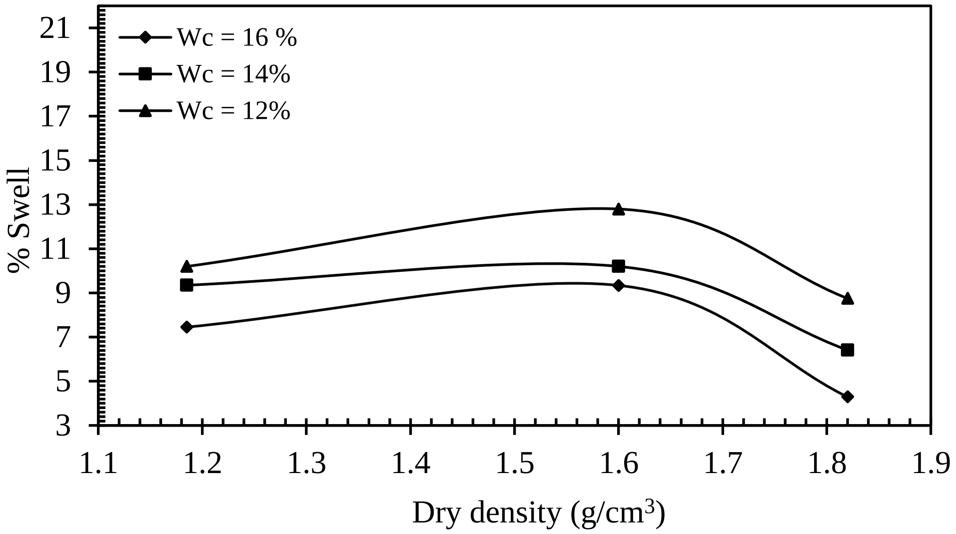

Figure 4.14: Total percent swelling versus dry density using different initial moisture contents under applied vertical stress of 15 kPa.

Table 4.9: Total percent swelling values using different initial moisture compacted at different dry density values under 15 kPa applied vertical stress.

Initial moisture content (%)	Dry density (g/cm^3)	Percent swell (%)
12	1.18	10.2
	1.6	12.8
	1.82	8.75
14	1.18	9.35
	1.6	10.2
	1.82	6.41
16	1.18	7.45
	1.6	9.34
	1.82	4.29

4.4 Soil suction measurements of expansive soil mixed with distilled water and the seawater

In this section, soil suction was measured using the filer paper method with respect to different initial moisture contents and different pore fluids which are distilled water and the seawater. Both total and matric suction of the expansive soil were measured under different soil initial conditions and soil-water characteristic curves (SWCC) were plotted using van Genuchten (1980) model.

4.4.1 Influence of initial moisture content and pore fluid chemistry on the soil suction of expansive soils

Figure 4.15 presents the measured total suction values of expansive soil at different initial moisture contents. Osmotic suction results from the salts that are present in the soil pores whereas matric suction occurs because of the physical factors such as the capillary, soil texture and surface adsorption forces of the soil (Fattah et al., 2013).

Obtained results in Figure 4.15 showed that the usage of seawater as a pore fluid increased the total suction values of the soil compared with distilled water. These findings were consistent with all used initial moisture contents. As expected, the increment of initial moisture content decreased the overall values of soil suction. The minimum soil suction values were reached for the soil specimens mixed at moisture content of 20%. The values of the matric suction of the expansive soil in the presence of distilled water and the seawater are given in Figure 4.16. It was found that matric suction values did not differ by the use of different types of pore fluid in the inspected expansive soil. Soil specimens prepared with the same initial moisture content, but different pore fluids generated nearly the same matric suction values in both cases. Also, the increment of initial moisture content values of expansive soils caused a gradually decrement in matric suction values. These findings indicate that the salinity of the natural seawater has no significant influence on the matric suction of the inspected soil. In terms of matric suction, the controlling factor is the variation of the capillarity action and the surface absorption forces of the soil (Rao & Shivanada, 2005). This clarifies that matric suction is independent with the salts content in the pore fluid (Pulat et al., 2014; Ying et al., 2021).

Figure 4.17 gives the osmotic suction of the inspected soil using distilled water and the seawater. As it can be seen in Figure 4.17, there is a significant difference between the values of the osmotic suction of the soil specimens prepared with distilled water and the seawater. When using seawater as pore fluid, the concentration of ions in the soil pores rise significantly which resulted in an increase in the osmotic suction. The increment of osmotic suction led to overall increasing of total suction values for all cases. As aforementioned, osmotic suction is attributed to dissolved salt concentration in the used pore water (Yukselen-Aksoy et al., 2008). The high ionic concentration of the seawater increased the osmotic suction values of the soil. The variation of total suction values between both pore fluids recorded in Figure 4.15, was generated due to the impact of the high salinity of seawater which resulted in a significant increase in osmotic suction of expansive soil.

Soil suction findings were consistent with the findings of percent swelling and swelling coefficients of the inspected soil considering the effect of initial moisture content and pore fluid chemistry. In all cases, soil suction values tend to decrease with the increase of initial moisture content, thus decreasing the swelling of the inspected soil. Also, changing the pore fluid had a significant impact on the total suction values. Soil specimens mixed with the seawater experienced an increment of soil suction.

The increase in soil suction due to the presence of the seawater can also be an indication of the changes in the soil texture. Mixing the soil with the seawater caused the texture of the soil to change from the fine to course texture resulting in reduction in soil swelling due to the reduced ability of storing moisture between soil particles. This behavior could also be explained due to the reduced diffused double layer thickness of soil particles in the presence of the seawater which resulted in the changes in soil fabric and produced a more aggregated soil texture fabric which was more similar to the behavior of course-grained soils. This finding is in good agreement with the findings of Ying et al. (2021) who found that the reduction of diffused double layer thickness restrict the water storing ability of the expansive soil and cause reduction in soil swelling.

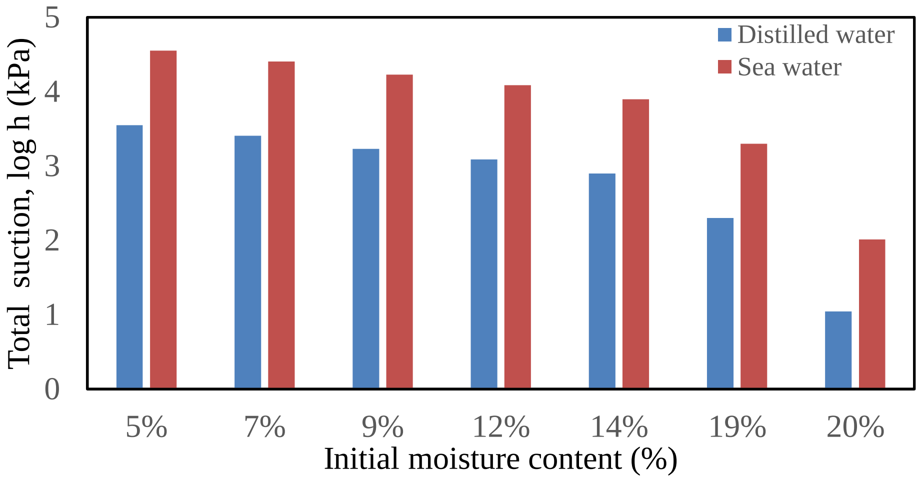

Figure 4.15: The effect of pore fluid on the total suction of expansive soil under different initial moisture contents.

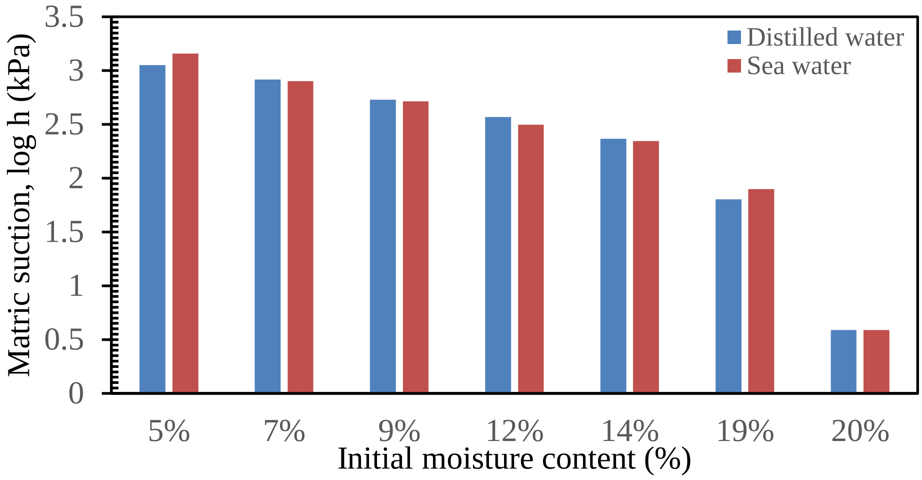

Figure 4.16: The effect of pore fluid on the matric suction of expansive soil under different initial moisture contents.

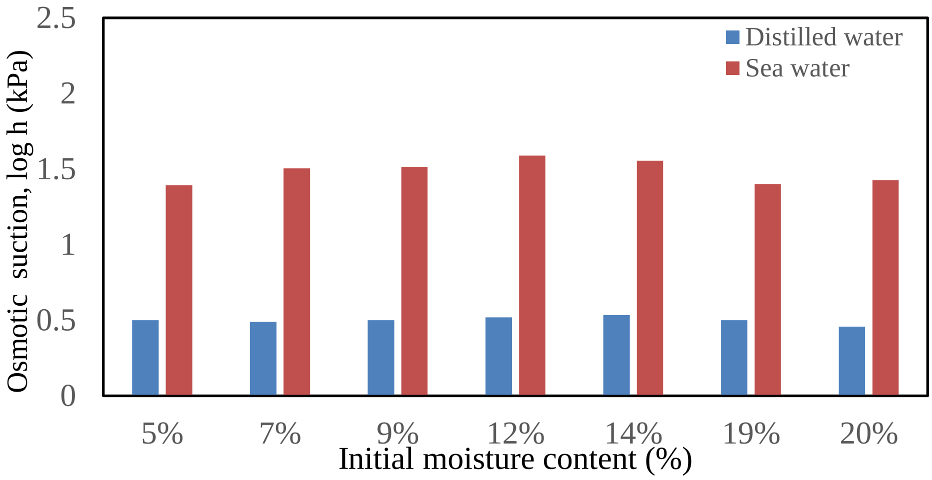

Figure 4.17: The effect of pore fluid on the osmotic suction of expansive soil under different initial moisture contents.

4.4.2 Soil Water Characteristics Curve (SWCC) of expansive soil mixed with distilled water and the seawater

In this study, the SWCCs were plotted using the obtained laboratory data from the filter paper test and the obtained data was fitted with a commonly used model proposed by van Genuchten (1980). Using Solver tool in Microsoft Excel software, the fitting parameters, a_{vg}, n_{vg}, and m_{vg} were estimated. Equation (4.5) proposed by van Genuchten (1980) SWCCs were plotted and the found laboratory data were fitted using three fitting parameters which defined below. It is advantageous to use this model, since it can cover a considerable range of soil suction values (Soltani et al., 2019).

$$w_w = w_{rvg} + (w_s - w_{rvg})\left[\frac{1}{\left[1+\left(a_{vg}\psi\right)^{n_{vg}}\right]^{m_{vg}}}\right] \quad (4.5)$$

Where,

ψ is soil suction (kPa),

w_w water content percentage with respect to soil suction,

w_{rvg} water content at desorption,

w_s water content at saturation,

a_{vg}, n_{vg}, and m_{vg} are fitting parameters.

For the SWCC shown in Figure 4.18 of the soil mixed with the seawater, the used fitting parameters a_{vg}, n_{vg}, and m_{vg}, were estimated using Solver tool as 0.000562, 1.25143, and 6.9025, respectively. However, for the SWCC shown in Figure 4.18 of the soil mixed with distilled water, the used fitting parameters a_{vg}, n_{vg}, and m_{vg}, were estimated as 0.00025, 1.2478, and 3.3424, respectively. Figure 4.18 display the soil water characteristics curves, SWCC of the tested expansive soil mixed at different initial moisture contents using two types of pore fluids: distilled water and the seawater. The total soil suction values found in the laboratory tests were fitted with van Genuchten (1980) model, and then different soil suction parameters were obtained from SWCCs as shown in Table 4.10.

The obtained suction values of the soil specimens prepared with different initial moisture content showed a general decrease when increasing the gravimetric moisture content. The same behaviour was obtained for both fluid types with respect to moisture content. However, considering the air-entry values (AEV) of both conditions, it was noticed that expansive soil prepared using seawater had a considerably lower AEV of 92.35 kPa than the expansive soil prepared using distilled water with AEV of 354.35 kPa. This is because of the change in soil texture due to the presence of the seawater which caused flocculation and aggregation of the soil fabric and resulted in a soil behaviour similar to the soil with course texture, giving lower swelling values. As Rowe (2001) stated, fine grained soils have higher holding water capacity compared to coarser grained soils. Because of this, for soils with fine texture, larger matric suction is needed to remove water from the soil than the soil with coarse texture. These findings in this experimental work indicated that specimens mixed with the seawater needs lower suction values to allow the air to dissipate into the soil pores and desaturation (drying) start.

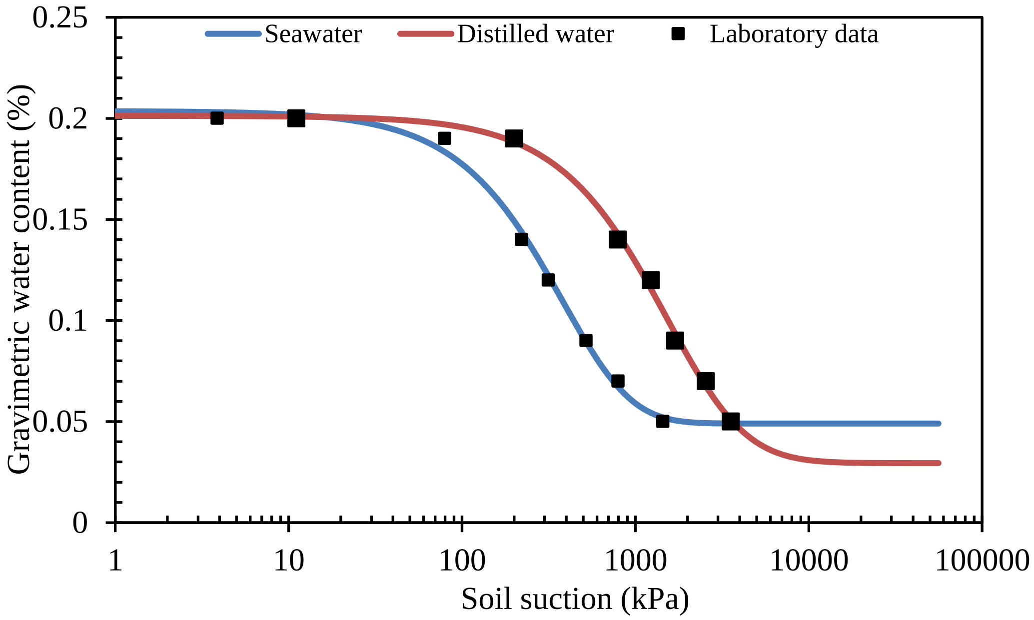

Figure 4.18: Laboratory data of SWCC using seawater and distilled water fitted by van Genuchten model (1980).

Table 4.10: Suction parameters obtained from SWCCs for the soils with different pore fluids.

Pore fluid	Slope	AEV (kPa)	R^2
Seawater	0.8114	92.35	0.9979
Distilled water	1.065	354.35	0.9975

According to Table 4.10, the high R^2 values emphasize the accuracy of the fitted laboratory data with the used van Genuchten model. Regarding to the slope of SWCCs, it was found that the usage of seawater reduced the slope of SWCC of the inspected expansive soil from 1.065 to 0.8114. The reduction of SWCC slope indicates the reduction in unsaturated hydraulic conductivity of the inspected soil and slower drying in the presence of seawater, and the steeper slope of SWCC for soils mixed with distilled water, indicates a higher sensitivity to moisture variations.

Chapter 5

CONCLUSIONS

This experimental investigation highlights the soil properties which have an influence on the geotechnical characteristics of a naturally obtained expansive soil. The obtained experimental outcomes revealed the following conclusions:

1. Regarding the findings of soil index properties, the inspected soil was classified as MH-CH which indicates a highly plastic silty clay. The relatively high liquid limit of 61% and fine particles content of more than 50% indicates the high capability of holding moisture the inspected soil has, which makes it sensitive to wetting and drying. Swelling percent measured under in-situ conditions found to be 9.2%. The soil excavation was done in winter season which explains the wet in-situ condition of the obtained soil which resulted in relatively low percent swelling.

2. The compaction curve using modified effort conducted values of 16% as optimum water content and maximum dry density of 1.82 g/cm^3. Soil specimens compacted at OMC showed low water absorption capacity, because the soil pores were almost filled by water and there were no empty pores to allow water entry. Percent swelling and swelling coefficients using MDD, and OMC was found to be decreasing with the increase of applied vertical stress from 0 kPa to 15 kPa. The influence of applied vertical stress was consistent for all swelling measurements regardless to the soil initial conditions.

3. The increment of initial moisture content had a significant impact of the plotted swelling curves of soil specimens compacted at constant dry density of 1.5 g/cm^3 using

both distilled water and seawater as pore fluids. Swelling percent and swelling coefficients of the inspected soil tend to decrease with the increase of initial moisture content. This behavior was noticed for both primary and secondary swelling phases of all tested specimens.

4. The effect of using the seawater as pore fluid on swelling curves was found to be critical. Further decrement on percent swelling values and swelling coefficients was noticed comparing with the soil prepared with distilled water. This behavior is a result of the high salts concentration of the seawater, which affected the pore chemistry of clay mineral particles causing shrinkage in the diffused double layer, DDL and reduction of the overall swelling of the inspected soil. Also, by referring to the plotted swelling curves using the seawater, it can be noticed that primary swelling phase needed shorter time interval to be finished and secondary swelling starts. This emphasizes the influence of using the seawater on the needed time to reach maximum possible percent swelling, which was less comparing with distilled water.

5. The plotted relationship between percent swelling and dry density showed consistent results. It was found that the effect of dry density increment on percent swelling is non-linear, where the behavior changes at high dry density value of 1.82 g/cm^3 and percent swelling tend to decrease, comparing with the noticed increase in percent swelling for the lower dry density values of 1.18 g/cm^3 and 1.6 g/cm^3. Also, the maximum percent swelling values were recorded at initial moisture content of 12% and the lowest values of swelling were at initial moisture content of 16%. Hence, the swelling of the soil increased with an increase in initial dry density up to a threshold value (1.6 g/cm^3) but decreased as the initial water content was higher. However, the presence of applied vertical stress had no influence on the found curves behavior, whereas it decreased the overall swelling percent values.

6. Soil suction measurements using filter paper method indicated an overall reduction of soil suction values with the increase of initial moisture content for both pore fluids used in the study. However, the high salinity of the seawater increased the osmotic suction values comparing with distilled water specimens. This can be explained by the fact that osmotic suction is linked with the amount of dissolved salts in the pore fluid. As a result, total suction of seawater specimens was higher than distilled water specimens, but matric suction values showed limited variations when the used pore fluid chemistry was changed which indicates that the controlling factors in terms of matric suction is not the pore fluid chemistry, but it is the variation of the capillary action and the surface absorption forces of the soil. The high salinity causes reduction in diffused double layer thickness of the soil and restricts its ability of holding water which causes reduction in soil swelling.

7. The obtained soil-water characteristics curves displayed the relationship between moisture percentage and matric suction of inspected soil using distilled water and the seawater. Air-entry value of the inspected soil dropped from 354.35 kPa to 92.35 kPa when using seawater as a pore fluid. This indicated that the presence of seawater permits easier dissipation of air into soil pores and starts drying, due to change in soil texture, which alert more resistance of storing water into soil pore and less soil swelling. Moreover, the slope of SWCC reduced from 1.065 to 0.8114 when using the seawater. This emphasizes the higher sensitivity to moisture variations of expansive soil prepared using distilled water, which resulted in increasing its tendency to increase in volume. Soil suction measurements revealed a reliable prediction of swelling with respect to the used pore fluid chemistry.

Finally, the tested initial conditions had an obvious effect on swelling characteristics of expansive soil. Changing the initial conditions had an impact on soil's physical and chemical properties, which influenced its sensitivity to moisture variations and the resulted volume changes.

Further studies

Further detailed study can be conducted and the swelling pressure of the expansive soil under different initial conditions can be measured by using different swell pressure measurement techniques. Also, different models proposed by different researchers can be used to fit the measured suction values of the expansive soil in the study.

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