Laboratory Behavior of Sand-Bentonite Mixtures

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ABSTRACT

In the engineering field, sand bentonite mixture is frequently used as a liner or barrier material for projects like hydraulic and waste containment construction whenever there exists a dearth of naturally existing clay at a particular site. The engineering properties of sand-bentonite mixtures are an active area of study. This study aims to develop methods for producing sand bentonite mixture which can be used as a waste-disposal liner. In the study, bentonite was chosen to be the admixture and the beach sand taken from the Famagusta Bay in North Cyprus was the main material. Different sand-bentonite mixes (10% B - 90% S (M1), 15% B - 85% S (M2), and 20% B - 80% S (M3)) were created by increasing the sand-bentonite mixture's bentonite concentration from 10% to 20% by dry weight. The Atterberg's limit compaction, swelling and compressibility attributes of sand-bentonite mixtures were studied. Furthermore, the hydraulic-conductivity, suction, and volume change characteristics of sand-bentonite mixtures were investigated. The ASTM standard was used for all testing. Test results indicate that M3 (the mixture with the highest bentonite content) had the highest values for percentage swell, coefficient of vertical consolidation (c_v), hydraulic conductivity (k) and suction values. Increased unconfined compressive and tensile strength was attained with higher bentonite concentration. A raise in the bentonite content also increases the volume change of the sand-bentonite mixtures. The most significant shift in the volume of the sand-bentonite mixtures was obtained for M3 soil. Findings indicate that all geotechnical features of sand-bentonite mixtures were shown to be affected by an increase in bentonite concentration.

Keywords: Bentonite, Compressibility, Hydraulic Conductivity, Landfill, Sand, Swell, Tensile Strength.

ÖZ

Mühendislik alanında, bir sahada doğal olarak oluşan kil eksikliği olduğunda, hidrolik ve atık muhafaza inşaatı gibi projeler için genellikle bir astar/bariyer malzemesi olarak kum-bentonit karışımları kullanılır. Kum-bentonit karışımlarının mühendislik özellikleri aktif bir çalışma alanıdır. Bu çalışmanın amacı, atık bertaraf astarı olarak kullanıma uygun kum-bentonit karışımlarının üretilmesi için yöntemler geliştirmektir. Bu çalışmada katkı maddesi olarak bentonit seçilmiş ve ana malzeme Kuzey Kıbrıs Gazimağusa Plajı'ndan alınan sahil kumu olmuştur. Bentonit içeriği kum-bentonit karışımının kuru ağırlığının %10'dan %20'sine kadar değiştirilerek farklı kum-bentonit karışımları (%10 B - %90 S (M1), %15 B - %85 S (M2) ve %20 B - %80 S (M3)) hazırlanmıştır. Kum-bentonit karışımlarının Atterberg limitleri, sıkışma, şişme ve sıkıştırılabilirlik özellikleri incelenmiştir. Ayrıca kum-bentonit karışımlarının hidrolik iletkenlik, emme ve hacim değiştirme özellikleri araştırılmıştır. Tüm testler için ASTM standardı kullanıldı. Test sonuçları, M3'ün (en yüksek bentonit içeriğine sahip karışım), şişme yüzdesi, dikey konsolidasyon katsayısı (c_v), hidrolik iletkenlik (k) ve emme değerleri için en yüksek değerlere sahip olduğunu göstermektedir. Bentonit içeriğindeki artışla birlikte serbest basınç ve çekme mukavemetinde artış elde edilmiştir. Artan bentonit içeriği, kum-bentonit karışımlarının hacim değişimini de artırmıştır. Kum-bentonit karışımlarının hacmindeki en yüksek değişim M3 zemin için elde edilmiştir. Bulgular, kum-bentonit karışımlarının tüm geoteknik özelliklerinin bentonit konsantrasyonundaki artıştan etkilendiğini göstermektedir.

Anahtar Kelimeler: Bentonit, Sıkıştırılabilirlik, Hidrolik İletkenlik, Depolama, Kum, Şişme, Çekme Dayanımı.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AEV	Air Entry Value
ASTM	American Society for Testing and Materials
DDL	Diffused Double Layer
ILW	Intermediate Level Wastes
LLWs/LAWs	Low Level or Low Activity Wastes
NP	Non Plastic
NA	Not Applicable
SB	Sand-Bentonite
SWCC	Soil Water Characteristic Curve

Chapter 1

INTRODUCTION

1.1 Background to the study

Several countries dispose of their waste mostly via the use of landfills, which are a kind of containment construction designed to restrict or minimize the amount of pollutants that seeps into underground water and the surrounding environment (Hjelmar, 1996).

There are a variety of engineering applications that call for sand-clay mixes to be utilized as a liner or barrier containment structures like landfills and cutoff walls. Sand-clay mixes are also utilized in a variety of other ways, such as in the production of concrete and asphalt (Thakur & Yadav, 2018). Many countries have considered sodium bentonite to be a viable material for use in buffering. Trials conducted by a large number of researchers have shown that bentonite and its various mixtures are beneficial (Komine et al., 1999; Villar & Lloret, 2004; Siddiqua et al., 2011; Rao & Ravi, 2015; Jia et al., 2019).

Engineers working in regions with sandy soils have a tough time acquiring clays at affordable prices for use in liner and barrier applications (Roper, et al., 2015). It's possible that the results of certain research that suggest an ideal clay content for sandy soils might be of significant benefit. It is feasible to manufacture barrier or barrier a cost-effective liner material for landfills by combining sandy soil with sodium bentonite as an active clay. This material may be utilized in landfills (Sommerer & Kitchens, 1982, Bonaparte, et al., 2002, Ghazi, 2015). Sand-bentonite mixtures have a higher compressive strength and less desiccation shrinkage than other types of sands (Galvão et al., 2008).

Several researchers have explored the bentonite's effect on different geotechnical parameters of sand-bentonite mixes, as shown by a review of the available literature (Stewart, et al., 2003, Graham, et al., 1989, Alawaji, 1999). The nuclear waste repository's liner and buffer materials have both been composed of compacted soil-bentonite combinations (Lo, 2001, Shariatmadari, 2011). The clay liner serves as barrier between leachates and ground water as part of a landfill to prevent contamination of the ground water due to leachate migration (Hughes, et al., 2008). In choosing buffer or linear materials, a low-hydraulic conductivity is thus regarded the primary factor among other significant factors like compression, thermal conductivity (ASTM D5084, 2010). Bentonite is an essential component of a liner and buffer material by the high swell, decreased hydraulic conductivity, and its ability to absorb pollutant easily (Middlehoff et al., 2020).

Bentonite is frequently added to a locally accessible soil, like sand, to make better engineering properties such as the maximum dry density, shear strength, shrinkage, and thermal conductivity. Due to Bentonite's ability to expand and then fill the crevices between sand grains, mixtures of bentonite and sand may produce low permeability (Fattah, et al., 2022) and also has a low compressibility. In comparison to natural clay that possess low shrinkage potential during drying or wetting processes (Zeng et al., 2019), the Sand-Bentonite has superior volume stability and greater strength (Ayininuola, et al., 2018). When it comes to geo-environmental applications, where sandy soils predominate, the sand-bentonite combination seems to be a cost-effective alternative (Ayininuola, et al., 2018). The mix ratio considerations include determining the materials' permeability and strength in order to arrive at an optimal solution (Thakur & Yadav, 2018).

1.2 Statement of the problem

The planning, building, and maintenance of a liner system are very important to the efficient functioning of any landfill. On the other hand, buried waste products almost never provide a stable foundation for the system that is placed on top of them (Suter et al., 1993). Failure of landfill liner systems may be caused by a number of different circumstances, including excessive waste settling, contaminant leaching, desiccation cracking, plant roots and burrowing animals, gas leaking, and many more (Rowe, 1998, Mitchell, et al., 1990, Seed, et al., 1990, Zhao & Karim, 2018, Koda, et al., 2019). When bentonite is added in small amounts, it improves the performance of granular materials by providing low permeability and enhanced mechanical stability. The behavior of compacted bentonite-sand mixtures is controlled largely by the properties of bentonite. At a certain bentonite content, the behavior of the compacted SB mixture is influenced by the properties of the sand, (Samingan, 2005). The failure of landfill liners may occur in many different ways, as shown in Figure 1.

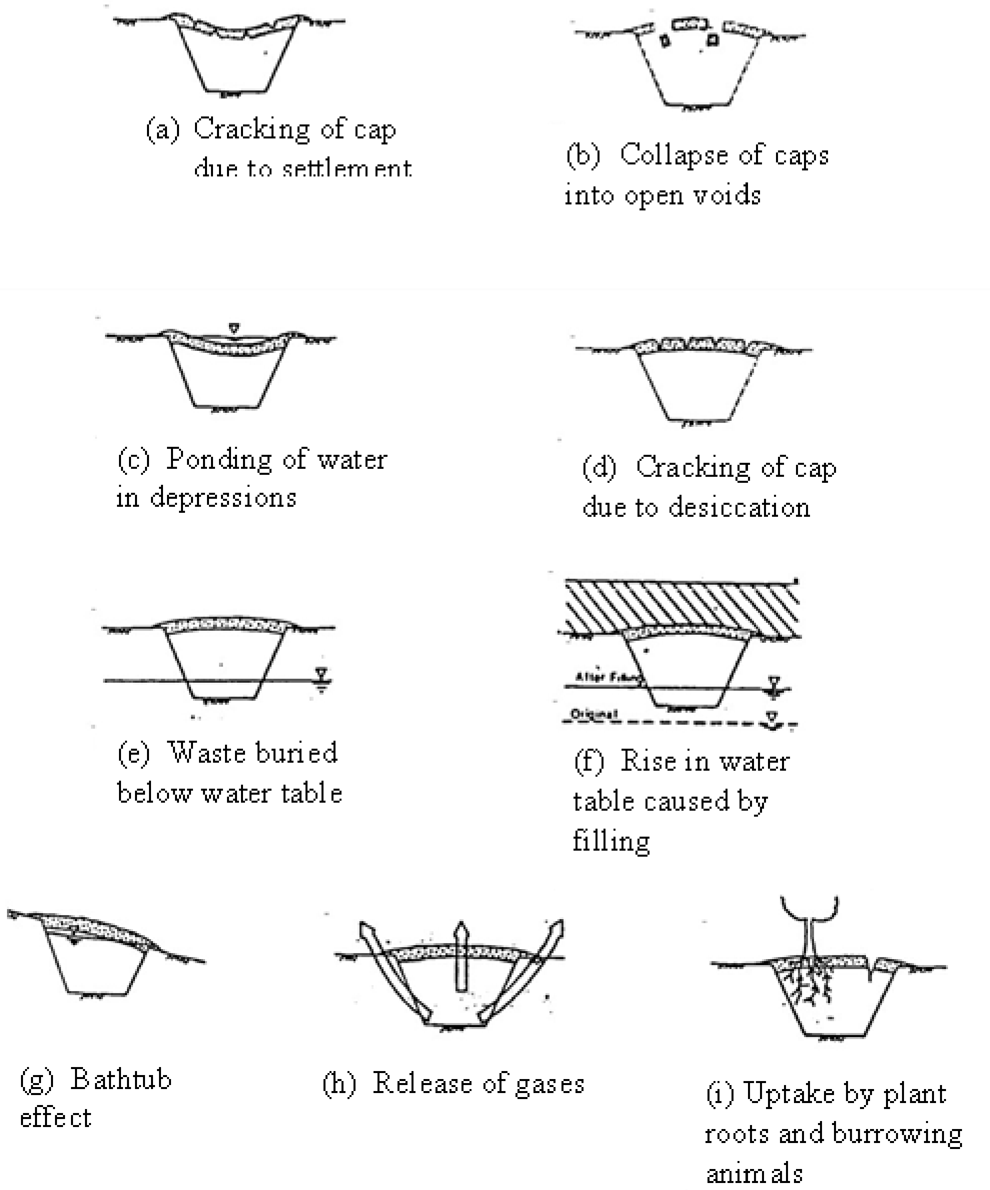

Figure 1: Failure modes of landfill liners (After Daniel 1983)

1.3 Aim and objectives

Aim:

This research study is aimed at investigating sand bentonite mixtures, their geotechnical properties based on different percentages of bentonite mixed in sand to obtain optimum sand bentonite mixture according to the engineering application requirements for landfills which indicate that sand bentonite mixtures should have low hydraulic conductivity less than 10^{-7} cm/sec. Engineering specifications for landfill liners permit a hydraulic conductivity lower than 1 x 10-9 m/s and requires the stability of the system in the operation process.

Objectives:

The primary objectives of the paper are to investigate:

1. Hydraulic conductivity, swell, and compressibility of SB mixtures.
2. Shear and tensile strength of sand-bentonite mixtures.
3. Soil suction (soil potential) of sand-bentonite mixtures.

1.4 Significance of the study

This research would serve as a preliminary study for further investigation into areas such as influence of soil type as well as particle size on the sand bentonite mixture in different types of tropical soils in Nigeria, which is the author's homeland.

1.5 Scope of the study

Within this study, the compaction characteristics of SB mixtures, the hydraulic conductivity, swell/compressibility characteristics as well as suction measurements will be calculated to understand better what characterizes SB mixes. The compaction attributes of sand-bentonite mixture will be gotten through the use of standard-Proctor compaction test according to ASTM D698-12 and for swell/compressibility and hydraulic conductivity measurements, the laboratory specimens will be compacted at optimum moisture content of SB mixture. The Atterberg limit of the sand bentonite mixture will be tested according to ASTM D4318.

To analyze the hydraulic-conductivity, swell, and compressibility of sand-bentonite mixes, consolidation tests will be carried out using the traditional consolidometer test methodology in line with ASTM D243.

Sand bentonite mixes' undrained shear strength will be evaluated using the ASTM D2166 unconfined compression test protocol, and its tensile strength will be determined using the double punch tensile strength test procedure recommended by Iravanian (2015).

The soil suction (soil potential) of sand-bentonite mixtures will be measured by using filter paper method in the laboratory according to ASTM D5298 on pure bentonite mixed with sand at optimum water content. Additionally, measurements of the volume change will be made on SB mixtures prepared above the Liquid limit.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

It has frequently been recommended that a sand-bentonite mixture be used in place of naturally impervious soil in geo-environmental engineering applications. For example, cutoff walls, landfill liners, buffers, and radioactive waste disposal facilities to prevent and reduce the migration of contaminants (Norouzi, et al., 2022).

Hydraulic barriers, such as reservoirs, may also benefit from the usage of this material (Abichou, et al., 2000).

2.2 Overview of bentonite

Montmorillonite clay minerals make up the bulk of Bentonite, an absorbent, swelling clay mineral (Murray, 2006). The volcanic glass in the ash weathers into clay particles during saltwater weathering, which is how bentonite generally develops (Akcanca & Aytekin, 2012). In addition to montmorillonite, bentonites may include a range of accessory minerals, depending on the process through which they formed. These minerals include calcite, gypsum, quartz, and feldspar (Dinh, et al., 2022). Depending on the use, the presence of these minerals may reduce or increase a deposit's industrial value (Consoli et al., 2013)

Adding water to bentonite produces a gelatinous and viscous solution because of its high colloidal strength and high-volume expansion (Komine & Ogata, 1994). There are a variety of uses and applications for bentonite because of its unique qualities. For example, its hydration; swelling; water absorption; viscosity; and thixotropy (Srasra & Bekri-Abbes, 2020).

Bentonite may be used in so many various industries because of its versatility. Examples of these include:

Foundry: The manufacturing of molding sand uses bentonite as a bonding agent in the iron, steel, and non-ferrous casting industries (Clem & Doehler, 1961; Murray, 2006).

Pelleting: During the manufacturing of iron-ore pellet, Bentonite is utilized as a binding-agent (Kawatra & Rikpe, 2002)

Construction and Civil Engineering: Civil engineering uses include diaphragm and foundation walls, tunneling, horizontal drilling, and pipe jacking where bentonite is historically employed as a support, lubricant, and thixotropic agent (Yang, et al., 2018). Bentonite can be utilized in Portland mortars and cement due to its plasticity and viscosity (El-Shamy, et al., 2015). Bentonite is a more ecologically friendly and cost-effective alternative to cement in the manufacturing process. Yoon and El Mohtar (2015) observed that bentonite can be used as a substitute to traditional grouts due to its cheap cost and environmental advantages. Adding bentonite to cement slurry is a potential strategy to reduce impact on the environment (Ghonaim & Morsy, 2020).

Environmental Markets: Adsorption/absorption qualities of bentonite are ideal for waste water treatment (Pandey, 2017). Standard environmental rules specify the use of low permeability soil that contains bentonite, as a sealing material to keep contaminants out of groundwater during landfill construction and restoration (Gates, et al., 2009).

Drilling: Oil and water well drilling are two of the most common uses of bentonite. Its three main purposes are to seal the borehole walls, remove drill debris, and lubricate the cutting head (Saad, 2021). Bentonite-polymer dispersions affect the rheology and filtration characteristics of mud, according to a study by Ahmad et al, (2018). Bentonite-polymer dispersions increased the rheological characteristics of the fluid for drilling, thereby implying that the bentonite-polymer may improve the performance of the drilling fluid (Baleyneh & Aadnøy, 2016)

Agriculture: It is used in animal feed as a supplement, a pelletizing aid, and a flowability aid for components such as soy meal that have not been fully consolidated (Attar, et al., 2019)

Pharmaceuticals: Due to its low cost, extensive availability, and special qualities like high surface area, tiny particle size, high adsorption capacity, high cation exchange capacity, and non-toxic features, bentonite is one of the most commonly utilized clays in environmental, industrial, and medical applications (Abukhadra et al., 2015). Natural bentonite sample's cation exchange capacity, mineral composition, swelling index, specific surface area, colloid properties, and capacity for absorption are the main factors influencing its use in medicinal and cosmetic applications (da Silva Favero, et al., 2019). Bentonite is employed in medicine as an antidote for heavy metal poisoning (Gamoudi and Srasra, 2017; Lismore and Scott, 2019). Bentonite is an ingredient in several care products, including baby powder, and beauty lotions. (Viseras, et al., 2021)

2.3 Sand-bentonite mixtures

2.3.1 Soil-bentonite liners

Swelling capacity, water retention, and poor hydraulic conductivity make bentonite an ideal sealing material for disposal systems (Norouzi, et al., 2022).

It was discovered that the rules governing the liner system varied from country to country. Most nations' bottom lining systems use impermeable layers 1.5 to 2.0 meters thick on average (Ojuri, et al., 2018). To ensure the liner's safety, the goal hydraulic conductivity of 5 x 10-10 m/s was selected. There must be at least a 1.5-meter-thick layer of topsoil or cover soil above the water drainage layer in order to promote plants and prevent erosion (Sapir, et al., 2021). Geomembrane layer above the impermeable layer is optional in both (top and bottom) lining systems, according to Tariq, (2020), and it depends on the kind and class of waste.

As hydraulic barriers, sand-bentonite mixes that have been compacted may be beneficial in water reservoirs and waste-containment systems (Jain, et al., 2022). Adding sufficient percent of bentonite to sand, will result in a mixture which will be able to absorb water and expand when it becomes wet, while at the same time, offering a reasonable level of opposition to desiccation-cracks in the summer period (Stewart et al., 2003). Including sand in the combination offers mechanical balance and prevents the mixture from shrinking below a certain bentonite level, which in turn reduces the swelling (Zhang, et al., 2019). Akgün and Kockar (2018) claim that by filling the spaces between granular sand particles, the presence of bentonite as tiny particles lowers the hydraulic-conductivity of composites. It will be in an unsaturated state and able to absorb water from the geological medium that it is compacted into when it is employed as a liner material. Temperature, chemical makeup, and water availability all have a substantial impact on a material's hydraulic conductivity and swelling capacity (Delage, et al., 2021). A list of common applications for sand bentonite mixture in civil engineering:

- Landfills
- Slurry cutoff walls
- Radioactive waste-disposal sites.

Some details of these application are given and discussed below:

Landfills: Open dumps were the traditional method of disposing of solid waste. It was found that this method had a negative impact on both human health and the environment, thus newer landfills with segregated liners have been utilized instead (Agamuthu & Fauziah, 2011). Isolated liners of many sorts have been proposed, including:

- Compacted clay liners,
- Geosynthetic clay liners, and
- Soil-bentonite liners.

In soil-bentonite liners, as an insulating barrier, sand and a small quantity of bentonite are mixed together to create a soil-bentonite liner. This liner aids in lessening the negative effects of trash on underground soil and water. Many research papers have dealt with this kind of obstacle (Sivapullaiah et al. 2000, Sun, et al., 2009, Chapius, 2012, Srikanth, & Mishra, 2016). This liner's usual cross-section size in landfills should be composed of layers, as shown in Figure 2 (Chapuis, 1990):

- sand-bentonite layer,
- two filter layers, and
- Protective layer.

These layers typically range in thickness from 15 - 20 cm.

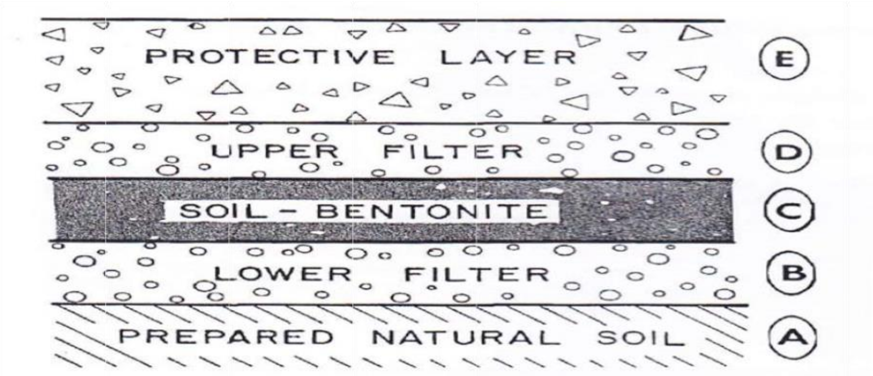

Figure 2: A typical cross section area of soil-bentonite liner (After Chapuis 1990)

Slurry cutoff walls: Slurry-cutoff walls are underground dividers designed to prevent pollution of soil and water below the walls from spreading into the ecosystem that is around the walls (Grube, 1992). These walls are used to separate surrounding soil and existing landfills (Koda & Osinski, 2016). Slurry cutoff walls have been constructed using soil that has been treated using bentonite (Evans 1993). By applying this, a narrow trench with a width of about 0.6 to 1.5 meters must be dug, and it must then be filled with a slurry of bentonite and water mixed with the excavated soils (D'Appolonia 1980). The depth of the trench is kept to a minimum. The bentonite percentage found in trenches typically falls around between 4% and 6% by weight (Barrier, 1995). The average hydraulic conductivity of soil bentonite, according to Barrier (1995), is somewhere between 10-7 and 10-8 cm/s.

Radioactive waste disposal facilities: Repositories for radioactive wastes that pose a danger to humans and the environment might be described as radioactive waste disposal facilities (Abdel, et al., 2020). The radioactive wastes were leveled according to their radioactivity, and the method of leveling varies from country to country (McCloy & Goel, 2017). These are the degrees of proficiency:

- Low-level/ low-activity wastes (LLWs/LAWs)
- Intermediate Level Wastes (ILW)
- High-level wastes.

Considering the Japanese program, hydraulic conductivity of backfill materials must be between 1011 and 1012 m/s (Japan Nuclear Cycle Development Institute 1999 a, b).

2.3.2 Compaction characteristics and index properties

Sand and bentonite are two extremely distinct forms of soil when compared based on particle size distribution, hydraulic conductivity, chemical activity, and strength. In spite of this, when combined in the correct proportions, they may produce an outstanding material that is suitable for use as an engineered barrier against the seepage of fluids (Iravanian & Bilsel, 2009). This material has a low hydraulic conductivity but an adequate shear strength (Farajollahi and Wareham, 1998). By occupying the gaps left by the sand particles, which serve as the mixture's "skeleton" and provide strength and stability, the incredibly small bentonite particles reduce the combination's permeability (Proia, et al., 2016, Srikanth & Mishra, 2016). Because of this, a SB mixture is appropriate as a hydraulic barrier, such as the lid or liner of a landfill.

It has been shown and verified in a number of experiments that bentonite added to sand causes a decrease in the maximum dry density of such combination while simultaneously producing a higher value of the mixture's optimal water content (Ameta & Wayal, 2008, Taha & Taha, 2015, Kolay, & Ramesh, 2016, Xu, et al., 2016). This fact is connected to the extraordinary qualities that bentonite has. Water acts as a lubricant, which makes it possible for soil particles to move closer to one another more easily. As a result, the volume of air spaces is reduced, which results in a greater dry density being reached. On the other hand, water content that is too high (one that is higher than the optimal water content) will create a significant swelling of the bentonite, which will occupy the compaction mold and lead to a raise in the amount of voids. As a result, there is a significant drop in the amount of dry unit weight. This discovery was explained by attributing bentonite's high swelling properties, which might produce a gel-like substance surrounding the soil particles, for a reduced maximum dry unit weight caused by an increase in bentonite concentration. To express it differently, the maximum dry unit weight drops as the bentonite concentration rose. The effective size of the soil particles increases as this gel grows around them. This therefore causes the void volume to grow, which in turn causes the dry unit weight to decrease (Kumar & Yong, 2002).

The liquid and plastic limit for a given clay soil is dependent on a number of properties such as swell behavior, compressibility, shear strength and hydraulic conductivity. As a result, it is reasonable to anticipate a rise in the LL and PL of the sand-bentonite mixes when the clay content of the mixtures increases (Rpout & Singh, 2021). However, the addition of some chemicals (KCl, NaCl, and $CaCl_2$) at concentrations ranging from 0.01-4m to clay soils can cause a decrease in the liquid limit (Di Maio 1996; Van Paassen 2002; Schmitz et al. 2004). The decrease is attributed to a reduction in diffused double layer (DDL) thickness caused by a reduction in forces of repulsion due to cations in the salt solutions which causes flocculation of the clay particles and also makes the clay fabric shrink (Norouzi, et al., 2022).

2.3.3 Hydraulic conductivity

The hydraulic-conductivity for bentonite is determined by a variety of parameters, the most important of which are the void-ratio and the soil fabric. (Farajollahi and Wareham, 1998).

To express the hydraulic conductivity of SB liners that have been compacted, Chapius (1990) utilized both flexible-wall and rigid-wall permeameter test setup. It is common knowledge that (Chapuis, 1990; Farajollahi and Wareham, 1998). To prepare a proper SB mixture for permeability experiments there needs to be replicating of saturated bentonite and sand as a homogenous, two-component mixture.

The findings of several investigations on the hydraulic conductivity of sand and bentonite mixtures indicate that the hydraulic conductivity can vary from 1 x 10-6 m/s to 1 x 10-11 m/s depending on the amount of Na-bentonite in the sand. Additionally, it was shown that even while the dry density remained constant, there was reduction in permeability as the bentonite concentration increased (Kumar and Yong, 2002). Additionally, it was shown that the hydraulic conductivity of sand with Na-bentonite was lower than the hydraulic conductivity of sand with Ca-bentonite at a particular dry density (Ahn & Jo, 2009). Kumar and Yong (2002) stated that the high specific surface of bentonite particles is what causes the reduction in hydraulic conductivity of sand-bentonite mixes. The water molecules cannot move as easily as they would in the remaining water in the gaps as a result of the high specific surface that permits bentonite particles to trap some of the water in a double layer. The hydraulic conductivity is reduced as a result.

According to Kumar and Yong (2002), the bentonite may have formed a gel or paste around the sand particles by absorbing water, which may be the reason why hydraulic conductivity of SB mixtures reduces. The majority of the pores would be filled by this gel or paste, which would prevent the water from passing through the gaps. This would cause the water to flow more slowly and the permeability to decrease (Kumar & Yong, 2002). Alternately, the incredibly small bentonite particles lessen the hydraulic conductivity by shrinking the clods and removing the gaps between them that may produce smaller minifabric pores. The hydraulic conductivity decreases as a result (Kumar and Yong, 2002).

2.3.4 Shear strength

Compaction factors, such as water amount, and dry density, play a role in determining the structure and fabric of compacted soils. Compaction effort also plays an important role (Tripathi et al., 2003).

According to Kumar and Yong (2002), when bentonite is added to a soil mixture, the interparticle repulsion decreases and, as a result, the soil structure becomes more flocculated. Given that increasing repulsion reduces shear strength, as demonstrated by Lambe (1969), it stands to reason that the addition of bentonite, which reduces repulsion, leads to an increased shear strength for the soil. A raise in bentonite concentration raises shear strength because a higher flocculation rate results in more randomly oriented particles (Kumar and Yong, 2002).

Chalermyanont and Arrykul (2005) talked about bentonite addition to a combination leads to reduced shear strength of the material because of its significant tendency to expand when exposed to water. The samples' cohesiveness would increase if there was a larger concentration of bentonite in the soil. Even after adding tiny amounts of bentonite, say 5%, sand would change from having qualities similar to a sand-like material having a high friction angle and low cohesiveness to having traits similar to a clay-like material having a low internal friction angle and strong cohesion (Chalermyanont & Arrykul, 2005).

2.3.5 Swelling characteristics

Swell pressure is the amount of force is needed to keep the volume of the soil constant (Mesri et al., 1994; Sridharan et al., 1986). It is understood that some unique characteristics can influence the degree of swelling pressure that expansive soil exhibits. Examples of internal variables include concentration and cations types in the pore water, while examples of external variables include compaction conditions (such as dry density and water content), method of application (such as compaction type and energy), and characteristics of the bulk fluid used to hydrate the soil (Nelson & Miller, 1997). The swelling-pressure that was detected is a macroscopic phenomenon that may, to some degree, be reflected by the behavior of the soil when seen on a microscopic scale. Clay expansion on a microscopic level is something that has been thoroughly discussed in the past (Langroudi & Yasrobi, 2009, Zhao, et al., 2020). For instance, the diffuse double-layer concept attributes the expansion of clay to the interaction of electrical double layers around the clay platelet surfaces (Mitchell, 1993). According to this theory, clay has the maximum conductivity conceivable when mixed with deionized water because the fully formed DDLs around the clay particles provide an infinite amount of electrically conductive channels (Mojid & Cho, 2006) As a result of the common negative charge of clay particles, several properties are influenced by the activity of boundary phenomena between water molecules and particles of clay. Clay particles, containing soluble cations of different charges, are suspended in water and covered by absorbed water. These cations, often referred to as exchangeable cations, produce diffuse double layers, or DDLs, and increase the electrical conductivity of DDLs to balance out the negative charges on particles of the clay (Waxman and Smith, 1968, Mogi et al., 1986).

2.3.6 Sand-bentonite suction

A soil's total suction is influenced by both matric and osmotic suctions. The single factor that causes osmotic suction in the soil is the quantity of dissolved salt (or ions) present (Rao & Thyagaraj, 2007). After then, the matric suction might be seen as being composed of the capillary and sorptive forces (Yong, 1999). Bentonites have an osmotic suction that is inherent to them as a result of the ions in their pore water (Castellanos, et al., 2008). In compacted bentonites, there are frequently holes of different sizes, including pores between unit layers, interparticle apertures between particles of clay in the aggregates, and interaggregate pores between clay particle-containing aggregates (Delage et al. 2006). Sand has a dominant impact on the mechanical behavior of a bentonite-sand combination when there is little bentonite present, primarily because of intergranular contact between the sand grains (Agus, et al., 2013). The parameters of the combination are affected by the load-deformation properties of the sand at various dry compaction densities (such as coefficient of permeability, swelling potential and shear strength) (Stewart et al., 1999). Graham et al. (1995) and Blatz et al. (2002) conducted research that investigated the effect that suction has on shear strength and stiffness of an unsaturated compacted bentonite–sand combination. Researchers from Sun et al. (2009) investigated the volume change that occurs naturally in a variety of sand–bentonite mixes. It is possible for compacted sand and bentonite mixes to generate metastable structures, which, in turn, are capable of demonstrating collapse upon flooding when large applied stresses are present (Agus, et al., 2013). The behavior of collapse was seen for compacted mixes that included a small amount of sand and had a dry density lower than about 1.25 Mg/m^3.

Chapter 3

MATERIALS AND METHODS

3.1 General

This section lays emphasis on the geotechnical properties of bentonite and sand-bentonite mixtures. When the addition of different amounts of bentonite to the sand is done, different sand and bentonite mixtures are produced. Sand and bentonite are combined in varying amounts to produce combinations with the necessary hydraulic conductivity and volume change properties. Bentonite and sand-bentonite combination characteristics were examined according to ASTM specifications.

For experimental investigations, the selection of sand and bentonite material was carried out based on the properties of these materials used by most investigators like Haug and Wong (1992), Kenney et al. (1992), Santucci de Magistris et al. (1998), and Abichou et al. (2000).

Several research work have been carried out on sand-bentonite mixtures by evaluating their laboratory properties with maximum limits being 25%. However, for the use of sand-bentonite mixtures as materials for backfill in some part of access tunnels of high level radioactive waste disposal facility, Dixon et al. (1999) and Komine and Ogata (1999) worked on sand-bentonite mixtures between 30-50%. In this research, it was chosen to formulate three sand-bentonite mixes having the amount of bentonite ranging from 10% to 20% in steps of 5%, as indicated in Table 1.

Table 1: Categories of sand-bentonite mixtures

Sand-Bentonite Mixtures	**Bentonite (%)**	**Sand (%)**
M1	10	90
M2	15	85
M3	20	80

The general testing program is given in Figure 3.

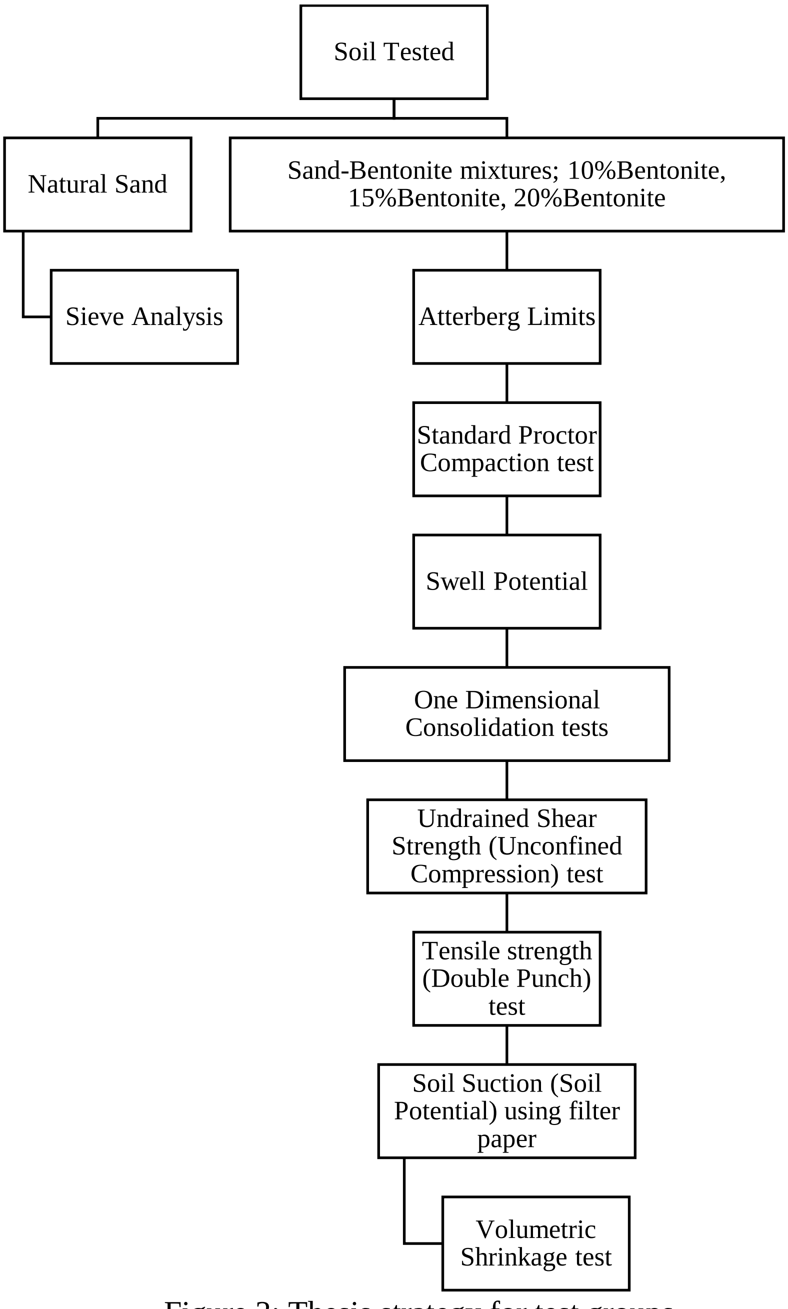

Figure 3: Thesis strategy for test groups

3.2 Materials

3.2.1 Sand

For this research, sand from the beach of Famagusta Bay was used for sand-bentonite mixtures (Abiodun and Nalbantoglu 2017, Golhashem and Uygar 2019, 2020; Alibrahim and Uygar 2021). The location of the site from which the sand was taken is shown in Figure 4.

Figure 4: Location of sand studied in the present study (Google map)

Figure 5 depicts the sand's grain size distribution utilized for the sieve analysis. The method used to establish the sand's grain size distribution was dry sieve analysis. With reference to ASTM D422-63 (ASTM 2007), which measured the sand's particle-size properties, the coefficient of uniformity (Cu) and coefficient of curvature (Cc) were 1.82 and 1.02, respectively. Sand has been discovered to have a maximum dry unit weight (dmax) and a minimum dry unit weight (dmin) of 16.0 and 13.6 kN/m3, respectively. Going by the Unified Soil Classification System, sand with no particles was categorized as poorly graded sand (SP) (ASTM D2487-11). As determined, the sand used in this research was in its natural state.

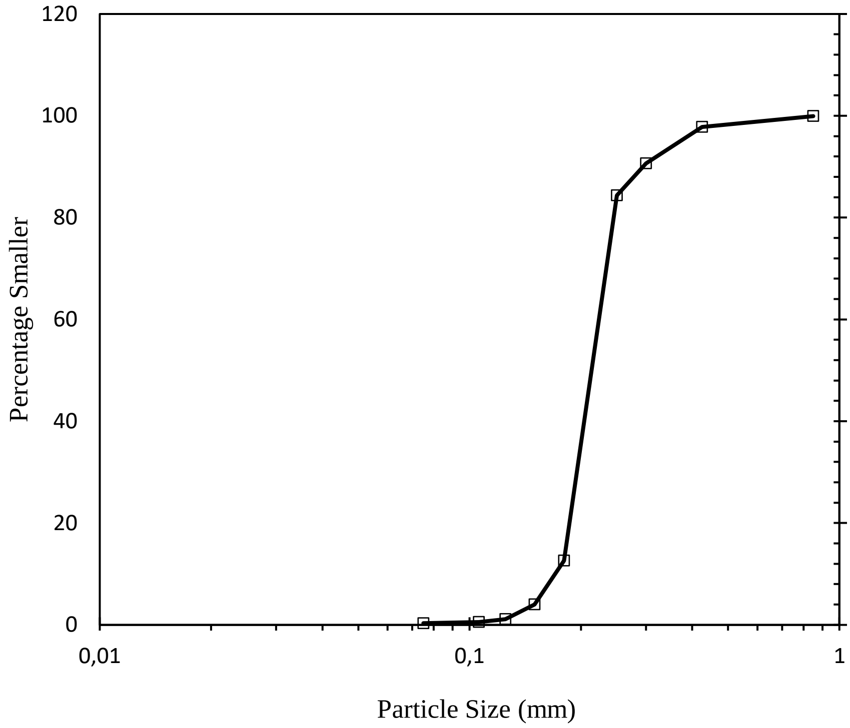

Figure 5: Particle size distribution of sand used in the study

3.2.2 Na bentonite

Na-bentonite, which was obtained from Karakaya Bentonite Inc. in Turkey, was the kind of bentonite employed in the current investigation. In general, "montmorillonite" minerals make up bentonite. The amount of montmorillonite present determines the physical characteristics, which include the high Cation Exchange Capacity (CEC), high swell potential, big specific surface area, and low hydraulic conductivity. Based on the external cation absorbed during mineral formation, bentonite may be divided into sodium and calcium varieties. However, with its greater swell capacity and extremely low hydraulic conductivity, sodium bentonite is more frequently utilized, as it was in this investigation. After being saturated with water, sodium-bentonite may absorb in water about five times its initial mass, which then forms a substance that is gel-like and about 15 times its initial volume (Ameta and Wayal, 2008). Montmorillonite is a volcanic ash byproduct that is a highly colloidal mineral made up of one gibbsite sheet sandwiched between two silica sheets. There are a lot of water molecules and a sparse number of exchangeable cations between each layer of montmorillonite. Due to the attraction of water molecules caused by the negative charge of its outer layer, the basal spacing of this mineral has a range of 9.6 to a point of complete separation in full hydration (Mitchell1 1993; Das 2006). Water permeates the crevices between the layers of montmorillonite when it comes into touch with it. The water trapped in the sheets of clay could vary from one to four molecules, this depends on the kind of vapor pressure and cation. Some clay kinds see a large volume shift as a result of this property (van Olphen, 1963). The liquid moves into the sodium montmorillonite interlayer, where it forms a thick, viscous double layer that surrounds the clay sheets and causes the particles of clay to inflate. This swelling may continue until the clay sheets entirely separate (Kenney et al., 1992).

The ASTM D4318 technique was applied to calculate the liquid and plastic limits. Bentonite was thoroughly combined with distilled water to create a thick paste, which was then allowed to hydrate for 24 hours.

3.2.3 Sand-bentonite mixtures

Table 2 below shows a list of the index properties of the SB mixtures used in this experiment. It was discovered that the bentonite used in this experiment had liquid and plastic limits that were very close to those of Wyoming bentonite (Mollins et al. 1996).

Table 2: Summary of properties of sand and bentonite used in the study

PROPERTIES	SAND	BENTONITE
Specific gravity	2.75	2.81
Atterberg limits		
Liquid limit (%)	NA	448.0
Plastic limit (%)	NA	39.5
Plasticity index (%)	NA	408.5

The liquid and plastic limits of sand bentonite mixtures were established as described in ASTM D4318. Each of the SB mixtures was mixed with distilled water to make a thick bentonite paste before proceeding to the liquid and plastic limit tests. Table 3 provides a list of the index properties for several sand-bentonite blends. The liquid limit of SB mixtures almost invariably varies linearly with the increasing of bentonite concentration. However, the plastic limit of the sand-bentonite mixes is not significantly affected by the increase of bentonite content. Santucci de Magistris et al. had described a similar pattern of activity (1998). For the sand-bentonite mixture M1 and M2, the plastic limit could not be determined. Hence, this sand-bentonite mixtures are termed as non-plastic (NP).

Table 3: Index properties of sand-bentonite mixtures

Sand Bentonite Mixture	Liquid Limit [%]	Plastic Limit [%]	Plasticity index [%]
M1	40.3	NP	NA
M2	55.1	NP	NA
M3	66.6	24.0	42.6

3.3 Sample preparation

By dry weight, these three mixtures are: 10% bentonite-90% sand for M1, 15% bentonite-85% sand for M2, and 20% bentonite-80% sand for M3. The used Bentonite was dried at a maximum temperature of 60° C while sand was pre-dried in an oven. The industry-standard ASTM D698-12 Proctor compaction test may be applied to establish the ideal water content and maximum dry density of sand-bentonite mixtures. Each batch was completely mixed in a mechanical mixer, placed in double nylon bags, and allowed to stand for 24 hours before being compressed in order to achieve a constant moisture content.

3.4 Test methods

3.4.1 Standard proctor compaction test

The SB mixtures that were employed in this experiment were compacted as follows. To begin, distilled water (DW) was added to the dry sand-bentonite mixtures. To provide the required initial wet weight (wi) for compaction, DW was added to the mixes at various water concentrations. The wet soil mixture was sealed, then allowed to cure for 24 hours to have an even water distribution in the mixture. After the curing time, each combination underwent standard Proctor compaction at various water contents. To ensure homogeneous compaction, the slurry was put into the mold in three stages and tamped with 25 blows each layer. The collar was taken off at the conclusion of the third layer, and the sample was then trimmed and weighed. Additionally, little portions of the compressed mixture were collected from the top, mid, and bottom to measure the water contents. The compacted sand-bentonite in the collar of the compaction mold is shown in Fig. 6.

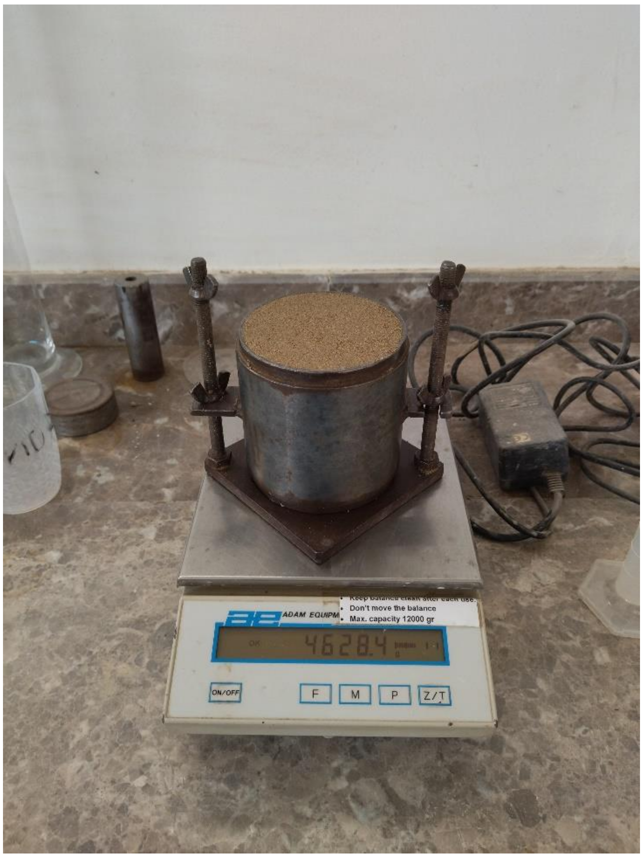

Figure 6: Compacted sand-bentonite sample after completion of compaction

3.4.2 Consolidation test

To measure compressibility of Sand-bentonite mixtures, an ASTM D 2435 (1996) consolidation test procedure was performed by using one dimensional consolidometer test apparatus. Fig. 7 shows the standard consolidometer used in the study.

Figure 7: A standard consolidometer used in the present study

As noted, SB mixtures were put in polyethylene bags, sealed, put in a desiccator for 24 hours to produce a moisture equilibrium were compacted, and samples with a 75 mm diameter and 14 mm thickness were prepared for a consolidation test. For the swelling that happens when water is absorbed into the soil sample, a 5 mm gap was formed between the top of the soil specimen and the consolidation ring (Sun, et al., 2009). Assembly was loaded at 7 kPa onto an assembly frame after being placed in a consolidation cell. The top cap was filled using distilled water, and swell was allowed to continue until the maximum swell was reached.

The loading and unloading stage commenced starting with loading. Loads ranging from 1kg, 2kg, 4kg, 8kg, 16kg and 32kg added after a period of 24 hours each to compress the sample after which unloading was done.

Coefficient of consolidation (c_v) is determined by Taylor's square root of time fitting method which is given as.

$$c_v = \frac{D^2 Tv}{t_{90}} \tag{1}$$

where,

t_{90} is time for 90 % degree of consolidation,

D is length of the drainage path

T_v is the dimensionless time factor.

Using the volume change coefficient mv, the unit weight of water (γw), coefficient of consolidation cv, the hydraulic conductivity at each pressure increment, k, was calculated, as

$$k = m_v c_v y_w \tag{2}$$

3.4.3 Unconfined compression tests

SB mixtures compacted following the ASTM D2166-06 (2016) at the ideal water content were tested for unconfined compressive strength using a continuous strain rate of 1.25 mm/min to simulate an undrained scenario. In order to match the standard specification, specimens with an inner diameter (D) 38 mm and an outer height (H) 76 mm were created. This target height-to-diameter ratio ranged from 2.0 to 2.5. The unconfined compression test equipment utilized in this work is seen in Fig. 8.

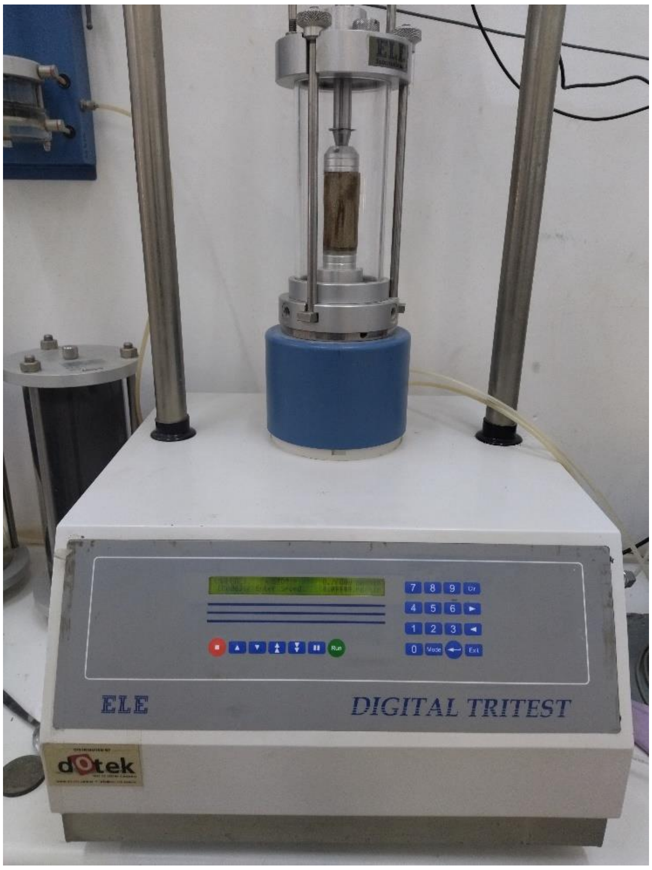

Figure 8: Unconfined compression test apparatus

It was determined that samples had unconfined compressive strengths based on:

$$\sigma_c = \frac{P}{A} \qquad (3)$$

Where; σ_c = unconfined compressive strength (kPa),

p = applied load (kN) and

A = corresponding average cross-sectional area (mm^2) which is given by:

$$A = \frac{Ao}{(1-\varepsilon)} \qquad (4)$$

A_o = initial average cross-sectional area of the specimen (mm^2)

Axial strain (%), $\mathcal{E} = \frac{\Delta I}{I} \times 100$ (5)

ΔI = Change in length of the specimen (mm) and

l = Initial length of the specimen (mm)

3.4.4 Suction measurements by filter paper method

Filter paper method is one of the earliest techniques for calculating suction. It is trustworthy, economical, and appropriate for several suction pressures, from ten to one million kPa. With this technique, suction pressures between 50 and 30,000 kPa may be attained. The initial suction of compacted soil bentonite mixes has been carried out using filter paper method, in accordance with ASTM D 5298-94. SB samples were statically compressed to their optimal water content and maximum determined dry density. The samples were placed one at a time, in sealed containers, at various drying stages, and dried in close contact with three different filter papers (Whatman No. 42). For reliable measurement of matric suction, a very near touch is necessary. The top filter paper, often known as the "sacrificial paper," was used so that the bottom two sheets would not be damaged. When doing an indirect measurement of suction, the amount of moisture contained in the sacrificial paper is not considered. After that, the containers were vacuum sealed and put in Styrofoam boxes that were stuffed with glass wool. They were then kept for a period of 10 days during a suction equilibration phase (Bilsel, 2004). Fig. 9 shows the prepared specimen kept in the glass jar.

Figure 9: Prepared specimen in the glass jar for suction measurement

3.4.5 Volumetric shrinkage test

Consolidation rings with 75 millimeters diameter and 20 millimeters in height were used to create the samples for the shrinkage test. In order to help create a homogenous slurry, the SB mixtures were prepared with a water concentration about 5% higher than the liquid limit. SB mixtures were placed in a controlled-temperature room where they could dry. The specimens' diameters, weights, and heights were measured throughout a range of time intervals until it reached a point where no reduction in volume could be measured in any of the samples.

Figure 10: Sand-bentonite samples in consolidation rings

3.4.6 Tensile strength-strain characteristics

To ascertain the tensile strength of soil, double punch test as discovered by Fang and Chen (1971) is used. Two circular discs are placed vertically between two plates of loading, with the soil sample placed in between them. One disc is placed above the soil, while the other is placed below it (Al-Hussaini & Townsend, 1974). After that, the specimen is put through a process in which it is compressed from both of its sides (Chen, 1975). Because the failure plane is not predetermined, it will only fail in the plane that has the lowest strength. This test typically yields lower tensile stress results than the Brazilian test because the Brazilian test's failure plane is predetermined, and cracks always form vertically, regardless of whether it is the strongest or weakest plane (Al Houri, et al., 2020). In contrast to other test, in double punch test, cracks always form horizontally (Chen, 1975). Because it does not need the use of any heavy apparatus, the double punch test has a tremendous advantage in that it may easily be paired to California bearing ratio test or compaction soil tests during testing in the laboratory (Fang & Chen, 1971). This is a huge benefit of the double punch test. The following formula may be used to compute the tensile strength for the double punch test:

$$\frac{P}{\pi a^2}=\frac{1\text{-}\sin\varphi}{\sin\alpha\cos(\alpha+\varphi)}\frac{q^u}{2}+\tan(\alpha+\varphi)(\frac{bh}{a^2}\text{-}\cos\alpha)\sigma_t \quad (6)$$

Where the maximal tensile stress is σ_t; P stands for applied load, a for disk radius, φ for inclined cone angle to the surface, α for cone angle, qu for unconfined compressive strength, b for specimen radius, and h for specimen height (Iravanian & Bilsel, 2016).

The equation may be simplified to the following equation when determining the maximum pressure that will cause failure, and tensile strength can be calculated as follows:

$$\delta_1=\frac{P}{\pi(kbh-a^2)} \quad (7)$$

Where δ_1 is tensile strength; P is the load that was applied; a diameter of the steel disc used; b is radius of specimen; h is height of specimen. k = tan $(2\alpha + \varphi)$. For stabilized soils, Fang and Chen (1971) recommended values of k for Proctor mold as 1.2 and for CBR mold as 1.

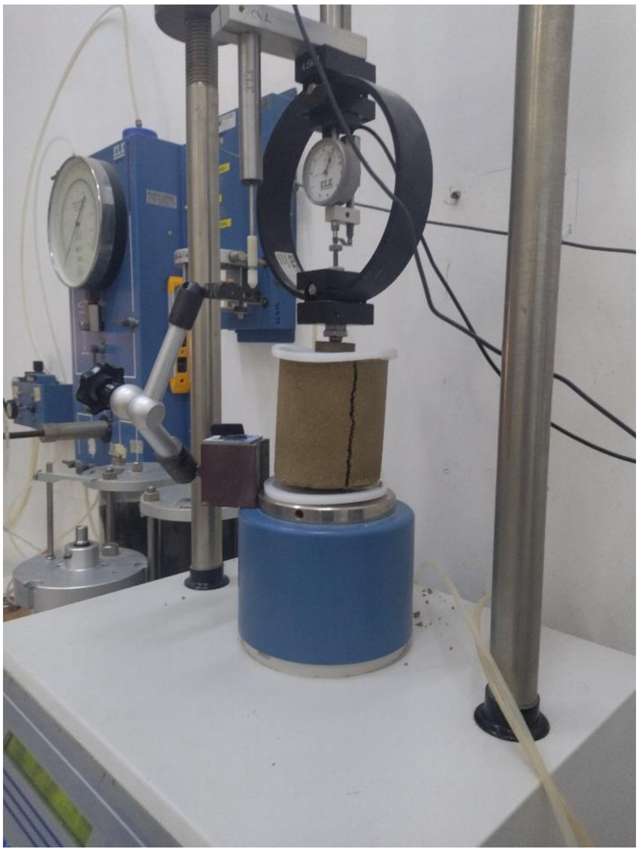

Figure 11: A set-up for double punch test

Chapter 4

RESULT AND DISCUSSION

4.1 Compaction characteristics

The results of standard Proctor compaction tests are summarized in Table 4 and the comparison of all mixtures is illustrated in Figure 12.

Table 4: Compaction characteristics of sand-bentonite mixtures

Bentonite content (%)	**Maximum dry density (g/cm^3)**	**Optimum water content (%)**
10	1.73	17.0
15	1.74	20.0
20	1.75	22.0

Before preparing the test specimens for compressibility and strength testing, the appropriate moisture content and maximum dry densities of sand-bentonite mixtures were determined using the traditional Proctor compaction test (ASTMD698). The discovered connections between maximum dry density and water content is given in Figure 12. The maximal dry density was at its greatest point (20%B) from the M3 combination. The bentonite concentration in sand-bentonite mixtures with the lowest propensity to absorb water corresponds to M1, which has the lowest optimum moisture content.

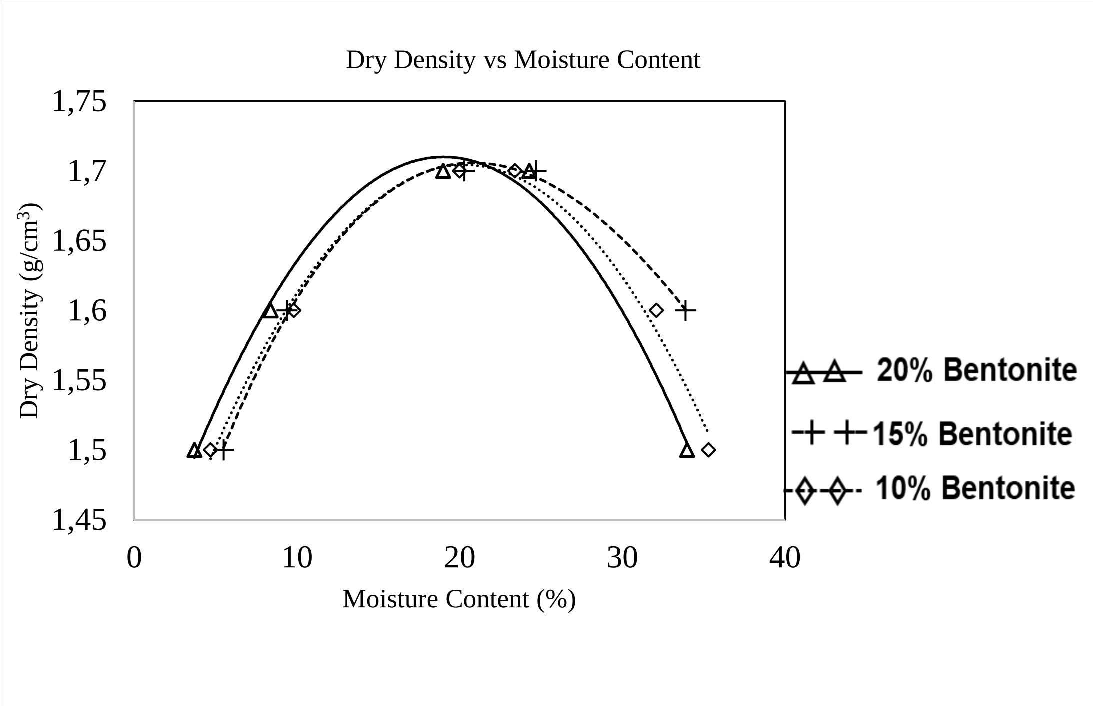

Figure 12: Comparison of the compaction curve of sand-bentonite mixture

4.2 Swell and compressibility characteristics

Figure 13 illustrates the relationship between the amount of time spent in various bentonite concentrations and the percentage of swell of SB mixtures compacted at the optimal water content. Swell in sand-bentonite mixtures was measured and expressed in % swell using the ratio of total rise in the specimen's height during the swell test at any time to the initial height of the specimen.

When the compacted sand-bentonite mixture was allowed to hydrate, water was absorbed by the montmorillonite mineral in the bentonite into the interlayers of the mineral, which increased the amount of bentonite in the soil. The amount of bentonite in the mixture had a significant impact on how much of the volume changed. Figure 13 shows that the sand-bentonite mixture with 20% bentonite produced the biggest swell. The swelling was greatest when the bentonite content was higher. Bentonites inflate as a result of particle-water-cation interactions, which alter the inter-layer structure of the expansive clay minerals contained in bentonite (Dutta & Mishra, 2016). Sand-bentonite combinations swell as a consequence of the expansive clay minerals in bentonite expanding as a result of the water being absorbed by them.

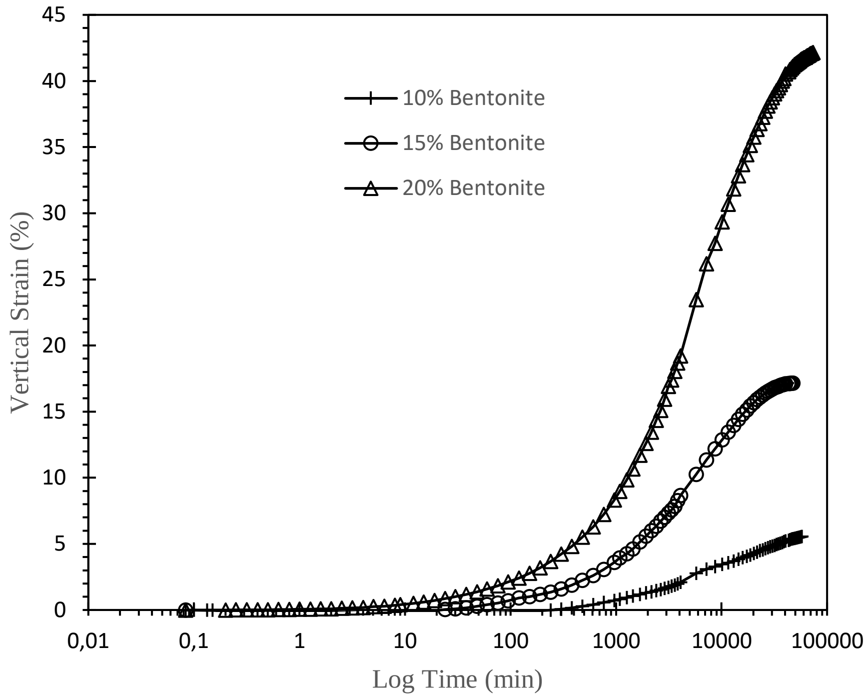

Figure 13: Graphs of percent swell versus time of sand-bentonite mixtures

In Table 5, the maximum percent swelling of sand-bentonite mixtures is reported. Because bentonite has a higher specific surface area and a greater ability to absorb water, sand-bentonite mixtures absorb more water as their bentonite content increases, which raises the swell potential. The swell potentials of three different combinations of bentonite percentages range from 5.5% to 43%. (Table 5). The highest percentage of bentonite in the 20% B combination is responsible for the highest swell potential in sand-bentonite mixtures. Table 5 also includes the swell pressure values that were obtained from the values found for the one-dimensional oedometer test. In the oedometer test, the sand-bentonite mixes' allowable volume changes are taken into account, and the equivalent pressure needed to return the soil to its initial volume is quantified as the swell pressure. The M3 combination, which had the highest bentonite content, had the highest swell pressure, which was 400 kPa, showing that higher swell pressure is required for the specimens with higher bentonite content to avoid swelling.

Expansive materials like bentonite undergo volume change and swell when exposed to water. When volume is constant, swell pressure is developed as water is absorbed by the bentonite. If a soil mixture with known dry density and water is used only for wetting with changes in pressure or volume, the extent of swell pressure depends only on the amount of water absorbed by soil, as it defines the distance of seperation between two clay parts, which in case of restricted swelling it leads to swelling pressure increase. Muntohar and Hashim (2003) concluded that swelling pressure, swelling and compressibility increase of kaolinite and bentonite mixed with sand has a direct relation with bentonite content. An increase in swell pressure was due to increased hydration force of bentonite within the samples.

Table 5: Maximum swell potential of sand bentonite mixtures

Sand-bentonite mixture	Maximum percentage swell (%)	Swell Pressure (kPa)
M1	5.5	76
M2	17	220
M3	43	400

After the one-dimensional swell tests in the consolidometer test apparatus, the sand-bentonite mixtures were loaded and void ratio, e versus log effective vertical stress, P curves (e vs log P) were drawn. Taylor's method was used in determining coefficient of vertical consolidation in doubly drained condition and time for 90% consolidation (t_{90}) was determined. Figures 14–16 show the e vs log P curves for 10%, 15% and 20% sand-bentonite mixtures. When the slopes for the loading and unloading of the e vs log P curves were considered, the compression index (C_c) and recompression index (C_r) of sand-bentonite mixtures were determined, respectively. With a rise in bentonite concentration, higher C_c and C_r levels are seen (Table 6). The C_c and C_r values of the 15% B specimen are 0.003 and 0.000373, respectively, while they are 0.001 and 0.000123 for the 10% B specimen. The data in Table 6 show that as the bentonite amount in the mixes increased, so did the compressibility and expansion properties of the SB mixtures.

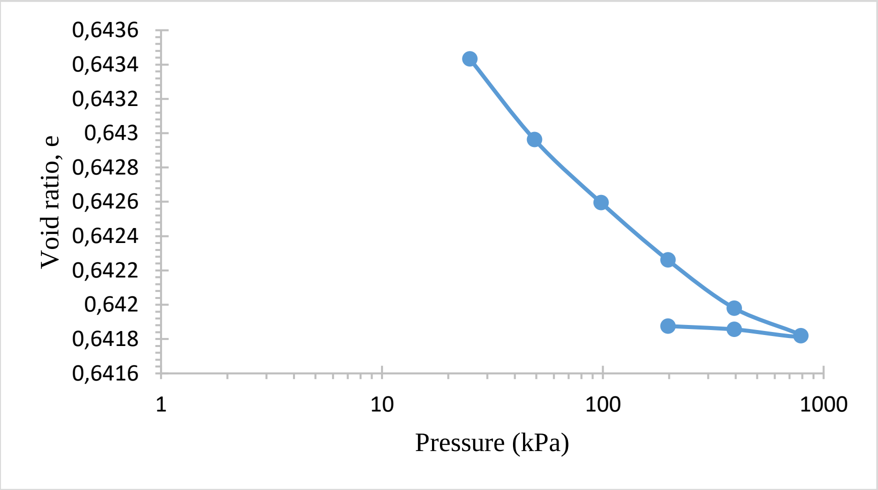

Figure 14: Plot of e versus log P for 10% bentonite

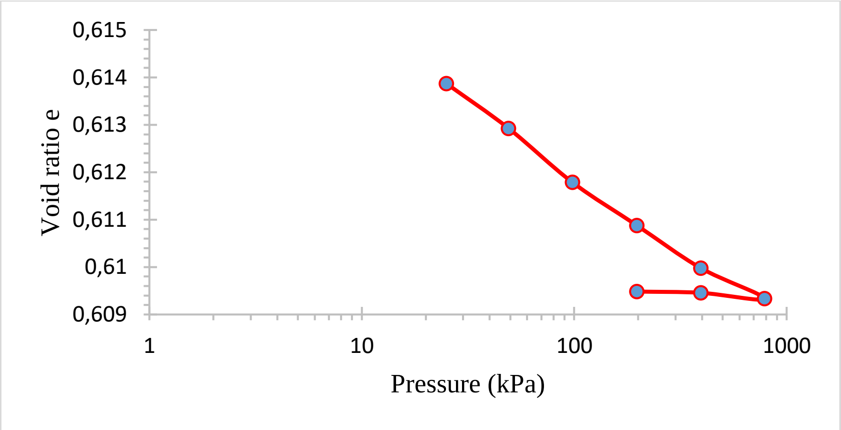

Figure 15: Plot of e versus log P for 15% bentonite

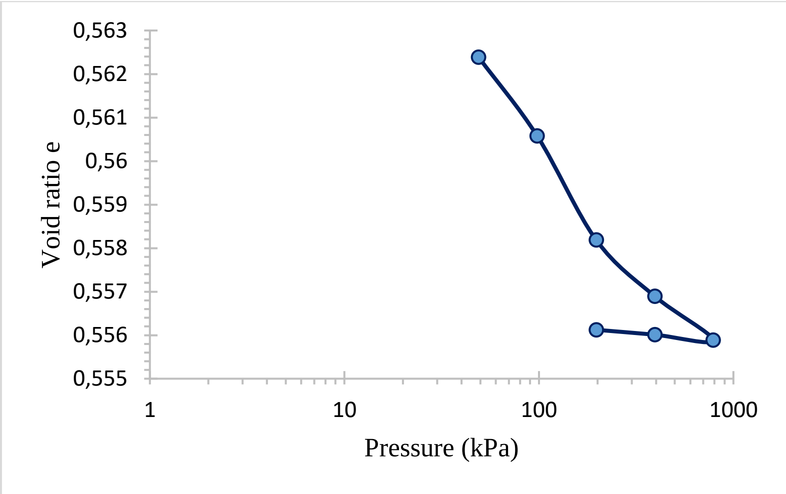

Figure 16: Plot of e versus log P for 20% bentonite

It was discovered by Chalermyanont and Arrykul (2005) that cohesion soil of samples would increase parallel to an increase in bentonite content. Addition of small amounts of bentonite, such as 5%, properties of sand would change from sand-like material with high friction angle and low cohesion to clay-like material with low internal friction angle and high cohesion. It was also mentioned that in high contents of bentonite, with high hydration, the swell would be so high that there would be no significant change in hydraulic conductivity and the mixture becomes gradually cohesionless and hence attain weak shear strength. This was also observed in this study as the samples were allowed to attain maximum swell which had an effect on the compressibility behavior and shear strength of the samples.

Table 6 gives the characteristics of compressibility for SB mixtures that were found in e versus log P curves. Compression and recompression indices, coefficient of volume compressibility (m_v) and the coefficient of consolidation (c_v) values are presented in Table 6.

The coefficient of volume compressibility (m_v) is known as change in volume per unit volume per unit increase in effective stress. Values of m_v were determined for a pressure increment of 98 kPa-197 kPa.

The compression index, C_c of the SB mixtures results in a larger value of Cc when a vertical pre-consolidation pressure is applied to the sand-bentonite mixtures. With an increase in bentonite, so did the Cc value. This observation is in line with that of Iravanian (2015).

Table 6: One dimensional consolidation test result

Bentonite Content	**10%**	**15%**	**20%**
Initial void ratio, e_0	0.644	0.615	0.564
Height of Soil Solid, H_s (cm)	0.852	0.867	0.895
Compression Index, C_c	0.001	0.003	0.004
Recompression Index, C_r	0.00012	0.00037	0.00041
Coefficient of Volume Compressibility, m_v (m^2/N)	2.06E-06	3.68E-06	4.2E-06
Average Coefficient of Vertical Consolidation, c_v (m^2/min)	0.019	0.027	0.034

The values in Table 6 shows that an increased bentonite content increases the c_v values of the sand-bentonite mixtures. When the vertical consolidation pressure is raised, a saturated soil sample's coefficient of consolidation (c_v) shows how quickly it consolidates in one dimension. A higher c_v number suggests a quicker rate of consolidation, while a lower C_v value indicates a slower consolidation rate. The increased c_v values can be simplified by the shorter time required for percent consolidation to be attained in the mixtures with high bentonite content. For each percent increase in bentonite concentration, the c_v value increased, showing that the mixture consolidates more quickly under higher bentonite content. The proportion of bentonite in the mixes was shown to enhance the c_v of the sand-bentonite mixtures. It is made known by the fact that increasing bentonite content resulted in an increased thickness of the bentonite coating, the sand-bentonite mixtures and led to a structure with more pore void space. This led to an increase in the rate of consolidation and increase in c_v values.

Using the one-dimensional consolidation theory by Terzaghi, which is represented by the following equation, hydraulic conductivity values of SB mixtures were calculated:

$k = c_v m_v y_w$

Where;

k is hydraulic conductivity (m/s)

c_v is coefficient of consolidation (m^2/s) by Taylor's method,

m_v is coefficient of volume compressibility (m^2/kN); and

y_w is the unit weight of water (kN/m^3)

In the present study, the values for hydraulic conductivity (k), the mixtures were calculated at the pressure level of 98kPa - 197kPa. Table 7 gives the hydraulic conductivity of the mixtures. Based on the one-dimensional consolidation theory by Terzaghi and the equation given above, increased c_v value suggests an increase in hydraulic conductivity. There was an increase in the hydraulic conductivity with an increased amount of bentonite. The highest hydraulic conductivity value of sand-bentonite mixture was obtained with the highest bentonite content of 20%. This could be explained with respect to an increase in bentonite content as a result of which some grains are generated in sand-bentonite mixtures and resulted in an increase in the pore void space available for water flow in sand-bentonite mixtures. And thus, there was increased rate of flow and hydraulic conductivity for the SB mixtures. This finding is in good agreement with Abichou et al., 2002.

Table 7: Hydraulic conductivity of sand-bentonite mixtures

Sand-Bentonite mixtures	**M1**	**M2**	**M3**
k(m/s)	3.7267E-7	9.7442E-7	1.4004E-6

4.3 Suction characteristics

In engineering practice, the water content of a soil decreases as suction increases in a drying path (desorption). A single valued function, usually the desorption curve, is used to classify the hydraulic properties of unsaturated soils (Iravanian, 2015). The drying curve has a breaking point that corresponds to the matric suction when the soil begins to de-saturate. The air-entry value (AEV), is known as the suction at which air enters the largest pores of the soil (Fredlund and Rahardjo, 1993; Rahardjo and Leong, 1997). SWCC contains significant information for unsaturated soils regarding the amount of water retained, pore size distribution and the stress state in soil-water (Sillers et al., 2001).

Soil Water Characteristic Curve (SWCC), of sand-bentonite mixes is steep and abrupt, as seen in Figure 17, demonstrating the strong sensitivity of soil for total suction to reduction in water content. The sand-bentonite mixture with the greatest bentonite concentration, 20%, produced the steepest SWCC. This is because water is tightly held to the soil in the zone of residual saturation and there is little hydraulic flow through the pores, which occurs mainly as vapor flow and the same sand-bentonite mixture also produced the highest suction measurement. Van Genuchten suction equation is used to model the data in Figure 17. The desorption suction curve shows that there is not much difference in suction values for 10B and 15B. But with an increased bentonite content to 20%, further increase in the suction values was obtained.

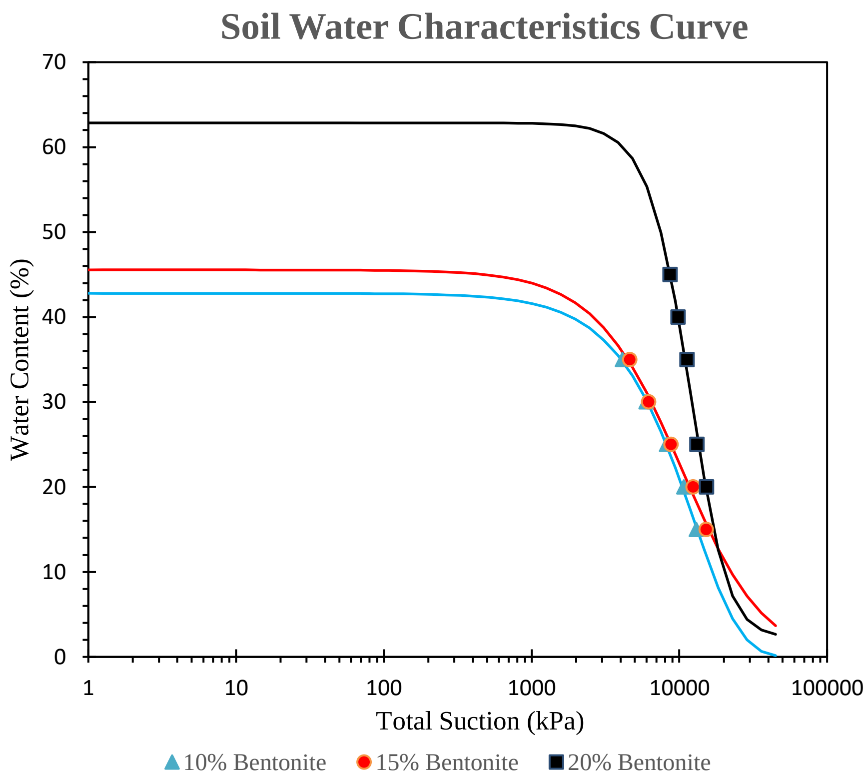

Figure 17: SWCC of sand-bentonite mixtures

4.4 Unconfined compressive strength

The results of the unconfined compression test for sand-bentonite mixes are shown in Figures 18 and 19. The figures show what was obtained for the unconfined compression tests conducted on the sand-bentonite mixes M1, M2 and M3 respectively. For all sand-bentonite combinations, Figure 18 gives an illustration of the stress-strain curves from the unconfined compression test, whereas Figure 19 gives the unconfined compressive strength.

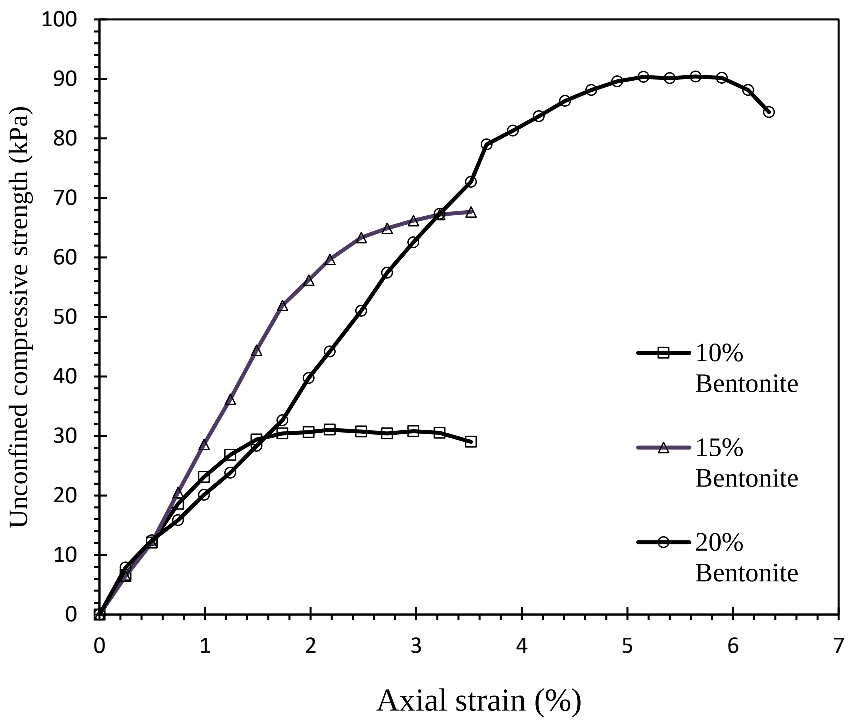

Figure 18: Plot of unconfined compressive stress vs axial strain

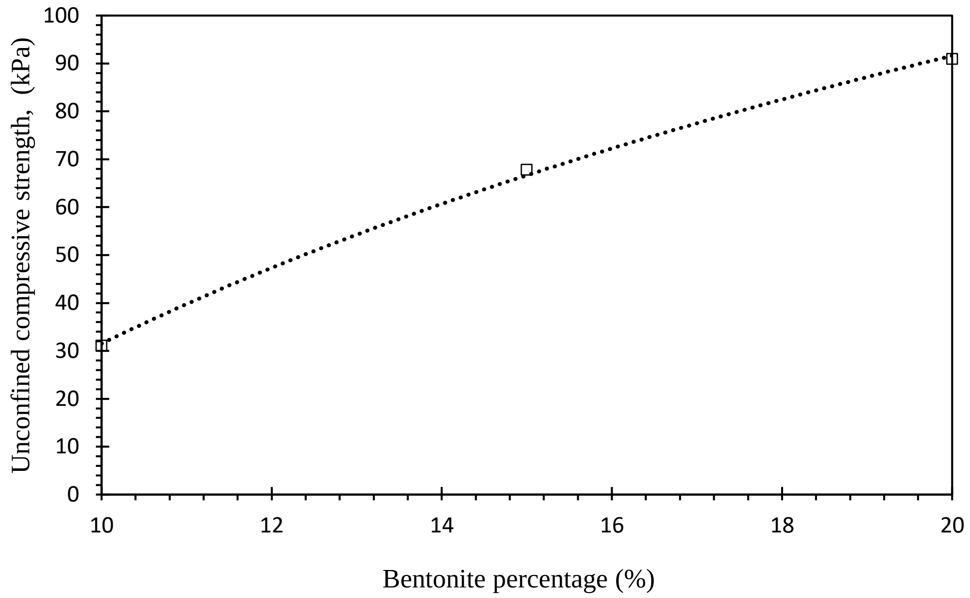

Figure 19: Plot of unconfined compressive strength versus bentonite percentage

In unconfined compression test, each specimen with a certain S/B ratio was tested three times for obtaining each stress–strain curve. The median results from the three tests were used. According to Figure 18, it is evident that the peak strengths of all specimens increase with increasing bentonite concentration. Considering the stress–strain curves, it is observed that the peak strength difference is largest between 15% and 20% bentonite. The stress–strain curves of the specimens in the mixture with 15% B were practically linear until the peak value was reached; there was then a rapid reduction in stress, indicating that the specimens in this range display more brittle failure behaviour than 20%B. The specimen with 20% bentonite had a rise in strength with increasing strain than the specimen with 15% bentonite, mostly because of the resulting ductile behaviour. As the amount of bentonite of the compacted cylindrical specimen increases, the unconfined compression strength increases and the deformation behaviour changes from brittle to ductile behavior, as shown by the stress–strain curves that were gotten in the UCS tests in general in Figure 19. The presence of bentonite in sand-bentonite mixtures generated a ductile behavior.

4.5 Double punch tensile strength-strain characteristics

Figure 20 displays the results found for the double punch test. The tensile strength reaches its maximum for the sand bentonite mixtures when each curve starts to fail. Figure 21 shows that with an increase in bentonite concentration in the combinations, the tensile strength of the sand-bentonite mixtures increased as well.

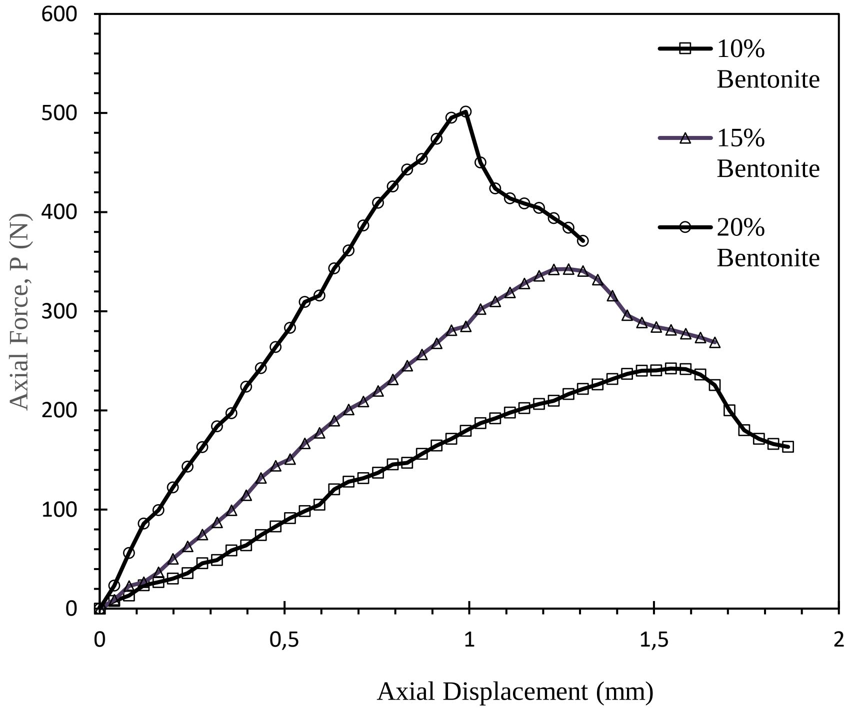

Figure 20: Double punch tensile test results for sand-bentonite mixtures

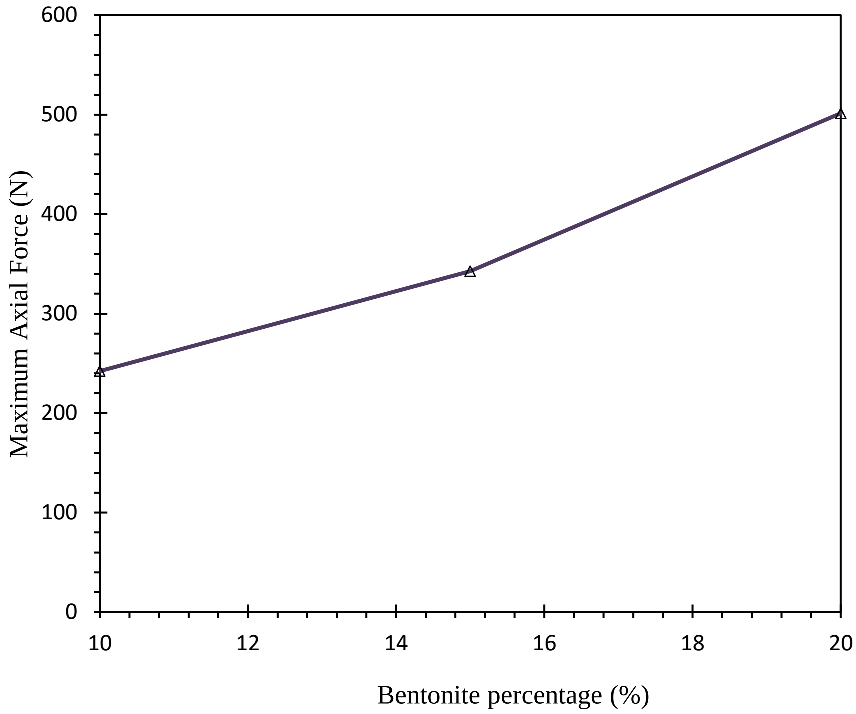

Figure 21: Plot of axial force versus bentonite percent

4.6 Volume change characteristics

Sand-bentonite mixes were created at water content a little above the liquid limit and kept to air-dry for ten days. The changes in weight, height, and diameter of the sand-bentonite mixtures were then recorded in order to understand how bentonite will influence the change in volume of the mixtures. During the air-drying process, the measurements of the weight and dimensions of sand-bentonite mixtures were taken at every twenty-four hours. In M1, the initial height, diameter and the weight of the sand-bentonite mixtures before air-drying were 20 mm, 75mm and 175.2 gram, respectively. In M2, the initial height, diameter and the weight of the sand-bentonite mixtures before air-drying were 20 mm, 75 mm and 145.1 gram respectively and in M3, the initial height, diameter and the weight of the sand-bentonite mixtures before air-drying were 20 mm, 75 mm and 131.1 gram, respectively. After ten days of air-drying, the sand-bentonite mixtures were put in an oven at a temperature of 105°C for 24hours to ensure no moisture is present and the final readings of the oven-dried specimens were recorded. Figure 22 shows the final weight, height and the diameter readings of the sand-bentonite mixtures after drying.

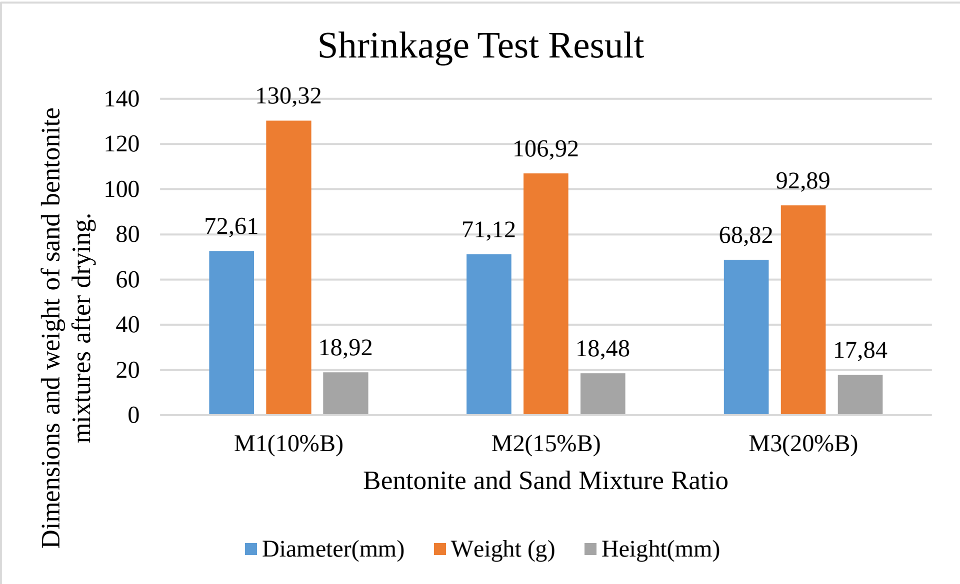

Figure 22: Dimensions and the weight of the sand-bentonite mixtures after oven drying

It was observed that M3 with the highest bentonite content has experienced the most volume change after drying. The initial volume of M3 was 8.83×10^{-5} m^3 and the final volume after oven drying dropped to 6.61×10^{-5} m^3.

Chapter 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

The study's objective was to determine the best sand-bentonite mixture for landfills by evaluating the laboratory geotechnical properties of SB mixtures based on different bentonite-to-sand ratios.

From this study, the following findings were reached;

- The liquid limit of SB mixtures is lower when there is a higher portion of sand included in the mix.
- When the percentage of bentonite is increased, the maximum dry density of the combinations consistently increased.
- Percentage swell increased in proportion to the increase in bentonite content. M3 had the highest maximum percentage swell and a swell pressure of 400 kPa was obtained for this mixture.
- It was observed that M3 with the highest bentonite content has experienced the highest volume change after drying.
- The findings of the common consolidation tests showed that the c_v values rose as the bentonite content rose. Increased bentonite content led to thicker bentonite coatings on sand-bentonite mixes as well as an expansion of the pore void area, which is akin to a course soil structure and accelerates the rate at which sand-bentonite mixtures consolidate. As a result, the sand-bentonite mixture's

hydraulic conductivity increased. The maximum bentonite level of 20% produced the sand-bentonite combination with the best hydraulic conductivity.

- Sand-bentonite mixes' unconfined compressive and tensile strengths increased when bentonite content in the sand increased. The combination M3 with 20% bentonite content produced the maximum strength and was found to be the most durable.
- From all the results obtained from this research, the mixture M3 was observed to be of optimal sand-bentonite properties.

5.2 Recommendations for further studies

- In order to further support the findings obtained within this study, Scanning Electron Microscopic study should be performed so that there would be detailed study into the changes in the microstructure of SB mixtures.
- Different percentages of SB mixtures should also be tested depending on the mode of application for engineering purposes.
- Direct measurement of hydraulic conductivity value should be tried.
- Other additive materials that can be used to supplement bentonite could be added for testing.

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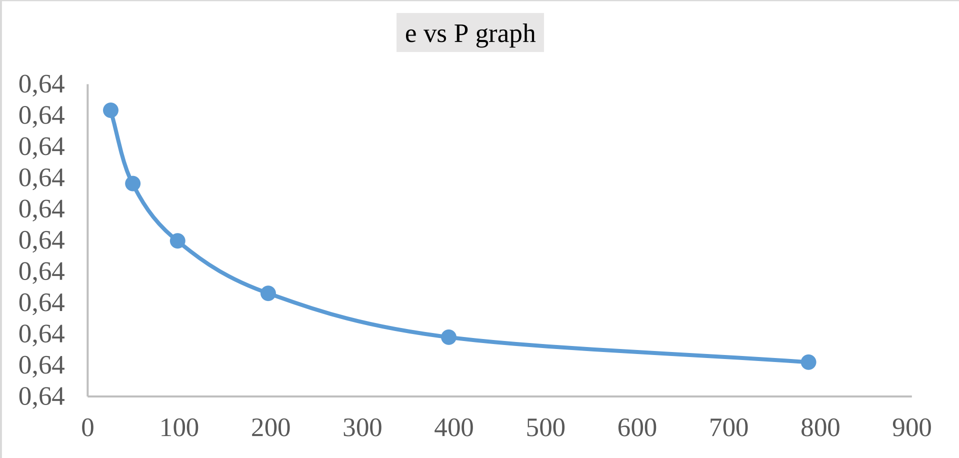
APPENDIX

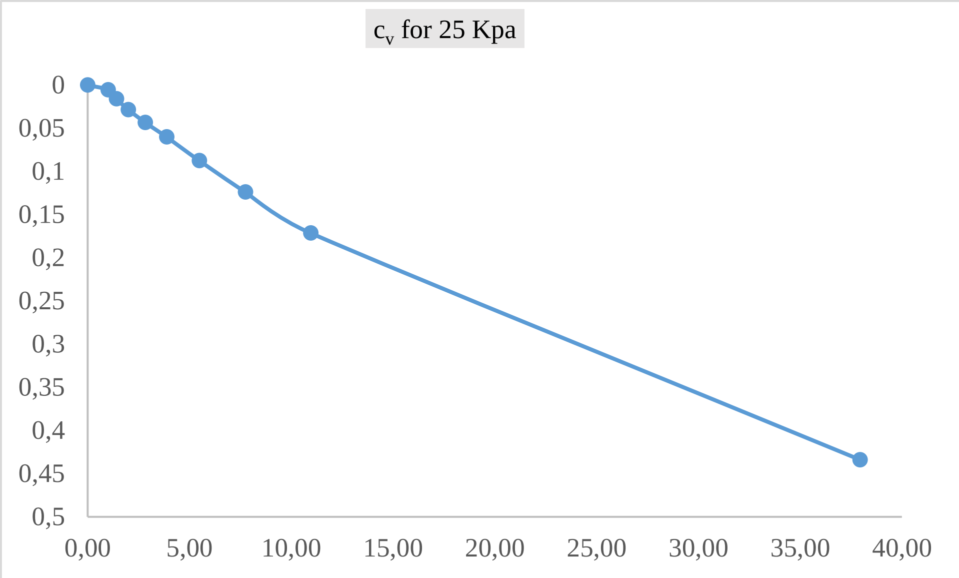
10% Bentonite consolidation data

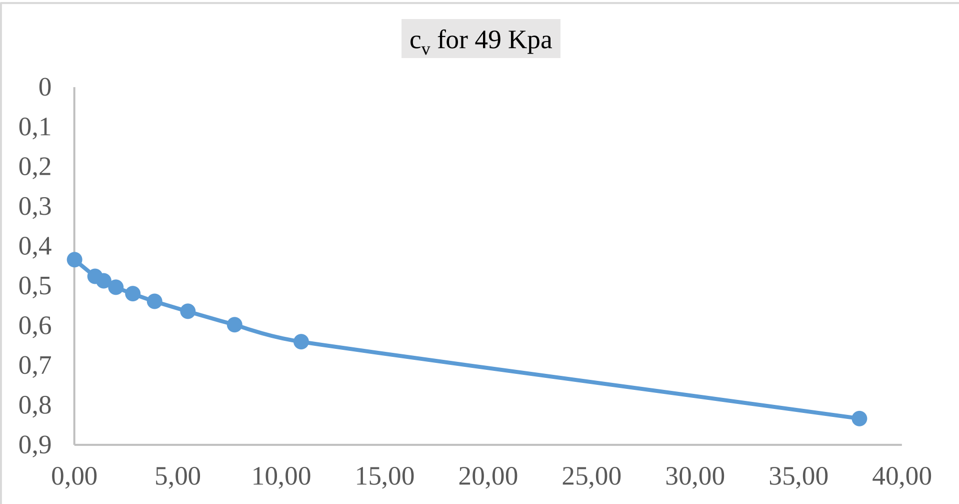
Input data				Observations and readings								
Initial height of soil sample	Ho	1.4	cm									
Diameter of sample	Dia	7.5	cm	Load (Kpa)	25	49	98	197	394	787	394	197
Cross sectional area	A	44.1782	cm^2	time (min)	Dr	Dr	Dr	Dr	Dr	Dr	Dr	Dr
Least count	LC	0.001	cm	0	0	0.4339	0.8337	1.1466	1.432	1.6716	1.8081	1.7766
Specific Gravity	Gs	2.65		1	0.0055	0.4759	0.8904	1.2138	1.4734	1.7212	1.8052	1.7737
density of water		1	g/cm3	2	0.016	0.4872	0.9043	1.2256	1.4826	1.7217	1.8052	1.7737
Drainage condition	doubly			4	0.0286	0.5032	0.9198	1.239	1.4944	1.7422	1.8039	1.7716
Method used for curves	Taylor			8	0.0433	0.52	0.9358	1.2516	1.5057	1.7514	1.8031	1.7703
Weight of ring	W1	119.9	g	15	0.0601	0.5389	0.9547	1.2642	1.5154	1.7619	1.8039	1.7695
Weight of wet soil + ring before test	W2	234.6	g	30	0.0874	0.5641	0.9736	1.2802	1.528	1.7724	1.8031	1.7674
				60	0.1239	0.5977	0.9975	1.2936	1.5406	1.7842	1.8018	1.7661
				120	0.1714	0.6405	1.0248	1.3104	1.5519	1.7968	1.801	1.7653
				1440	0.4339	0.8337	1.1466	1.432	1.6716	1.8081	1.7766	1.76

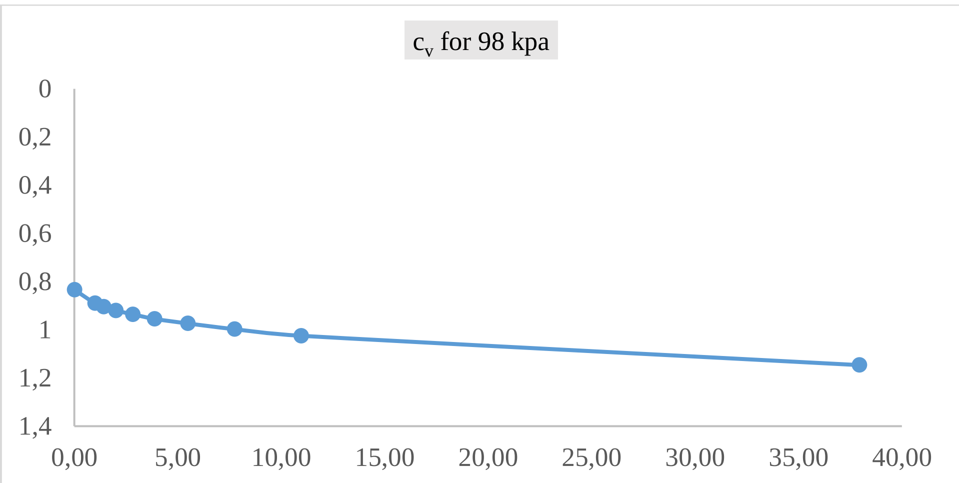


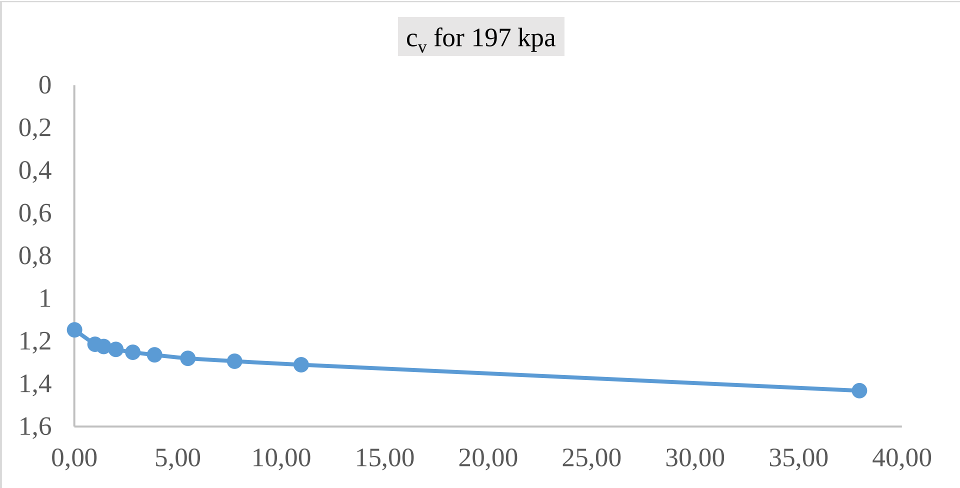
e vs log P					
Pressure	Initial Dr at start test	Final Dr of load	ΔH (cm)		
Kpa				Δe =ΔH/Hs	e=eo - Δe
A	B	C	D=LC x C	E=D/Hs	F=eo-F
25	0	0.4339	0.000434	0.0005095	0.643433
49	0	0.8337	0.000834	0.00097897	0.642964
98	0	1.1466	0.001147	0.00134639	0.642596
197	0	1.432	0.001432	0.00168152	0.642261
394	0	1.6716	0.001672	0.00196287	0.64198
787	0	1.8081	0.001808	0.00212315	0.641819
394	0	1.7766	0.001777	0.00208616	0.641856
197	0	1.76	0.00176	0.00206667	0.641876

Coefficient of consolidation using Taylor method








c_v for 197 kpa
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0,4
0,6
0,8
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1,2
1,4
1,6
0,00
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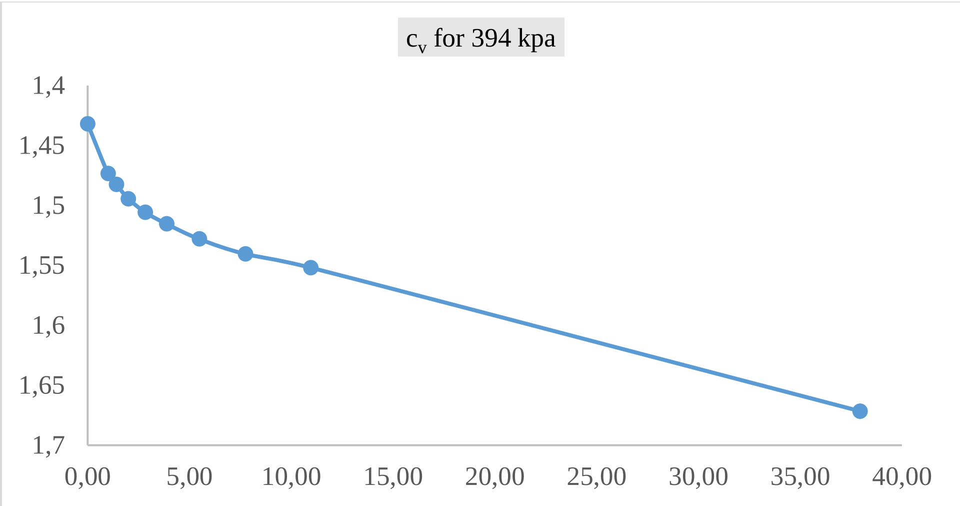
30,00
35,00
40,00


c_v for 394 kpa
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1,5
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5,00
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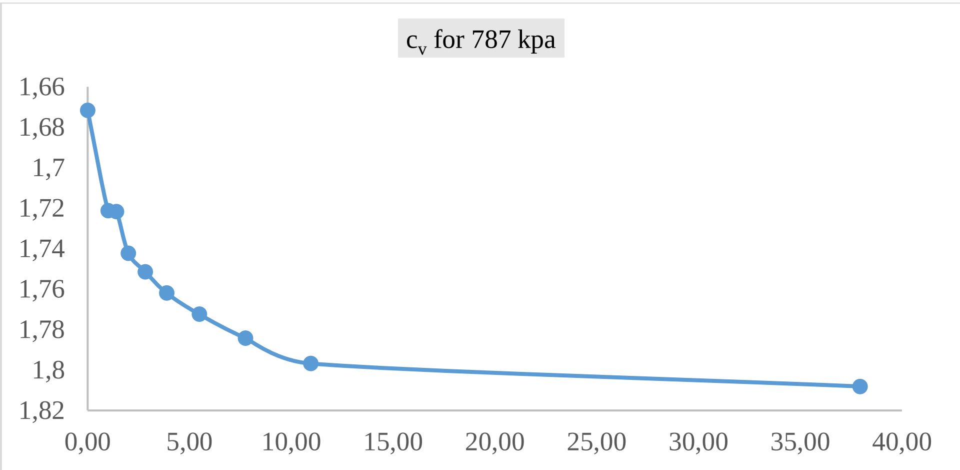
30,00
35,00
40,00


c_v for 787 kpa
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1,7
1,72
1,74
1,76
1,78
1,8
1,82
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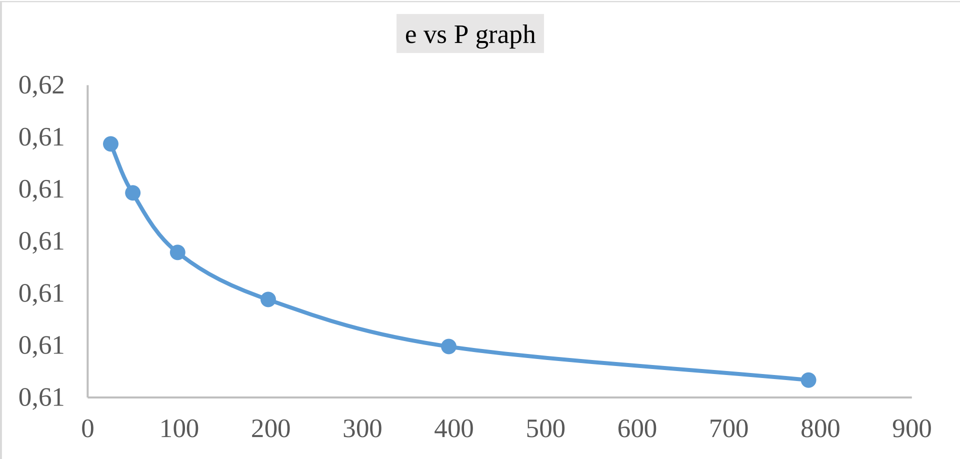
5,00
10,00
15,00
20,00
25,00
30,00
35,00
40,00

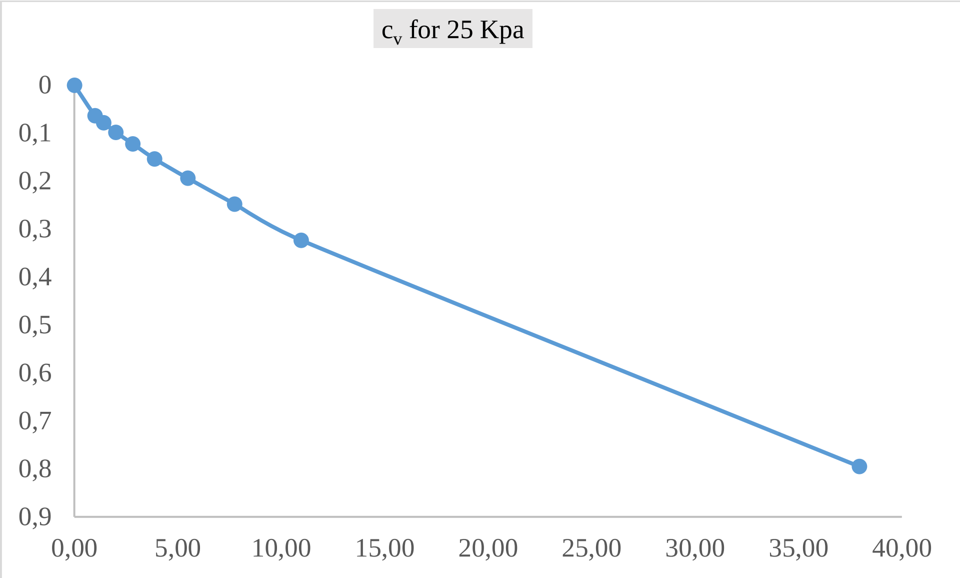
15% bentonite consolidation data

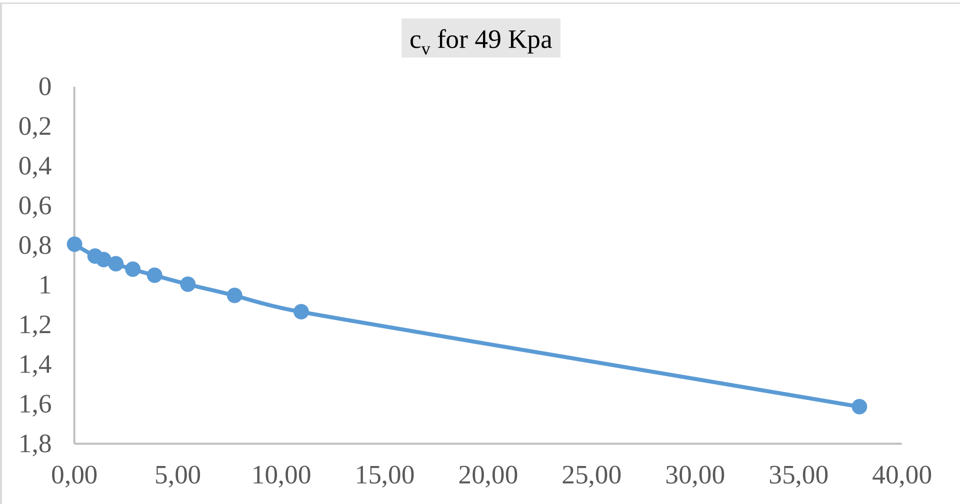
Input data				OBSERVATIONS and READINGS								
Initial height of soil sample	Ho	1.4	cm									
Diameter of sample	Dia	7.5	cm	Load (Kpa)	25	49	98	197	394	787	394	197
Cross sectional area	A	44.17819	cm^2	time (min)	Dr	Dr	Dr	Dr	Dr	Dr	Dr	Dr
Least count	LC	0.001	cm	0	0	0.7951	1.6132	2.6018	3.3888	4.1705	4.7288	4.6218
Specific Gravity	Gs	2.65		1	0.0638	0.8545	1.7687	2.6886	3.5564	4.4703	4.6864	4.6218
density of water		1	g/cm^3	2	0.078	0.8726	1.7938	2.7149	3.5928	4.4957	4.6864	4.6177
Drainage condition	doubly			4	0.0982	0.8928	1.8241	2.7444	3.632	4.522	4.6836	4.6169
Method used for curves	Taylor			8	0.1224	0.9211	1.8584	2.7815	3.6724	4.549	4.6824	4.6137
Weight of ring	W1	120.7	g	15	0.1535	0.9506	1.8988	2.8199	3.7148	4.5753	4.6775	4.6129
Weight of wet soil + ring before test	W2	233.5	g	30	0.1939	0.9959	1.9533	2.8724	3.7653	4.6056	4.6755	4.6096
				60	0.2477	1.0524	2.0212	2.9371	3.8574	4.6339	4.6743	4.6076
				120	0.3232	1.1352	2.1129	3.0219	3.9511	4.6622	4.6743	4.6056
				1440	0.7951	1.6132	2.6018	3.3888	4.1705	4.7288	4.6218	4.5994

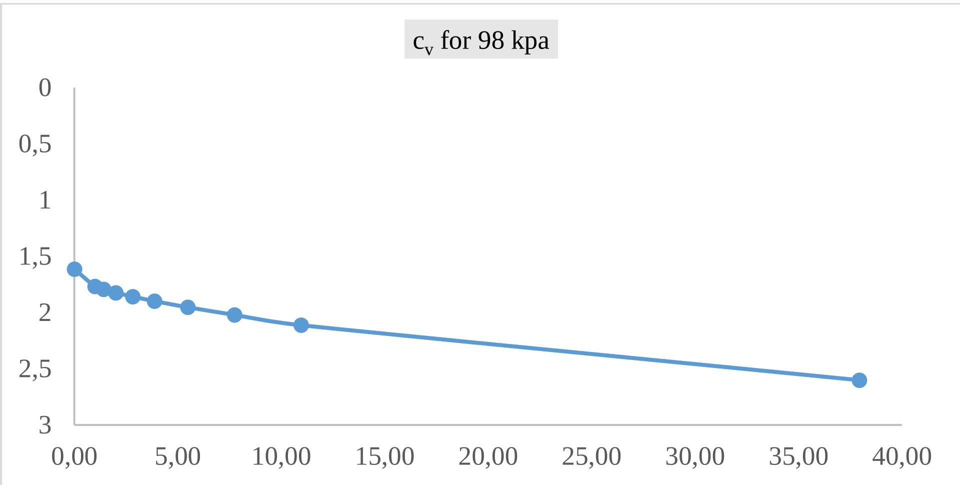


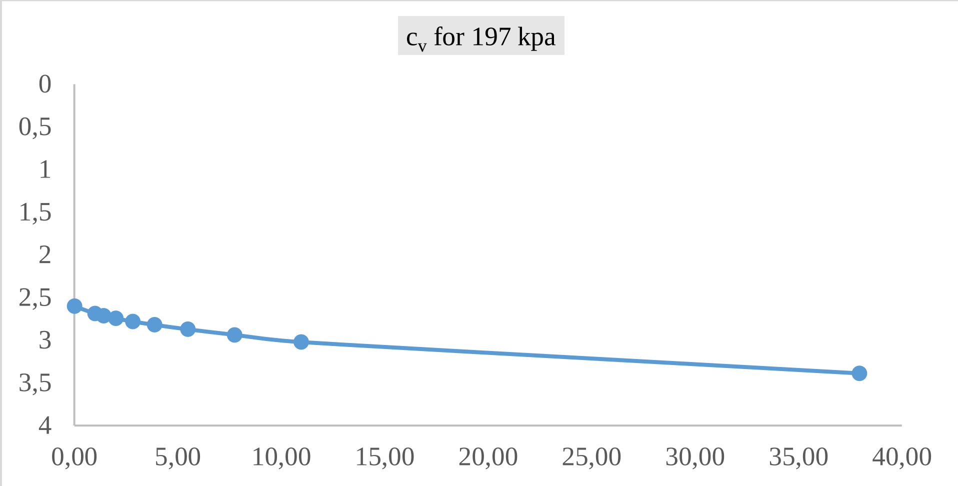
e vs log P					
Pressure Kpa	Initial Dr at start test	Final Dr of load	ΔH (cm)	Δe =ΔH/Hs	e=eo - Δe
A	B	C	D=LC x C	E=D/Hs	F=eo-F
25	0	0.7951	0.000795	0.00091708	0.613872
49	0	1.6132	0.001613	0.0018607	0.612928
98	0	2.6018	0.002602	0.00300097	0.611788
197	0	3.3888	0.003389	0.00390871	0.61088
394	0	4.1705	0.004171	0.00481034	0.609979
787	0	4.7288	0.004729	0.0054543	0.609335
394	0	4.6218	0.004622	0.00533088	0.609458
197	0	4.5994	0.004599	0.00530504	0.609484

Coefficient of consolidation using Taylor method








c_v for 197 kpa
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0,5
1
1,5
2
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3
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4
0,00
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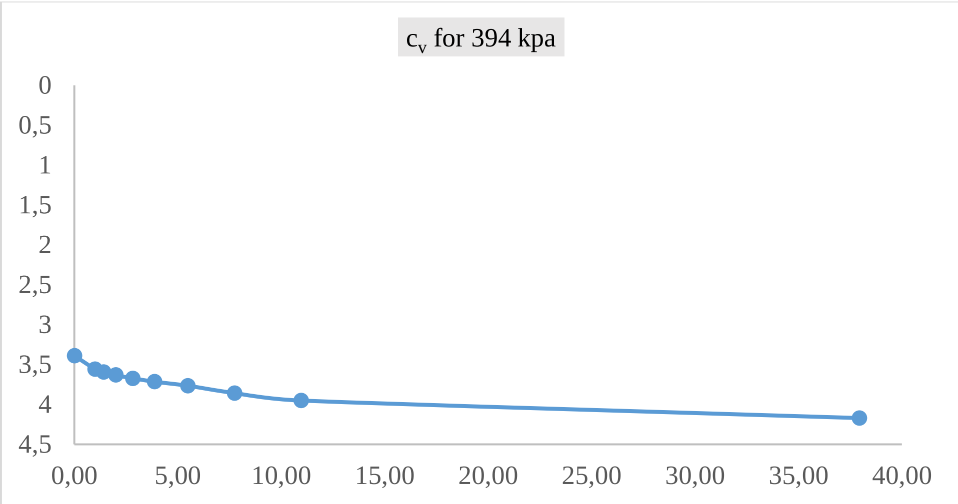
30,00
35,00
40,00


c_v for 394 kpa
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2
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4,5
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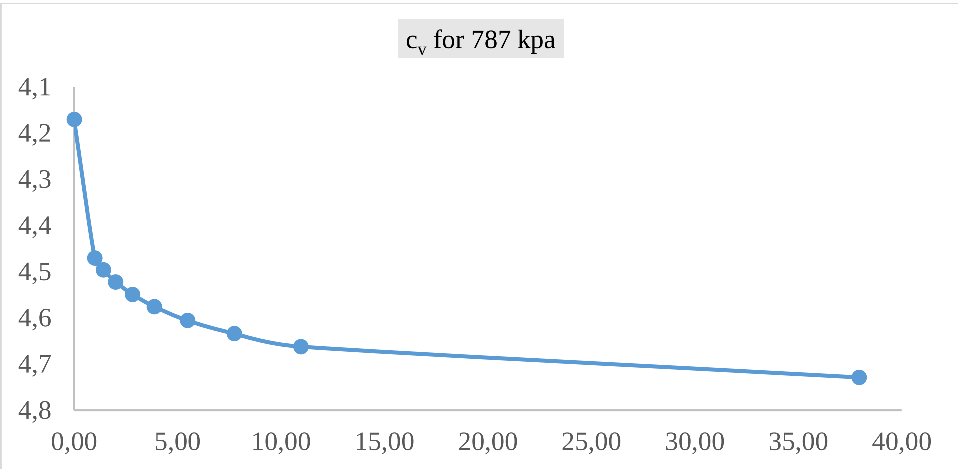
30,00
35,00
40,00


c_v for 787 kpa
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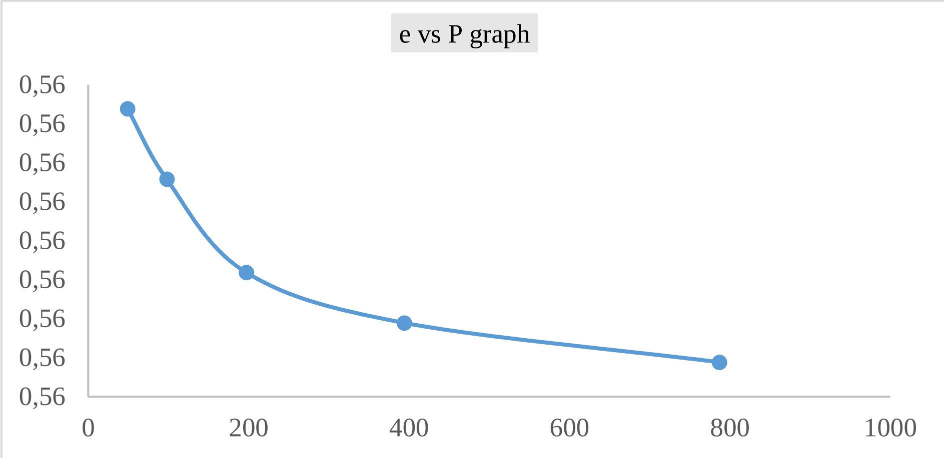
4,2
4,3
4,4
4,5
4,6
4,7
4,8
0,00
5,00
10,00
15,00
20,00
25,00
30,00
35,00
40,00

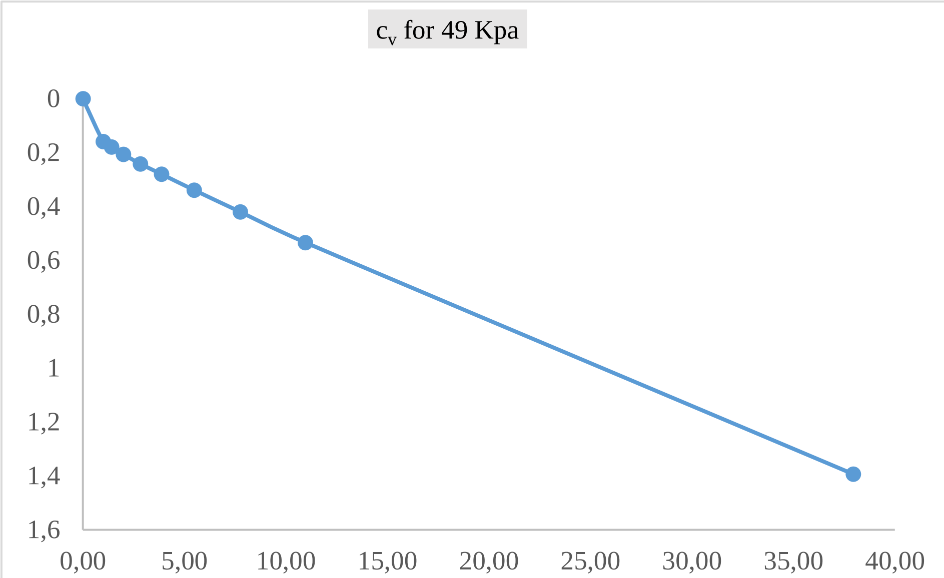
20% bentonite Consolidation data

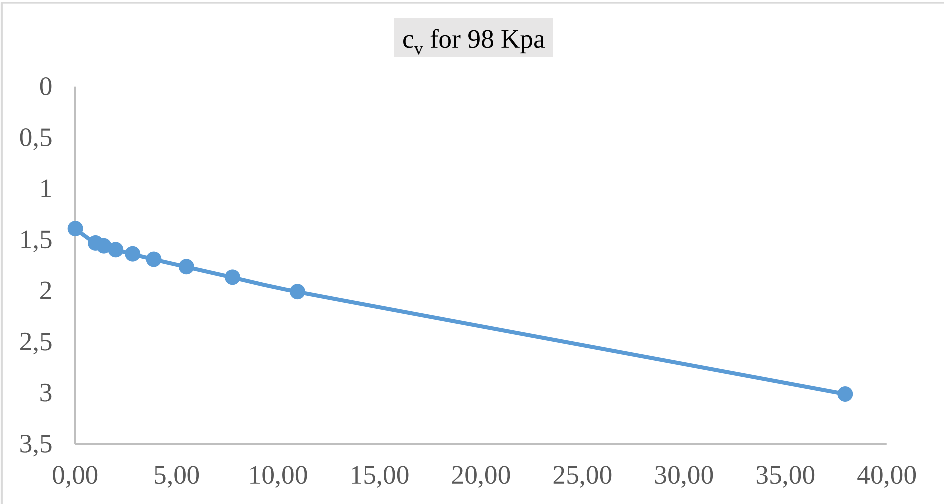
Input data				Observations and readings							
Initial height of soil sample	Ho	1.4	cm								
Diameter of sample	Dia	7.5	cm	Load (Kpa)	49	98	197	394	787	394	197
Cross sectional area	A	44.1782	cm^2	time (min)	Dr	Dr	Dr	Dr	Dr	Dr	Dr
Least count	LC	0.001	cm	0	0	1.3931	3.011	5.1514	6.3094	7.2119	7.0993
Specific Gravity	Gs	2.65		1	0.1586	1.5339	3.2872	5.3418	6.5122	7.1788	7.0856
density of water		1	g/cm^3	2	0.1793	1.562	3.3195	5.3737	6.5362	7.1779	7.0815
Drainage condition	doubly			4	0.2062	1.598	3.3588	5.4081	6.5681	7.1746	7.0773
Method used for curves	Taylor			8	0.2414	1.6407	3.4085	5.4495	6.6074	7.1738	7.0691
Weight of ring	W1	120.4	g	15	0.2795	1.6924	3.4706	5.4971	6.6551	7.1705	7.0649
Weight of wet soil + ring before test	W2	235.7	g	30	0.3387	1.7657	3.5575	5.5675	6.7246	7.1697	7.0546
				60	0.4194	1.8684	3.6817	5.6627	6.8198	7.1663	7.0434
				120	0.5332	2.01	3.8514	5.7931	6.9378	7.1663	7.0289
				1440	1.3931	3.011	5.1514	6.3094	7.2119	7.0993	6.9987

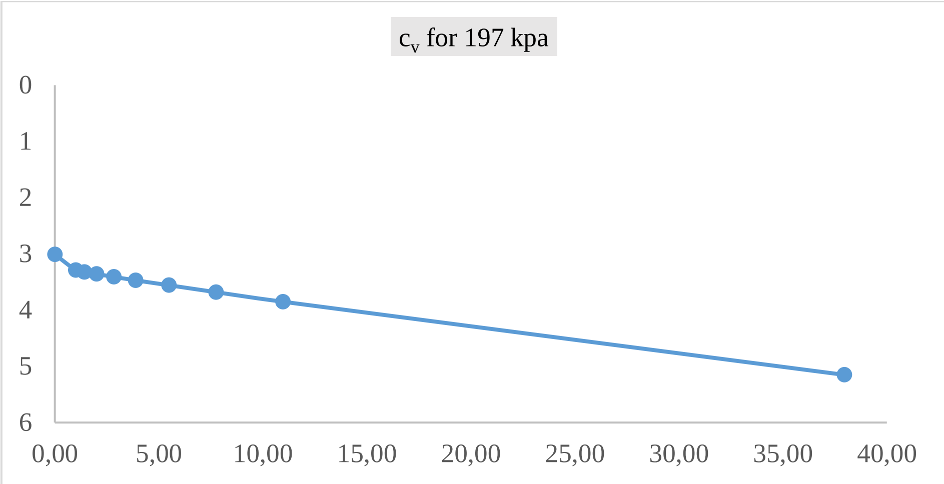


e vs log P					
Pressure Kpa	Initial Dr at start test	Final Dr of load	ΔH (cm)	Δe =ΔH/Hs	e=eo - Δe
A	B	C	D=LC x C	E=D/Hs	F=eo-F
49	0	1.3931	0.001393	0.0015562	0.562385
98	0	3.011	0.003011	0.0033636	0.560578
197	0	5.1514	0.005151	0.0057546	0.558187
394	0	6.3094	0.006309	0.0070482	0.556893
787	0	7.2119	0.007212	0.0080564	0.555885
394	0	7.0993	0.007099	0.0079306	0.556011
197	0	6.9987	0.006999	0.0078183	0.556123

Coefficient of consolidation using Taylor method







c_v for 197 kpa
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2
3
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5
6
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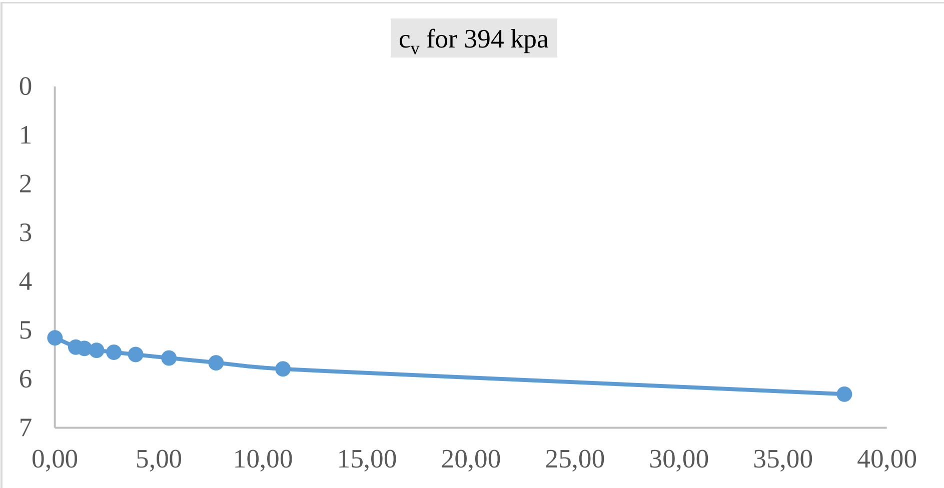
5,00
10,00
15,00
20,00
25,00
30,00
35,00
40,00



c_v for 394 kpa
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1
2
3
4
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7
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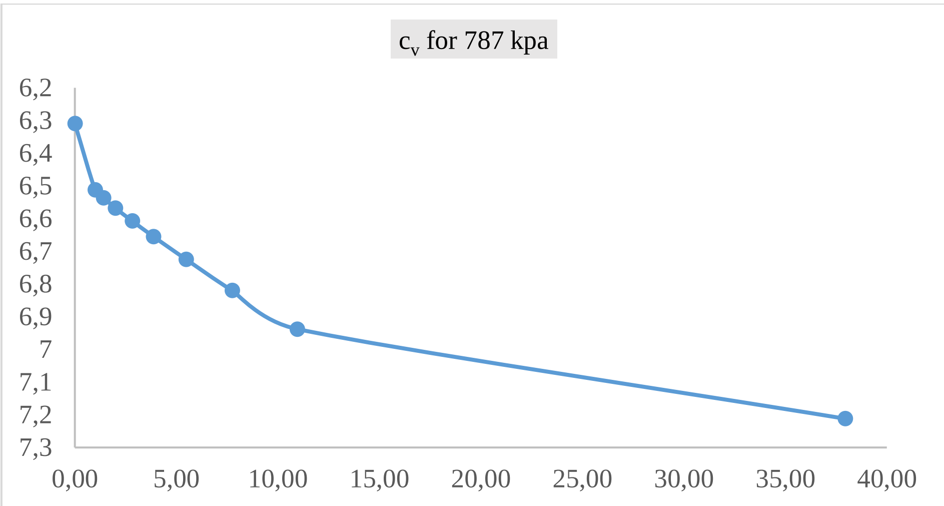
30,00
35,00
40,00



c_v for 787 kpa
6,2
6,3
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6,5
6,6
6,7
6,8
6,9
7
7,1
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7,3
0,00
5,00
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15,00
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