Effects of freezing temperature on interface shear strength of landfill geosynthetic liners

Bhavya Paruchuri

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A Thesis

Entitled

Effects of Freezing Temperature on Interface Shear Strength of Landfill Geosynthetic Liners

by

Bhavya Paruchuri

Submitted to the Graduate Faculty as Partial fulfillment of the requirements for the
Master of Science Degree in Civil Engineering

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In modern days, municipal and hazardous waste containment facilities i.e., landfills are performance standard designed, well-engineered, operated, and monitored in compliance with federal regulations in 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations. Hence, application of geosynthetic materials as landfill bottom liners and capping systems has seen a substantial increase over the past few decades. The present work emphasizes the shear strength of geocomposite clay liner (GCL) and geomembrane interface in landfills. Using direct shear tests, shear stress was measured as a function of normal load to determine the values of interface frictional angle and adhesion of the geosynthetic interface. The variation of interface friction angle and shear strength for both frozen and unfrozen samples was observed. In the current work, we tried to simulate the conditions in a landfill of northwest Ohio. We conducted 66 direct shear tests on 4
different types of GCL’s at 5 different moisture contents subjected to 3 different normal stresses 1.038 psi, 2.076 psi, and 4.152 psi which represented the general normal pressure range applied to the capping system in most of the landfills in frozen as well as unfrozen conditions. We observed that the shear stress values of the samples in frozen and unfrozen conditions had no significant difference. Therefore, it is concluded that the effects of freezing temperature on the geosynthetic interface in a capping system of a landfill is negligible.
I dedicate my thesis to the Soldiers of every country who devote their lives for the motherland.

I also dedicate my thesis to my Father Mr Kishore Babu, Mother Mrs Jhansi, Sister Mrs Rajita, Brother Mr Gopinath, Daughter Anjali and Dear Rohit Nadendla for their anomalous love and support that helped me progress.
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Chapter 1

Introduction

1.1 Background

Since the Resource Conservation and Recovery Act (RCRA) had been enacted in 1976, well-engineered landfills have been the waste containment facilities that hold different waste materials to prevent the migration of toxic leachate and gases that may harm the environment and human health. United States Environmental Protection Agency (USEPA) suggests that a landfill should have an appropriate bottom liner and cover/cap system to protect human health and environment from contaminants in any form, be it solid, gas or liquid. The liner system and capping system are typically constructed with layers of low permeability natural materials (compacted clay liners (CCLs) with hydraulic conductivity not greater than $1 \times 10^{-6} \text{ cm/sec}$) and/or geosynthetic materials (high density polyethylene) (NSWMA, 2008). In the present-day, Geosynthetic Clay Liners (GCLs) have proven to be more cost-effective than compacted clay liners (CCLs) in terms of labor, material, and time, especially in areas where suitable clay soil is not accessible locally (Heerten, 2002). GM/GCL composite liner has a possible downside
when compared to a GM/CCL liner i.e., the reduced interface shear strength of GM/GCL composite liner. It is therefore critical to study this interface in order to design the waste landfills more efficiently and effectively and prevent landfill slope instability which can be very expensive to repair (Fox 1998).

If the bottom liner system is not well-engineered the landfill will pose potential problems such as contamination of insitu soil, surface and groundwater due to a leakage of leachate produced as a result of substandard condition of the liners (Daniel & Richardson, 1995). Similarly, the cap system is one of the vital components of the landfill. It is the most common and effective form of landfill remediation/containment technology as it is generally less expensive than the other technologies and it efficiently takes charge of the environmental risks associated with the remediation while limiting the migration of the contaminants. But it has a drawback i.e., it can only prevent the vertical entry of water into waste but cannot mitigate the horizontal flow of groundwater through the waste. Typical RCRA Subtiltle C Landfill Cap System is designed to satisfy the following requirements (Deuren, Lloyd, Chhetry, Liou, & Peck, 2002):

- Containment and protection of the dumped waste
- Prevent vertical infiltration of surface water/rainwater that would produce toxic leachate
- Control of gas release from underlying waste
- Provide a land surface to support vegetation, so that the landfill surface can be used for other purposes.
A cap system typically consists of a barrier layer and a drainage layer. The barrier layer can be a low permeability soil like clay and/or geosynthetic clay liners (GCLs). Usually, an impermeable Geomembrane liner is laid on top of the barrier layer. In Ohio, it is acceptable to replace 12” of recompacted clay layer by a layer of GCL.

Figure 1-1 Components of the cover and bottom liners of a modern hazardous waste landfill. (Landfill Techniques, 2011)

The above figure 1-1, depicts different components of a modern hazardous waste landfill. In the figure, the cover liner or the cap system includes five layers i.e., vegetation layer, general fill layer, drainage layer, moisture barrier layer and gas-collection layer. The first layer on the top is topsoil with grass vegetation. Environmental solid waste management regulations have prohibited trees on the vegetative layer as the roots were believed to
clog the drainage layer, deteriorate the lining system and provide preferential water flow channels (Licht, Aitchison, Schnabel, English, & Kaempf, 2001). The second layer is a general fill layer that serves three purposes i.e., provides additional moisture storage for vegetation, spare space for vegetation root development other than grass that is grown on the cover liner for aesthetic purposes; lastly and most importantly frost protection for the moisture – barrier layer. An important criterion to be considered while choosing an effective landfill barrier system is hydraulic conductivity. The design of the general fill layer is made such that the combined thickness of the vegetative layer, general fill layer, and drainage layer is greater than the depth of frost penetration with pertinence to location of the landfill (Net Industries and its Licensors, 2011). The third layer is a high-permeability subsurface drainage layer that is made of either a geocomposite layer or granular layer. This drainage layer and its cap drainage pipes transmit the infiltrated moisture/water away from the cap. The fourth layer is a high-permeability material made of clayey soil or a geomembrane or both. The fifth layer is a gas collection layer responsible for collection of various gases (Methane and carbon dioxide majorly) that are released from the waste materials. These gases are collected and further converted to alternative uses.

In the figure 1-2, the purpose of the four layers of geosynthetics can be explained: the bottom layer of geotextile collects the seeping leachate, an intermediate textured geomembrane to prevent water infiltration. The geomembrane is protected by GCL by draining away any accumulation of water on top of the geomembrane. The top layer geotextile filter stabilizes the capping material. (Airport Express, Kwai Chung Park Viaduct, 2005)
While designing a cap system, there are certain potential problems to be observed; these include vacillating air temperature and precipitation, subsoil piping and topsoil collapse, soil moisture, animal burrows, plant roots and earth movement. Failures usually occur due to excessive movement of uncontrolled water through or over the cover soils. These factors undermine the cap’s integrity by breaching or eroding it. At times, it may be problematic to determine the reason and mechanism of a failure, but often faulty design
and construction techniques, altered landfill conditions or poor weather conditions may be the culprit (Siebecker, 2005). The longevity of the cap system can be fostered by covering the infiltration barriers with a soil layer that is thick enough to extend below the frost line and probable depths of animal burrows and plant roots (Vasudevan, S, & Sridhar, 2003).

A look into the design of a landfill reminds us that designing a landfill is not just about the application of liner system and covering it with layers of geosynthetics and soil but it also involves a lot of concentration on appropriate slopes for runoff and design of an efficient leachate collection and treatment system in order to treat it before discharge. Coming to the liner installation process, it usually takes several weeks as it has to be done with thorough precautions to prevent any leakage of leachate. The landfills today have a primary and secondary lining system; the secondary lining system monitors the functioning of the primary. The primary system consists of a textured high density polyethylene (HDPE) with a minimum 60 mil to optimize friction control of the liner and cover soil. Over the geomembrane there is a geocomposite liner that acts as a leachate collection system. As water percolates through trash in the landfill, it picks up contaminants; this contaminated water is called “leachate” and is typically acidic (Daniel & Koerner, 1991). Leachate is reaches the perforated pipes in the landfills that drain into leachate pipes which carry leachate into a leachate collection pond. The secondary lining system is similar to the primary lining system consisting of geomembrane and geocomposite liners.

It is important to remember that, once waste reaches design elevation in the cell (Cell is
an area in the landfill where the waste is dumped, compacted, and compressed to make more space for the incoming waste.), it has to be capped with geomembrane layer, a thick layer of compacted clay and vegetative cover in order to eliminate the problems like odor, leachate generation due to precipitation (Yack & O'Neill, 1998).

1.2 Deployment of geosynthetics in a landfill

A landfill operator can install a geosynthetic liner layer much faster and more easily than compacted clay liner layer. The basic procedure of installing geosynthetics involves rolling out large rolls of geosynthetics onto the site subgrade that is smooth, dry and well compacted. Figure 1-3 below depicts the geomembrane deployment procedure using a large roll of geomembrane supported by a crane (Trauger, 1991), (Trauger, Geosynthetic Clay Liners: An overview, 1992).

![Geomembrane Deployment](image)

Figure 1-3 Geosynthetic deployment
1.3 Geosynthetic Clay Liner and Geomembrane

Geosynthetic Clay Liner (GCL) is a woven fabric like material made of bentonite either bonded to a geomembrane or sandwiched between two layers of geotextile. While a geomembrane is a polymeric sheet material that is typically impervious to liquids. A geotextile is a woven or non-woven sheet material with more resistance to punching but with potential for higher permeability when compared to a geomembrane. In general, the permeability of GCL products varies from about $1 \times 10^{-5}$ cm/sec to $1 \times 10^{-12}$ cm/sec. The Bentonite present in the GCL is an extremely absorbent, granular clay which when exposed to liquids such as water or leachate swells rapidly giving it the ability to “self-mend” the holes present in the GCL.

Needlepunching of GCL yields a stronger, rigid barrier when compared to stitchbonding. While needlepunching a GCL it is important to have a nonwoven geotextile on at least one side. The primary manufacturers of GCL products in the United States are CETCO Lining Technologies and GSE Lining Technology.

When a wetted GCL is under conditions of tension and cycles of freeze and thaw, it has a very low coefficient of permeability ($k < 10^{-11}$ m/s) (Li, Shu, & Wu, 2008). In our work, we have experimented on four different samples of geosynthetic clay liners: Bentomat DN, Bentomat ST, BFIX330NWL, and BFIX230NSL. We received the Bentomat DN, Bentomat ST samples from CETCO Lining Technologies and the BFIX330NWL and BFIX230NSL samples from GSE Lining Technology.

**Bentomat DN** is commonly used in some of the most demanding applications including canyon landfills in the western United States. It finds its applications on slopes as steep as
1.5H: 1V. This GCL is reinforced and consists of a layer of Volclay sodium bentonite between two heavier weight non-woven geotextiles, making this GCL suitable for applications requiring high internal and interface shear strength. The figure shows a reinforced Bentomat DN sample.

![Figure 1-4 Bentomat DN Sample](image)

**Bentomat ST** has proved to be ideal for standard applications involving slopes up to 3H: 1V. Bentomat ST consists of a layer of Volclay sodium bentonite encapsulated between woven and non-woven geotextiles, which are needle-punched together to provide internal reinforcement. This internal reinforcement minimizes clay shifting, thus allowing the GCL to maintain constant low permeability and maximum performance under a wide variety of field conditions. The figure is the image of an internally reinforced Bentomat ST sample.

![Figure 1-5 Bentomat ST Sample](image)

**Bentomat SDN** is also a reinforced GCL consisting of a layer of Volclay sodium bentonite between two non-woven geotextiles. The two non-woven geotextiles convey good interface friction between the GCL and adjacent soils or textured geomembranes,
making this GCL a cost-effective alternative for moderate to steep slopes requiring good overall liner system stability. The figure shown below is a Bentomat SDN sample.

![Bentomat SDN Sample](image)

**Figure 1-6 Bentomat SDN Sample**

**Bentomat CL** is a reinforced GCL consisting of two carrier geotextiles encapsulating a layer of Volclay sodium bentonite, with a geomembrane laminated to one side. This GCL provides excellent hydraulic performance and has tensile strengths exceeding that of conventional plastic membranes. These characteristics make this GCL applicable for use in landfill covers, ponds and reservoir projects with slopes up to 3H: 1V (BENTOMAT Geosynthetic Clay Liners (GCL), 2009). The figure depicts clearly the image of a Bentomat CL GCL.

![Bentomat CL Sample](image)

**Figure 1-7 Bentomat CL Sample**

**GSE BentoLiner NSL (BFIX230NSL)** is a needlepunched composite GCL that comprises of a uniform layer of granular sodium bentonite between a carrier slit-film woven and nonwoven geotextile. The BFIX230NSL finds its applications in moderate to steep slopes approximately ranging upto 4H: 1V and moderate to high loads where large internal shear strength is required. (GSE BentoLiner NSL Geosynthetic Clay Liner; Product Data Sheet)
For GSE BentoLiner NWL (BFIX330NWL), the GSE lining technology product data sheets stated that BFIX330NWL is a needle punched reinforced composite GCL comprised of a uniform layer of granular sodium bentonite enveloped between a nonwoven and scrim-nonwoven geotextile for flawless functioning. Its utilization is in situations demanding large GCL internal shear strength and interface shear strength (i.e., between adjacent textured geomembranes and soils). (GSE BentoLiner NWL Geosynthetic Clay Liner; Product Data Sheet)

A stable final cover system is ruled by an understanding of the shear strength and interface friction properties of the geosynthetic layers can solve problems like landfill instability (Deuren, Lloyd, Chhetry, Liou, & Peck, 2002).

**Shear strength** ($\tau_f$) of a material is the maximum shear stress the material can withstand without failure, under normal stress of $\sigma$. The theoretical state at which the shear stress and density remain constant while the shear strain increases may be called the critical state, steady state, or residual strength. Shear strength of a material at failure, is given by Mohr-Coulomb failure criterion that can be expressed as

$$\tau_f = C + \sigma \tan \phi \quad \text{.................................1}$$

Where, $\tau_f$ is the shear strength, $\sigma$ is normal stress, $\phi$ is friction angle and $C$ is adhesion. Hence, from Equation 1 it is clear that the values of shear strength increase with increase in $\phi$ and $C$. It was also found that interface friction angle is temperature dependent and it is in direct proportion with temperature. Shear displacement rate has a little influence on
the residual internal shear strength of GCL regardless of normal stress applied on it (Eid, Stark, & Doerfler, 1999). Our work focuses on shear strength behavior of geosynthetic interface depending upon the variation of friction angle between the GCL and geomembrane interfaces subjected to freezing. Hydraulic conductivity of GCLs is relatively insensitive to freeze-thaw.

The following normal loads were applied to the test specimens: 75 lbs, 150 lbs and 300 lbs. A total of 66 tests were conducted on the four samples at 5 different (20, 35, 50, 65 and 80 %) moisture contents. The tests were conducted in both frozen and unfrozen conditions. Collios et al. (1980) and Ingold (1982) suggest that direct shear test is the most appropriate method to analyze the strength attributes of soil-geosynthetic interface. Unfortunately, from literature it is found that not much research is done on the variation of friction angle between geo synthetic clay liner and geo membrane.

### 1.4 Summary

The cardinal purpose of a landfill is to isolate the dumped waste from the surrounding environment. This is achieved by lining the top and bottom of the landfill with different synthetics like HDPE geomembranes/FML, geosynthetic clay liners (GCL), and compacted clays liners. But the liners need to be strong enough to resist the effects of long term loads and chemicals to prevent the entry of wastes into the environment. The behavior of capping system changes with change in temperature. The shear strength of a GCL-geomembrane interface depends on friction angle between them. From literature it is observed that the interface friction angle is temperature dependent and decreases with decrease in temperature. The winter months of Ohio have very low temperature reaching
upto -15°C on an average. This harsh weather has an impact on the values of interface friction angle. Cool temperatures lower the interface friction angle values. This leads to shear failure of the entire capping system leading to leachate and gas migration into the environment. Our research largely necessitates desirable values of friction angle between geocomposite and geomembrane layers hence conform to commendable shear strength.
Chapter 2

Literature Review

Use of geosynthetic clay liners in bottom liners and capping systems of landfills and impoundments is steadily increasing (Schubert, 1987), (Koerner & Daniel, 1992), (Woodward & Well, 1995). Freeze-thaw in GCLs has severe effects on few projects either during or after construction work (Robert & David, 1997). The freeze-thaw process in natural clays and silts results in moisture migration, cracking and increased values of coefficient of permeability (Chamberlain & Gow, 1979). Bentonite exhibits less vulnerability to freeze-thaw process than other soils (Robert & David, 1997). Apparently the swelling and self-sealing characteristics of bentonite give GCLs its ability to withstand freeze-thaw (Robert & David, 1997). From the available literature, we can say that 3-5 freeze-thaw cycles are sufficient to determine the effects of freeze-thaw (Clem, J. 1992). Therefore, in the present work we preferred to subject the GCL to 1, 4 and 6 freeze-thaw cycles.

The type of interface plays a major role in agreeing on the interface shear behavior and on the results of direct shear box and inclined board tests. The interface shear strengths are significantly higher for direct shear tests than those of inclined board tests in rough
geomembrane - geotextile interfaces because of the large adhesion intercept values in direct shear envelopes. Research reveals that experiments working on shear properties of rough geomembrane - geotextile interface are recommended to use of anticipated normal stress rather than lower normal stress which could lead the experiment to higher risk of making an unconservative assessment of $\delta_f$. In the concern of precise measurements, it is advised to perform inclined board tests for lower normal stress levels and direct shear tests for higher levels of normal stress. Hence, we have opted to conduct direct shear tests on the samples in order to avoid any risks.

GCLs are used successfully in hazardous waste containment (Geotech. Fabrics Ep., 10 (3), 4-7). The stability of the lining systems is governed by interface strengths between geomembranes and geotextiles. The exothermic reactions due to waste decomposition and cocooning effects of waste vary the temperatures in liners from those in the laboratory. As per Benson, Barlaz, Lane, & Rawe, 2003, the bottom liner of a three filled landfills in the Midwestern USA have temperatures between 10 – 15˚C. In a polymer, as temperature increases the coefficient of friction increases (Bely, Sviridenok, Petrokovets, & Savkin, 1982). Pasqualini, Sand, & Roccato, 1993 conducted tests on geosynthetics and found that the interface friction angle was 12.4˚ at 26˚ C and 14.7˚ at 30˚ C for smooth LDPE geomembrane and polypropylene (PP) geotextile; 13.8˚ at 26˚ C and 15.9˚ at 30˚ C for smooth LDPE geomembrane and polyester (PET) geotextile. Akpinar, 1997 used a double-interface shear device contained in a temperature-controlled chamber to find the shear strength of smooth geomembrane–nonwoven geotextile (GMS-GT) and textured geomembrane–nonwoven geotextile (GMT-GT). The GMT–GT and GMS–GT interfaces were tested at 0, 10, 21, and 33˚ C at a displacement rate of 0.9, 1.1, and 1.5
mm/ min with normal stresses ranging between 7.5 and 49.5 kPa. Examination of the specimens showed us that polishing of the GMS–GT interface was the chief reason behind the post-peak strength loss while loss in GMT–GT interface was due to pulling out and reorientation of the geotextile fibers. It was concluded that regardless of shearing rate, interface friction angle increased with increase in temperature. Akpınar, M. (1997) thus determined the interface shear strength of geomembranes and geotextiles at different temperatures.

A cognizance of frictional behavior between different types of geosynthetics and soil is required for design, in the field of geotechnology (Wasti & Ozduzgun, 2001). The work by Wasti & Ozduzgun (2001) involves the measurement of shear strength parameters i.e., interface friction angle, adhesion values of geomembranes-geotextile interface using inclined board and direct shear box tests. In order to help in the process smooth and rough HDPE, PVC geomembranes and nonwoven needle-punched geotextiles were used. The HDPE geomembranes used were designated as GM (A), GM (B), GM(C) preceded by S or R depending on if it is smooth or rough respectively and GM (PVC) for PVC geomembrane. Two different brand nonwoven needle-punched geotextiles were designated GT (A) and GT (B) (Izgin & Wasti, 1998). The rate of shear (Shear Displacement Rate) used in the direct shear tests was 0.3 mm/s. The inclined board tests, standard and large-scale shear box tests including the repeat tests summed up to 366. As the board in the inclined board test tilts up, normal stress acting on the geosynthetic interface decreases. From experimental results, failure corresponds to the peak of the plot between shear stress and shear displacement in the direct shear test. On the interface at failure, normal stress was calculated using the relation $\sigma = \sigma_a \cos \delta_f$ and $\tau = \sigma_a \sin \delta_f$. 

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The best fitting straight lines were taken as failure envelopes to the point’s $\sigma$ and $-\Gamma$ by linear regression analysis. In an inclined board test, depending on surface roughness if the geomembrane, the raw material of the geomembrane and brand and the raw material of the same type of geotextile, interface friction angle ranges between 10° and 28°. In a Direct shear test, smooth HDPE geomembrane-geotextile interfaces have friction angle values about 12°-14° and rough HDPE geomembrane-geotextile interfaces have about 28°-30°. The results of the single inclined board test were interpreted by assuming adhesion = 0 and $\delta = \delta_f$. The dependence of $\delta_f$ on the normal stress is as follows, according to (Giroud, Swan, Richer, & Spooner, 1990), the highest $\delta = 48^\circ$ of a rough HDPE geomembrane-geotextile interface corresponds to the lowest normal stress in inclined board tests. From the results, it is evident that the inclined board and direct shear tests do not show a large discrepancy for the PVC and needle-punched geotextile used in the experiments.

Research indicates that sand with rounded particles change their interface friction angles easily to surface roughness of geomembrane and this was different with smooth geomembranes of different brands. Potential failure planes have low in-plane shear resistance. This property can be applied in canal linings or waste containment systems where correct assessment of interface shear properties between geosynthetics and soils or between different types of geosynthetics is a cardinal issue.

Interfacial shear strength parameters are determined using direct shear testing under high normal stresses; under low normal stresses the results are not accurate due to mechanical complications (Girard, Fisher, & Alonso, 1990, Giroud, Swan, Richer, & Spooner, 1990,
Koutsourais, Sprague, & Pucetas, 1991). Experimental observations revealed that various geomembrane-geotextile interfaces make generalization of results impossible.
Chapter 3

Research Statement

The objective is to investigate the shear strength behavior of GCL-geomembrane interfaces depending upon the variation of friction angle between the interfaces subjected to freezing and normal temperatures. Towards this goal, 66 experiments were conducted on four different types of geosynthetic samples subjected to 1.038 psi, 2.076 psi, and 4.152 psi normal stresses at 5 different (20, 35, 50, 65 and 80 %) moisture contents. The resulting shear strength values for both freezing and non-freezing were compared while considering adhesion and not considering adhesion as well. That interface friction angle value at which the shear strength is high is chosen to be the desired friction angle.
Chapter 4

Procedure

4.1 Apparatus set up:

The maximum sample dimensions of the direct shear apparatus are 40” longitudinally and 17” transversely and 4.5” deep. A Styrofoam layer that is approximately 1.5” thick is laid in the wooden frame that is overlain by a 40 mil HDPE textured geomembrane 15”X17”. The geomembrane is overlain by a geosynthetic clay liner (GCL) 8.5”X17” with its woven side facing up. The GCL is clamped with the Geomembrane at the ends to provide a good grip. A different geomembrane 18”X8.5” is bonded to a pullout plate 19”X8.5” using waterproof contact cement with the textured side of the geomembrane exposed. Before the geomembrane is glued to the pullout plate, one side of the geomembrane is sanded with an 80-grit sanding disc so as to make the gluing effective. After careful bonding of the geomembrane to the pullout plate, it is placed over the GCL with its textured surface facing the GCL. The tests were performed in general accordance with ASTM procedure D-5321 with an effective area of 8.5” X 8.5”. Normal stresses to the samples were applied using dead weights.

A light birchwood piece is placed over the pullout plate to provide room for the vertical
dial gauges to rest and for uniform distribution of normal stress. One end of the pullout plate is clamped to the load cell with the aid of a clevis. The load cell is connected to an electronic load transducer which is connected to a read-out apparatus that reads the load (lbs.) exerted on the sample while shearing it. A dial gauge is placed at the load cell to measure the pullout distance while collecting the loads on the sample while shearing it. A motor driven shaft is used to apply horizontal forces on the sample. A variable transmission apparatus on the motor regulates the number of rotations of the gear wheels that in turn regulate the rotations of the drive shaft. The motor has the provision that allows forward and reverse movements of the drive shaft.

Figure 4-1 Components of the Direct Shear Test Apparatus

Normal loads are placed on the wooden piece to subject the sample to normal/vertical stress and the pullout plate is pulled at a shear rate of 1mm/min until it is determined that there is sufficient horizontal deformation to reach the residual shear strength. Figure 4-2 depicts the arrangement of 300 lbs. (4.152 psi) normal load over a GCL sample with dial
gauges to read the extent of consolidation.

Figure 4-2 Experimental Set-up

4.2 Conditioning:

As per the manufacturer (CETCO Lining Technologies), the dry weight of the clay in a Bentomat DN sample at 0% moisture content is 0.844 lbs/sq.ft. The sample was tested for moisture content. In order to obtain the moisture content of the sample, it was placed in oven at $78^0\text{C}$ till the moisture in the samples was irreducible. It was observed that temperatures above $78^0\text{C}$ were affecting the integrity of the sample. The numbers obtained from the experiments have helped in calculating the weight of water to be added to the sample during conditioning. After adding the required amount of water to the sample it was wrapped in a plastic wrap to prevent any evaporation of moisture from the sample. ASTM D 3080 standard for conducting direct shear tests on soil recommends the
soil sample be consolidated under normal pressure before shearing. The same principle was applied here as well; the sample was allowed to cure for 2 days under 1 psi vertical stress. The vertical stress (1 psi) applied to the sample in the first stage of conditioning was lower than the least normal stress (1.038 psi) being applied to the sample in the second stage of conditioning. This is the first stage of conditioning. In this stage, the samples were placed one over the other under a Styrofoam board to distribute the stress uniformly. Figure 4-3 is a Bentomat DN sample at 20% moisture content wrapped in plastic to avoid escape of moisture from the sample. Figure 4-4 depicts the stack of samples under 1 psi vertical stress while conditioning.

![Figure 4-3 Bentomat DN sample at 20% moisture content](image)
In the second stage, the specimen was placed on the lower shearing surface with the woven side of the GCL facing upwards against the textured geomembrane that was glued to the pullout plate. A normal stress of 1.038 psi was applied on the specimen and it was subjected to consolidation for three hours i.e., until the dial gauges indicated consistent readings of the consolidating sample. It was observed that clay was compressed out from the sides of the GCL samples at high moisture contents like 50% and 80% under high normal stresses. Like the data shown in Fox et al. (2006), almost all the specimens reached a constant volume in not more than 6 hrs using this procedure. The two stage procedure greatly reduces the required in-machine hydration time for a GCL specimen.
4.3 Methodology:

*Testing the sample for moisture content*

Firstly, a sample specimen was placed in an oven for 48 hrs. at 78°C to make the moisture content of the sample irreducible. The sample was weighed at regular intervals. After obtaining the final weight of the sample, percentage of water in the sample was calculated. Further calculations resulted in weight of water to be added to the sample.

*Sample subjected to normal stress*

After adding the predetermined amount of water to the specimen, it was allowed to cure according to stage 1 and placed in the apparatus for consolidation. A normal load of 1.038 psi was applied to the sample and the deflections were taken until the dial gauges indicated consistent readings of the consolidating sample. Each sample took 3 hours to consolidate completely. After the samples were consolidated, the specimen was sheared to failure.

*Sample subjected to shearing*

After consolidation of the sample, it was sheared at a shear displacement rate (SDR) of 1mm/min. The pullout loads on the sample while shearing were collected from the read-out apparatus. This was done at every 0.020 inches on the dial gauge that was placed touching the load cell. The load on the sample reached a maximum value and started decreasing. Readings were taken until the load on the sample remained fairly constant or until the geomembrane glued to the pullout plate sheared the GCL for 2.5” (63.5 mm) or the tests were terminated after 2.5” of displacement. After the sample was sheared to
failure, it was unloaded and taken out of the apparatus to replace it with a new sample. Figure 4-5 is the image of pullout plate clamped to a load cell at one end and placed over a GCL sample.

Figure 4-5 Pullout plate clamped to a load cell at one end and placed over a GCL sample

Sample subjected to Freeze - thaw Cycles

Samples were initially conditioned according to stage 1 and then subjected to freeze-thaw. Three samples at 50% moisture content wrapped in plastic were placed in the freezer maintained at -20°C. The samples were subjected to a nominal load of 15.69 lbs. Figure 4-6 is the image of samples in the freezer during freeze – thaw cycles.
The samples were exposed to different number of freeze – thaw cycles. This was done to confirm that there is no significant difference in the loads on the sample while shearing, resulting in an overlap of curves. Sample 1 was subjected to 1 freeze - thaw cycle while samples 2 and 3 were subjected to 3 and 5 freeze-thaw cycles, respectively. Each cycle came up to 24 hrs. taking 12 hrs. to freeze and 12 hrs. to thaw. After completing the required number of freeze-thaw cycles (each cycle consisted of 12 hrs. freeze and 12 hrs. thaw, only then the sample was subjected to additional stress), the samples were subjected to a 2.076 psi normal stress and sheared as illustrated in the earlier sections.

The same procedure was observed for all the four samples: Bentomat ST, Bentomat DN, BFIX330NWL and BFIX230NSL at 20%, 35%, 50%, 65%, 80% moisture contents under 1.038 psi, 2.076 psi and 4.152 psi normal stresses. The same procedure was practiced in both frozen and unfrozen conditions of the sample.
Chapter 5

Results and Discussion

The present work involves testing of four different specimens at five different moisture contents subjected to three different normal stresses. We received rolls of Bentomat DN (BDN) and Bentomat ST (BST) samples from CETCO Lining Technologies. The product specifications are provided in the appendix. The samples BFIX230NSL and BFIX330NWNL were received from GSE Lining Technology, LLC. The samples were tested at 20%, 35%, 50%, 65%, and 80% moisture contents under a normal stress of 1.038 psi, 2.076 psi, and 4.152 psi. The samples were tested both under frozen condition (i.e., the samples that were subjected to freeze-thaw before testing) and unfrozen condition. The present section considers the results of 66 tests on different geosynthetic samples. The purpose of these tests was to obtain the interface friction angle and peak shear stress of each geosynthetic sample at particular moisture content under a specific normal stress. To arrive at our requirements, generally we had three figures for each material that was tested. Figure one depicts the shear stress values of the sample at a
particular moisture content under a specific normal stress. Figure two illustrates a curve with the three peak shear stresses while adhesion is considered and the trend line shows the trends in our data. The slope of the curve yielded the interface friction angle and the y-intercept yielded the adhesion (usually used for geo synthetics-only tests) or cohesion (usually used for tests involving soils) value. Figure three makes use of the data of graph two i.e., peak shear stress and normal stress values while ignoring adhesion. It reveals the change in the value of interface friction angle when adhesion is not considered. The interface friction angle and adhesion (or cohesion) values were based on mathematically determined best fit line.

![Shear Stress Vs Displacement](chart)

Figure 5-1  Shear stress (psi) Vs Displacement (in) of BDNU at 20% Moisture Content
Figure 5-1 is the graph of a Bentomat DN sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The sample Bentomat DN in unfrozen condition is abbreviated as BDNU in our project. The figure is a shear stress (psi) versus displacement (in) graph i.e., it has displacement (in) of the geomembrane that is glued to the pullout plate along the x-axis and shear stress (psi) on the geosynthetic interface along the y-axis. We can see that the blue curve is the shear stress versus displacement curve of the BDNU sample with a peak value of 0.678 psi under a normal stress of 1.038 psi at 20% moisture content in an unfrozen condition while the red curve is the shear stress versus displacement curve of the BDNU sample with a peak value of 1.629 psi under a normal stress of 2.076 psi at 20% moisture content in an unfrozen condition and the green curve is the shear stress versus displacement curve of the BDNU sample with a peak value of 2.96 psi under a normal stress of 4.152 psi at 20% moisture content in an unfrozen condition. It is evident from the figure that the shear stress values increase as the normal stress acting on the geosynthetic interface increases which indicates that there is a frictional component to the interface shear resistance.
Figure 5-2 Shear stress (psi) Vs Normal stress (psi) of BDNU at 20% Moisture Content

Figure 5-2 is graph two of the Bentomat DN sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The figure is a shear stress (psi) versus normal stress (psi) graph i.e., it has the normal stress (psi) acting on the geosynthetic interface along the x-axis and shear stress (psi) over the geosynthetic interface along the y-axis. The figure has the peak shear stress values of the BDNU sample under 1.038 psi, 2.076 psi, and 4.152 psi normal stresses. The curve shows a steep increase in values of the shear stress as the normal stress on the geosynthetic interface increases. Likewise, the shear strength increases as per the equation,

\[ \tau_f = a + \sigma \tan \phi \]

\[ y = 0.7203x + 0.0118 \]

\[ R^2 = 0.9912 \]
The trendline of the curve gave us the slope and y-intercept of the curve. The slope of the curve represents Tan of the interface friction angle (\(\phi\)) while the y-intercept represents adhesion (a) of the geosynthetic interface. The interface friction angle from the figure is calculated as 35.8\(^o\) and the adhesion value is calculated as 0.012 psi which is a very small adhesion value. This could be the result of an experimental error. The regression value indicates that the interface shear strength can be represented as a linear function with high accuracy for the range of values of normal stress used for the testing.

![Shear Stress Vs Normal Stress](image)

Figure 5-3Shear stress (psi) Vs Normal stress (psi) of BDNU at 20% Moisture Content,

\[ y = 0.7241x \]

\[ R^2 = 0.9912 \]

Figure 5-3 is the graph three of the Bentomat DN sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when
adhesion (a) between the geosynthetic interface is assumed to be zero. When a=0, we see a slight increase in the interface friction angle value from $35.8^0$ to $35.9^0$. This shows that there is only minimal increase in shear strength of the geosynthetic interface that results by ignoring the interface adhesion.

Figure 5-4 represents Bentomat DN sample at 35% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. We can see that the blue curve is the shear stress (psi) versus displacement (in) curve of the BDNU sample with a peak value of 0.95 psi under a normal stress of 1.038 psi at 35% moisture content.
in a unfrozen condition while the red curve is the shear stress (psi) versus displacement (in) curve of the BDNU sample with a peak value of 1.39 psi under a normal stress of 2.076 psi at 35% moisture content in a unfrozen condition and the green curve is the shear stress (psi) versus displacement (in) curve of the BDNU sample with a peak value of 2.44 psi under a normal stress of 4.152 psi at 35% moisture content in a unfrozen condition. It is evident from the figure that the shear stress values increase as the normal stress on the geosynthetic interface increases.

Figure 5-5 Shear stress (psi) Vs Normal stress (psi) of BDNU at 35% Moisture Content

Figure 5-5 is graph of the Bentomat DN sample at 35% moisture content under three
different normal stresses in a normal unfrozen condition at room temperature. The curve shows a steep increase in values of the shear stress as the normal stress on the geosynthetic interface increases. It is evident that the shear strength increases as well. The interface friction angle from the figure is calculated as $25.6^\circ$ and the adhesion value is calculated as 0.43 psi.

Figure 5-6 Shear stress (psi) Vs Normal stress (psi) of BDNU at 35% Moisture Content, $a=0$

Figure 5-6 is graph of the Bentomat DN sample at 35% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion ($a$) between the geosynthetic interface is assumed to be zero. At $a=0$, there is a significant increase in the interface friction angle from $25.6^\circ$ to $31.7^\circ$. In this case, the
shear strength decreases under low normal stress, less than about 3 psi, when the interface friction angle increased considering adhesion to be zero.

![Shear Stress Vs Displacement](image)

**Figure 5-7** Shear stress (psi) Vs Displacement (in) of BDNU at 50% Moisture Content

Figure 5-7 is graph of a Bentomat DN sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in) of the BDNU sample with a peak value of 0.33 psi under a normal stress of 1.038 psi while the red curve has a peak value of 1.41 psi when the BDNU sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the BDNU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.4 psi. From the figure it is evident that the blue curve is close to the origin i.e., shear stress values of the sample under 1.038 psi normal stress are
very low when compared to the samples under higher normal stresses.

![Shear Stress Vs Normal Stress](image)

Figure 5-8 Shear stress (psi) Vs Normal stress (psi) of BDNU at 50% Moisture Content

Figure 5-8 is graph of the Bentomat DN sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows a steep increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The interface friction angle from the figure is calculated as 32.6° and the adhesion value is calculated as -0.168 psi (-24.22 psf). The negative value of adhesion could be the result of an error during the experimental procedure. The value -0.168 psi is well within the range of error/accuracy. On the other hand, negative adhesion does not exist in real life; if the experiments yield negative values of adhesion then such values are just neglected. Hence, negative values of adhesion can never be
detrimental. The precision of the graph can be read from its regression value.

![Graph: Shear Stress Vs Normal Stress](image)

**Figure 5-9** Shear stress (psi) Vs Normal stress (psi) of BDNU at 50% Moisture Content, a=0

Figure 5-9 is graph of the Bentomat DN sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. At a=0, there is a significant decrease in the value from 32.6° to 30.3°. In this case, the shear strength value decreases when the interface friction angle increased considering adhesion to be zero.
Figure 5-10 Shear stress (psi) Vs Displacement (in) of BDNU at 65% Moisture Content

Figure 5-10 is the graph of a Bentomat DN sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in) curve of the BDNU sample with a peak value of 0.876 psi under a normal stress of 1.038 psi while the red curve has a peak value of 1.326 psi when the BDNU sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the BDNU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.46 psi. From the curves it is clear that the shear stress values of the samples under 1.038 psi and 2.076 psi normal stresses were close while those of the sample under normal stress 4.152 psi were much higher.
Figure 5-11 Shear stress (psi) Vs Normal stress (psi) of BDNU at 65% Moisture Content

Figure 5-11 is graph of the Bentomat DN sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows a steep increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The interface friction angle from the figure 4-11 is calculated as 27.2° and the adhesion value is calculated as 0.309psi.
Figure 5-12 is graph of the Bentomat DN sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. As the a=0, we see a difference in the interface friction angle value. It is observed that there is a significant increase in the value from 27.2° to 31.5°. In this case, the shear strength value increases when the interface friction angle increased as per Mohr-Coulomb criterion.
Figure 5-13 Shear stress (psi) Vs Displacement (in) of BDNU at 80% Moisture Content

Figure 5-13 is the graph of a Bentomat DN sample at 80% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in) curve of the BDNU sample with a peak value of 0.66 psi under a normal stress of 1.038 psi and red curve has a peak value of 1.21 psi when the BDNU sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the BDNU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.39 psi. The blue and red curves of the figure show that the shear stress values of the samples under 1.038 psi and 2.076 psi normal stresses were close while those of the sample under normal stress 4.152 psi were much higher.
Figure 5-14 Shear stress (psi) Vs Normal stress (psi) of BDNU at 80% Moisture Content

Figure 5-14 is graph of the Bentomat DN sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows a steep increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The interface friction angle from the figure is calculated as 27.2° and the adhesion value is calculated as 0.309 psi.
Figure 5-15 is the graph of the Bentomat DN sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. As the a=0, we see a difference in the interface friction angle value. It is observed that there is a significant increase in the value from 27.2° to 31.5°. In this case, the shear strength value increases when the interface friction angle increased as per Mohr-Coulomb criterion.
Figure 5-16 is the graph of a Bentomat ST sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The sample Bentomat ST in unfrozen condition is abbreviated as BSTU in our project. The figure is a shear stress (psi) versus displacement (in) graph i.e., it has displacement (in) of the geomembrane that is glued to the pull out plate along the x-axis and shear stress (psi) on the geosynthetic interface along the y-axis. We can see that the blue curve is the shear stress (psi) versus displacement (in) curve of the BSTU sample with a peak value of 1.077 psi under a normal stress of 1.038 psi at 20% moisture content in a unfrozen condition while the red curve is the shear stress (psi) versus displacement (in) curve of the BDNU sample with a peak value of 1.686 psi under a normal stress of 2.076 psi at
20% moisture content in an unfrozen condition and the green curve is the shear stress (psi) versus displacement (in) curve of the BSTU sample with a peak value of 2.67psi under a normal stress of 4.152 psi at 20% moisture content in an unfrozen condition. It is evident from the figure that the shear stress values increase as the normal stress acting on the geosynthetic interface increases. From the figure, it is observed that the curves of these samples at 20% moisture content are not as flat as the BDNU samples.

Figure 5-17 Shear stress (psi) Vs Normal stress (psi) of BSTU at 20% Moisture Content

Figure 5-17 is the graph two of the Bentomat ST sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The figure is a shear stress (psi) versus normal stress (psi) graph i.e., it has the normal stress (psi) acting on the geosynthetic interface along the x-axis and shear stress (psi) over the
geosynthetic interface along the y-axis. The figure has the peak shear stress values of the BSTU sample under 1.038 psi, 2.076 psi, and 4.152 psi normal stresses. The curve shows a steep increase in values of the shear stress as the normal stress on the geosynthetic interface increases. Since, the slope of the curve represents interface friction angle (\(\phi\)), the interface friction angle is higher. The interface friction angle from the figure is calculated as 26.9° and the adhesion value is calculated as 0.585 psi. The regression value indicates that the interface shear strength can be represented as a linear function with high accuracy for the range of values of normal stress used for the testing.

Figure 5-18 Shear stress (psi) Vs Normal stress (psi) of BSTU at 20% Moisture Content, a=0
Figure 5-18 is the graph three of the Bentomat ST sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. When a=0, we see that there is a significant increase in the value from $26.9^0$ to $34.8^0$. The shear strength will be lower under low normal stress when a=0.

![Shear Stress Vs Displacement](image)

Figure 5-19 Shear stress (psi) Vs Displacement (in) of BSTU at 35% Moisture Content

Figure 5-19 is the graph of a Bentomat ST sample at 35% moisture content under threedifferent normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in)curve of the BSTU sample.
with a peak value of 1.082 psi under a normal stress of 1.038 psi while the red curve has a peak value of 1.453 psi when the BSTU sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the BSTU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.545 psi. From the blue and red curves of figure, it is clear that the shear stress values of the samples under 1.038 psi and 2.076 psi normal stresses were proximate while those of the sample under normal stress 4.152 psi were much higher.

![Shear Stress Vs Normal Stress](image)

Figure 5-20 Shear stress (psi) Vs Normal stress (psi) of BSTU at 35% Moisture Content

Figure 5-20 is graph of the Bentomat ST sample at 35% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows that there is an increase in values of the shear stress as the normal stress on the
geosynthetic interface increases from 1.038 psi to 4.152 psi. The interface friction angle from the figure is calculated as $25.5^0$ and the adhesion value is calculated as 0.536 psi.

![Shear Stress Vs Normal Stress](image)

Figure 5-21 Shear stress (psi) Vs Normal stress (psi) of BSTU at 35% Moisture Content, $a=0$

Figure 5-21 is graph of the Bentomat ST sample at 35% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion ($a$) between the geosynthetic interface is assumed to be zero. It is observed that there is a significant increase in the value from $25.5^0$ to $33^0$. 
Figure 5-22 is the graph of a Bentomat ST sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in) curve of the BSTU sample with a peak value of 0.962 psi under a normal stress of 1.038 psi and red curve has a peak value of 1.37 psi when the sample is subjected to a normal stress of 2.076 psi and green curve is obtained when the BSTU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.57 psi. The blue and red curves, show that the shear stress values of the samples under 1.038 psi and 2.076 psi normal stresses were relatively close to each other while the sample under normal stress 4.152 psi had higher shear stress values.
Figure 5-23 is graph of the Bentomat ST sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows that there is an increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The interface friction angle from the figure is calculated as $27.7^\circ$ and the adhesion value is calculated as 0.362 psi.
Shear stress (psi) Vs Normal stress (psi) of BSTU at 50% Moisture Content, a=0

Figure 5-24 is the graph of Bentomat ST Sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. It is observed that there is a significant increase in the value from 27.7$^0$ to 32.7$^0$. 
Figure 5-25 Shear stress (psi) Vs Displacement (in) of BSTU at 65% Moisture Content

Figure 5-25 is the graph of a Bentomat ST sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in) curve of the BSTU sample with a peak value of 0.873 psi under a normal stress of 1.038 psi while the red curve has a peak value of 1.36 psi when the BSTU sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the BSTU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.5 psi. We have observed an increase in the values of shear stress with increase in normal stress.
Figure 5-26 is graph of the Bentomat ST sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows that there is an increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The interface friction angle from the figure is calculated as $27.7^0$ and the adhesion value is calculated as 0.305 psi.
Figure 5-27 is the graph of Bentomat ST sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. It is observed that there is an apparent increase in the value from 27.7° to 31.9°. Therefore, the shear strength value increases when the interface friction angle increased as per Mohr-Coulomb criterion.
Figure 5-28 is the graph of a Bentomat ST sample at 80% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in) of the BSTU sample with a peak value of 0.87 psi under a normal stress of 1.038 psi while the red curve has a peak value of 1.29 psi when the sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.41 psi. The blue and red curves, show that the shear stress values of the samples under 1.038 psi and 2.076 psi normal stresses were relatively close to each other while the sample under normal stress 4.152 psi had higher shear stress values.
Figure 5-29 Shear stress (psi) Vs Normal stress (psi) of BSTU at 80% Moisture Content

Figure 5-29 is graph of the Bentomat ST sample at 80% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows that there is an increase in values of the shear stress as the normal stress on the geosynthetic interface increases from 1.038 psi to 4.152 psi. The interface friction angle from the figure is calculated as 26.6\(^{0}\) and the adhesion value is calculated as 0.312 psi.
Figure 5-30 Shear stress (psi) Vs Normal stress (psi) of BSTU at 80% Moisture Content, a=0

Figure 5-30 is graph of the Bentomat ST sample at 80% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. It is observed that there is a significant increase in the value from 26.6⁰ to 31⁰.
Figure 5-31 Shear stress (psi) Vs Displacement (in) of BNSLU at 20% Moisture Content

Figure 5-31 is the graph one of a BFIX230NSL sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The sample BFIX230NSL in unfrozen condition is abbreviated as BNSLU in our project. The figure is a shear stress (psi) versus displacement (in) graph i.e., it has displacement (in) of the geomembrane that is glued to the pull out plate along the x-axis and shear stress (psi) on the geosynthetic interface along the y-axis. We can see that the blue curve of the BNSLU sample with a peak value of 0.833 psi under a normal stress of 1.038 psi at 20% moisture content in an unfrozen condition while the red curve is the shear stress (psi) versus displacement (in) curve of the BNSLU sample with a peak value of 1.427 psi under a normal stress of 2.076 psi at 20% moisture content in an unfrozen condition and
the green curve has a peak value of 2.6 psi under a normal stress of 4.152 psi in an unfrozen condition. It is evident from the figure that the shear stress values increase as the normal stress acting on the geosynthetic interface increases.

Figure 5-32 Shear stress (psi) Vs Normal stress (psi) of BNSLU at 20% Moisture Content

Figure 5-32 is the graph two of the BNSLU sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The graph two is a shear stress (psi) versus normal stress (psi) graph. The figure consists of peak shear stress values of the BNSLU sample under 1.038 psi, 2.076 psi, and 4.152 psi normal stresses. The curve shows a steep increase in values of the shear stress as the normal
stress on the geosynthetic interface increases. The slope of the curve represents interface friction angle ($\phi$) while the y-intercept represents adhesion ($a$) of the geosynthetic interface. The interface friction angle from the figure is calculated as 28.9$^\circ$ and the adhesion value is calculated as 0.267 psi. The regression value indicates that the interface shear strength can be represented as a linear function with high accuracy for the range of values of normal stress used for the testing.
Figure 5-33 is the graph three of the BNSLU sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. When a=0, we see an increase in the interface friction angle value. It is observed that there is a significant increase in the value from $28.9^0$ to $32.6^0$. Henceforth, we can say that there is a definite increase in shear strength of the geosynthetic interface under low normal stress, less than 3 psi.
Figure 5-34 Shear stress (psi) Vs Displacement (in) of BNSLU at 35% Moisture Content

Figure 5-34 is the graph of a BNSLU sample at 35% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus normal stress (psi) curve of the BNSLU sample with a peak value of 0.792 psi under a normal stress of 1.038 psi while the red curve has a peak shear stress value of 1.372 psi when the BNSLU sample is subjected to a normal stress of 2.076 psi and the green curve is drawn when the BNSLU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.57 psi.
Figure 5-35 is the graph of BNSLU sample at 35% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The interface friction angle from the figure is calculated as 29.8° and the adhesion value is calculated as 0.193 psi. From the curve we observe that there is an increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The regression value indicates that the interface shear strength can be represented as a linear function with high accuracy for the range of values of normal stress used for the testing.
Figure 5-36 is the graph of BNSLU sample at 35% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion \( a \) between the geosynthetic interface is assumed to be zero. It is observed that there is an apparent increase in the value from 29.85\( ^0 \) to 32.4\( ^0 \). Therefore, the shear strength value increases when the interface friction angle increased as per Mohr-Coulomb criterion.
Figure 5-37  Shear stress (psi) Vs Displacement (in) of BNSLU at 50% Moisture Content

Figure 5-37 is the graph of a BNSLU sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in) curve of the BNSLU sample with a peak value of 0.824 psi under a normal stress of 1.038 psi while the red curve has a peak value of 1.32 psi when the BNSLU sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the BNSLU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.5 psi. From the curves it is clear that the shear stress values of the samples under 1.038 i and 2.076 psi normal stresses were proximate while those of the sample under normal stress 4.152 psi were relatively higher.
Figure 5.38 Shear stress (psi) Vs Normal stress (psi) of BNSLU at 50% Moisture Content

Figure 5.38 is the graph of BNSLU sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows that there is an increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The interface friction angle from the figure is calculated as 28.5° and the adhesion value is calculated as 0.233psi.
Figure 5-39 Shear stress (psi) Vs Normal stress (psi) of BNSLU at 50% Moisture Content, a=0

Figure 5-39 is the graph of BNSLU sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. As the a=0, we see a difference in the interface friction angle value. It is observed that there is a significant increase in the value from 28.5° to 31.7°. In this case, the shear strength value increases when the interface friction angle increased while considering adhesion to be zero.
Figure 5-40 Shear stress (psi) Vs Displacement (in) of BNSLU at 65% Moisture Content

Figure 5-40 is the graph one of a BNSLU sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the displacement versus shear stress curve of the BNSLU sample with a peak value of 0.746 psi under a normal stress of 1.038 psi while the red curve has a peak value of 1.21 psi when the BNSLU sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the BNSLU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.44 psi. From the blue and red curves, it is clear that the shear stress values of the samples under 1.038 psi and 2.076 psi normal stresses were close while those of the sample under normal stress 4.152 psi were much higher.
Figure 5-41 is the graph of BNSLU sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows a steep increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The interface friction angle from the figure is calculated as 28.8° and the adhesion value is observed to be a very low value 0.134 psi.
Figure 5-42 is the graph of BNSLU sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. It is observed that there is a significant increase in the interface friction angle value from 28.8° to 30.6°.
Figure 5-43 is the graph one of a BNSLU sample at 80% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the displacement versus shear stress curve of the BNSLU sample with a peak value of 0.745 psi under a normal stress of 1.038 psi at 80% moisture content while the red curve has a peak value of 1.323 psi when the BNSLU sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the BNSLU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.5 psi. We have observed an increase in the values of shear stress with increase in normal stress. The green curve i.e., the shear stress values of the BNSLU under 4.152 psi were rapidly decreasing after the peak.
Figure 5-44 Shear stress (psi) Vs Normal stress (psi) of BNSLU at 80% Moisture Content

Figure 5-44 is the graph of BNSLU sample at 80% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The interface friction angle from the figure is calculated as 29.4° and the adhesion value is calculated as 0.156 psi. From the curve we observe that there is an increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The regression value indicates that the interface shear strength can be represented as a linear function with high accuracy for the range of values of normal stress used for the testing.
Figure 5-45 Shear stress (psi) Vs Normal stress (psi) of BNWLU at 80% Moisture Content, a=0

Figure 5-45 is the graph of BNSLU sample at 80% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. When a=0, we see that there is a significant increase in the value from 29.4° to 31.57°.
Figure 5-46 Shear stress (psi) Vs Displacement (in) of BNWLU at 20% Moisture Content

Figure 5-46 is the graph one of a BFIX330NWL sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The sample BFIX330NWL in unfrozen condition is abbreviated as BNWLU in our project. The figure is a shear stress (psi) versus displacement (in) graph i.e., it has displacement (in) of the geomembrane that is glued to the pull out plate along the x-axis and shear stress (psi) on the geosynthetic interface along the y-axis. We can see that the blue curve of the BNWLU sample with a peak value of 0.912 psi under a normal stress of 1.038 psi at 20% moisture content in an unfrozen condition while the red curve is the shear stress (psi) versus displacement (in) curve of the BNWLU sample with a peak value of 1.528 psi under a normal stress of 2.076 psi at 20% moisture content in an unfrozen condition.
and the green curve has a peak value of 2.76 psi under a normal stress of 4.152 psi in an unfrozen condition. It is evident from the figure that the shear stress values increase as the normal stress acting on the geosynthetic interface increases.

![Shear Stress Vs Normal Stress](image)

Figure 5-47 Shear stress (psi) Vs Normal stress (psi) of BNWLU at 20% Moisture Content

Figure 5-47 is the graph two of the BNWLU sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The figure is a shear stress (psi) versus normal stress (psi) graph. The figure consists of peak shear stress values of the BNWLU sample under 1.038 psi, 2.076 psi, and 4.152 psi normal stresses. The curve shows a steep increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The slope of the curve represents interface
friction angle (\(\phi\)) while the y-intercept represents adhesion (a) of the geosynthetic interface. The interface friction angle from the figure is calculated as 30.7° and the adhesion value is calculated as 0.294 psi. The regression value indicates that the interface shear strength can be represented as a linear function with high accuracy for the range of values of normal stress used for the testing.
Figure 5-48 Shear stress (psi) Vs Normal stress (psi) of BNWLU at 20% Moisture Content, a=0

Figure 5-48 is the graph three of the BNWLU sample at 20% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. When a=0, we see that there is a significant increase in the value from 30.7° to 34.6°. Henceforth, we can say that there is a definite increase in shear strength of the geosynthetic interface.
Figure 5-49 is the graph of a BNWLU sample at 35% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus normal stress (psi) curve of the BNWLU sample with a peak value of 0.757 psi under a normal stress of 1.038 psi while the red curve has a peak shear stress value of 1.355 psi when the BNWLU sample is subjected to a normal stress of 2.076 psi and the green curve is drawn when the BNWLU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.55 psi.
Figure 5-50 is the graph of BNWLU sample at 35% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The interface friction angle from the figure is calculated as 29.9° and the adhesion value is calculated as 0.159 psi which is the lowest adhesion value when compared to other BNWLU sample at different moisture contents. From the curve we observe that there is an increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The regression value indicates that the interface shear strength can be represented as a linear function with high accuracy for the range of values of normal stress used for the testing.
Figure 5-51 Shear stress (psi) Vs Normal stress (psi) of BNWL at 35% Moisture Content, a=0

Figure 5-51 is the graph of BNWL sample at 35% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. It is observed that there is an apparent increase in the value from 29.9 to 32.1.
Figure 5-52 Shear stress (psi) Vs Displacement (in) of BNWLU at 50% Moisture Content

Figure 5-52 is the graph of a BNWLU sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in) curve of the BNWLU sample with a peak value of 0.745 psi under a normal stress of 1.038 psi while the red curve has a peak value of 1.38 psi when the BNWLU sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the BNWLU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.5 psi. From the curves it is clear that the shear stress values of the samples under 1.038 i and 2.076 psi normal stresses were proximate while those of the sample under normal stress 4.152 psi were relatively higher.
Figure 5-53 is the graph of BNWLU sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows that there is an increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The interface friction angle from the figure is calculated as 28.5° and the adhesion value is calculated as 0.213 psi.

\[ y = 0.5422x + 0.2125 \]

\[ R^2 = 0.9978 \]
Figure 5-54 is the graph of BNWLU sample at 50% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion \( a \) between the geosynthetic interface is assumed to be zero. As the \( a=0 \), we see a difference in the interface friction angle value. It is observed that there is a significant increase in the value from 28.5\(^0\) to 31.4\(^0\). In this case, the shear strength value increases when the interface friction angle increased while considering adhesion to be zero.
Figure 5-55 Shear stress (psi) Vs Displacement (in) of BNWLU at 65% Moisture Content.

Figure 5-55 is the graph of a BNWLU sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in) curve of the BNWLU sample with a peak value of 0.747 psi under a normal stress of 1.038 psi while the red curve has a peak value of 1.336 psi when the BNWLU sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the BNWLU sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.36 psi. We have observed an increase in the values of shear stress with increase in normal stress.
Figure 5-56 Shear stress (psi) Vs Normal stress (psi) of BNWLU at 65% Moisture Content

Figure 5-56 is graph of the Bentomat ST sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The curve shows that there is an increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The interface friction angle from the figure is calculated as 27.2° and the adhesion value is calculated as 0.235 psi.
Figure 5-57 Shear stress (psi) Vs Normal stress (psi) of BNWLU at 65% Moisture Content, a=0

Figure 5-57 is the graph of BNWLU sample at 65% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. It is observed that there is an apparent increase in the value from 27.2° to 30.5°. Therefore, the shear strength value increases when the interface friction angle increased as per Mohr-Coulomb criterion.
Figure 5-58 Shear stress (psi) Vs Displacement (in) of BNWLU at 80% Moisture Content

Figure 5-58 is the graph of a BNWLU sample at 80% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The blue curve is the shear stress (psi) versus displacement (in) of the BNWLU sample with a peak value of 0.73 psi under a normal stress of 1.038 psi while the red curve has a peak value of 1.27 psi when the sample is subjected to a normal stress of 2.076 psi and the green curve is obtained when the sample is subjected to normal stress of 4.152 psi resulting in a peak value of 2.33 psi. The blue and red curves, show that the shear stress values of the samples under 1.038 psi and 2.076 psi normal stresses were relatively close to each other while the sample under normal stress 4.152 psi had higher shear stress values.
Figure 5-59 is the graph of BNWLU sample at 80% moisture content under three different normal stresses in a normal unfrozen condition at room temperature. The interface friction angle from the figure is calculated as $27.1^0$ and the adhesion value is calculated as 0.201 psi. From the curve we observe that there is an increase in values of the shear stress as the normal stress on the geosynthetic interface increases. The regression value indicates that the interface shear strength can be represented as a linear function with high accuracy for the range of values of normal stress used for the testing.
Figure 5-60 Shear stress (psi) Vs Normal stress (psi) of BNWLU at 80% Moisture Content, a=0

Figure 5-60 is the graph of BNWLU sample at 80% moisture content under three different normal stresses in a normal unfrozen condition at room temperature when adhesion (a) between the geosynthetic interface is assumed to be zero. It is observed that there is a significant increase in the value from 27.1° to 30°. Therefore, it shows a considerable increase in shear strength of the geosynthetic interface.
5.1 Effects of Moisture Content on the Shear Strength Parameters of Different Geosynthetic Interfaces (Unfrozen)

The figure 5-61 effectively demonstrates the variation of adhesion values of the four different types of GCL samples at four different moisture contents. If we consider the Bentomat DN sample, we observed its adhesion values were comparatively very low at moisture contents 20%, 50%, and 80%. The Bentomat DN at 50% moisture content had negative adhesion value of -0.168 psi which was within the range of error. However, this negative value of adhesion does not have significant effect on the interface shear strength. Highest adhesion value of 0.585 psi was observed by Bentomat ST sample at 20% moisture content.
moisture content. The adhesion values of the samples BFIX230NSL and BFIX330NWL were more or less in a close range. The adhesion values of the Bentomat ST sample were relatively higher for a given moisture content. It can be concluded that generally the adhesion value decreases as the moisture content increases.

![Variation of Interface Friction Angle of the Samples](image)

**Figure 5-62** Variation of Interface Friction Angles of the GCL Samples at Different Moisture Contents

The Figure 5-62 illustrates the variation of interface friction angles of the four different types of GCL samples at four different moisture contents. The interface friction angle values of the samples approximately ranged from $25^0$ to $35^0$. The average interface friction angle of the four different GCL samples at five different moisture contents was found to be $28.7^0$. Bentomat DN sample at 20% moisture content had the highest
interface friction angle of $35.8^0$ while the Bentomat ST sample at 35% moisture content had the lowest interface friction angle of $25.5^0$. From the Figure 5-61 we have observed that the adhesion values of the samples BFIX230NSL and BFIX330NWL were in a close range; similarly from Figure 5-62 we have observed that the samples BFIX230NSL and BFIX330NWL had interface friction angles in a close proximity. There is a weak trend that the interface friction angles decrease with increase in moisture content, but the trend is not as strong as for adhesion.

Figure 5-63 Variation of Interface Friction Angles of the GCL Samples at Different Moisture Contents when adhesion, C=0
The Figure 5-63 illustrates the variation of interface friction angles of the four different types of GCL samples at four different moisture contents. The interface friction angle values of the samples approximately ranged from $30^0$ to $36^0$. The average interface friction angle of the four different GCL samples at four different moisture contents was found to be $33^0$. Bentomat DN sample at 20% moisture content had the highest interface friction angle of $35.9^0$ while the BFIX330NWL sample at 80% moisture content had the lowest interface friction angle of $30^0$. From the figure 5-62 and figure 5-63 it is evident that the highest values of interface friction angle are almost the same. The variation of the interface friction angle with moisture content is in a close proximity. It is also observed that the interface friction angle decreased with increase in moisture content which in turn decreases the interface shear strength of the geosynthetics; this could be because of the clay coming out from the sides of the GCL as a result of increase in moisture content and normal stress over the GCL.
5.2 Effects of Freezing Temperature on the Shear Strength Parameters of Different Geosynthetic Interfaces

Figure 5-64 Shear stress (psi) Vs Displacement (in) of BSTFT at 50% Moisture content

Bentomat ST sample was subjected to different number of freeze-thaw cycles i.e., 1, 4 and 6 under a normal stress of 2.076 psi at 50% moisture content in order to determine the effect of temperature on the geosynthetic interface of a capping system in a landfill. From the above figure 5-64, we observed that the shear stress value of the sample when subjected to 4 freeze-thaw cycles was relatively higher than that of the samples at 1 and 6 freeze-thaw cycles. This variation can be clearly observed from figure 5-65 below. When we perform a point-to-point comparison of shear stress values of Bentomat ST sample subjected to 2.076 psi at 50% moisture content, we observed that there is no significant
variance in the values when the sample is exposed to frozen and unfrozen conditions. The shear stress value Bentomat ST sample when subjected to normal stress 2.076 psi at 50% moisture content in unfrozen condition is 1.37 psi.

![Graph showing variation of shear stress with change in number of freeze-thaw cycles](image)

Figure 5-65 Variation of shear stress with change in number of freeze-thaw cycles

When the sample is subjected to 1 freeze-thaw cycle the peak shear stress is 1.309 psi, when subjected to 4 freeze-thaw cycles the peak shear stress is the highest 1.359 psi and when subjected to 6 freeze-thaw cycles the peak shear stress is 1.33 psi. From Figure 5-22, the peak shear stress value of an unfrozen Bentomat ST sample at 50% moisture content under a normal stress 2.076 psi was found to be 1.369 psi; this value is higher than that of the samples subjected to freeze-thaw.
Bentomat ST sample was subjected to different number of freeze-thaw cycles i.e., 1, 4 and 6 under a normal stress of 2.076 psi at 80% moisture content in order to determine the effect of temperature on the geosynthetic interface of a capping system in a landfill. From Figure 5-66, we observed that the shear stress value of the sample when subjected to 4 freeze-thaw cycles was relatively higher than that of the samples at 1 and 6 freeze-thaw cycles. This variation can be clearly observed from the Figure 5-7 below. When the shear stress values of Bentomat ST sample are compared in frozen and unfrozen conditions, it was evident that there was no observable difference in the values of shear stress. The shear stress value of Bentomat ST sample when subjected to normal stress 2.076 psi at 80% moisture content in unfrozen condition is 1.29 psi.
When the sample is subjected to 1 freeze-thaw cycle the peak shear stress is 1.29 psi, when subjected to 4 freeze-thaw cycles the peak shear stress is the highest 1.392 psi and when subjected to 6 freeze-thaw cycles the peak shear stress is 1.215 psi. From Figure 5-28, the peak shear stress value of an unfrozen Bentomat ST sample at 50% moisture content under a normal stress 2.076 psi was found to be 1.293 psi; this value lies between the highest and lowest peak shear stress values of the samples subjected to freeze-thaw.
Chapter 6

Conclusions

After conducting 66 direct shear tests on four different types of geosynthetic clay liners against 40 mil textured HDPE geomembrane, we have obtained interesting results. The results have been discussed in details in chapter 5.

Conclusions drawn from the direct shear testing are listed below:

- The major percentage of the geosynthetic sample interfaces exhibited a similar pattern of curves where the shear stress values of the samples under low normal stresses (1.038 psi and 2.076 psi) were relatively proximate while those of the sample under normal stress 4.152 psi were considerably higher.

- The regression values of all the figures indicated that the interface shear strength can be represented as a linear function with high accuracy for the range of values of normal stress used for the testing i.e., 1.038 psi, 2.076 psi, and 4.152 psi.

- The adhesion and interface friction angle values obtained from the samples BFIX230NSL and BFIX330NWL were in close proximity.

- The Bentomat ST sample at 50% moisture content when subjected to 4 freeze-thaw cycles under a normal stress of 2.076 psi exhibited maximum shear stress when compared to samples at 1 and 6 freeze-thaw cycles.
• The average interface friction angle of the four different GCL samples at four different moisture contents was found to be 28.7°.

• When comparing the average shear strength values of Bentomat ST sample in unfrozen and frozen conditions at a moisture content of 50% under a normal stress of 2.076 psi, we observed that there is only 4% difference in the values that is negligible. Likewise, when the shear strength values of Bentomat ST at 80% moisture content were compared, there was a 1% difference in the values.

• We have observed that the shear stress values of the samples in frozen and unfrozen conditions had no significant difference. Henceforth, we can say that the effect of freezing temperature on the geosynthetic interface in a capping system of a landfill is negligible.

The following tables summarize the results of all the direct shear tests conducted on 4 different types of GCL’s at 5 different moisture contents subjected to 3 different normal stresses in frozen as well as unfrozen conditions.

Table 6.1 summarizes the results of the direct shear tests conducted on Bentomat DN sample in unfrozen condition. The Bentomat DN sample at 20% moisture content under 4.152 psi yields the highest value of shear stress of 2.962 psi when compared to all the other conditions on Bentomat DN. Interface friction angle values at zero adhesion are relatively higher than the interface friction angle values when adhesion is considered. The sample at 20% moisture content when adhesion is not considered yielded highest interface friction angle value of 35.9°. The table shows a negative adhesion at 50%
moisture content. But negative adhesion does not exist in real life; if the experiments yield negative values of adhesion then such values are just neglected. Hence, negative values of adhesion can never be detrimental.

Table 6.1 Results of the Direct Shear Tests conducted on Bentomat DN (Unfrozen)

<table>
<thead>
<tr>
<th>Moisture Content ( % )</th>
<th>Normal Stress (psi)</th>
<th>Adhesion ( C )</th>
<th>Tan φ</th>
<th>Interface Friction angle, φ (degrees)</th>
<th>Peak Shear Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.038</td>
<td>0.0118</td>
<td>0.7208</td>
<td>35.8</td>
<td>0.678</td>
</tr>
<tr>
<td></td>
<td>2.076</td>
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<td></td>
<td></td>
<td>1.629</td>
</tr>
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<td></td>
<td>4.152</td>
<td></td>
<td></td>
<td></td>
<td>2.962</td>
</tr>
<tr>
<td>35</td>
<td>1.038</td>
<td>0.4311</td>
<td>0.4797</td>
<td>25.6</td>
<td>0.952</td>
</tr>
<tr>
<td></td>
<td>2.076</td>
<td></td>
<td></td>
<td></td>
<td>1.392</td>
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<tr>
<td></td>
<td>4.152</td>
<td></td>
<td></td>
<td></td>
<td>2.435</td>
</tr>
<tr>
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<td>1.038</td>
<td>-0.1682</td>
<td>0.6393</td>
<td>32.6</td>
<td>0.331</td>
</tr>
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<td></td>
<td>2.076</td>
<td></td>
<td></td>
<td></td>
<td>1.406</td>
</tr>
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<td>4.152</td>
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<td>0.5138</td>
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<td></td>
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<td>0.0706</td>
<td>0.557</td>
<td>29.1</td>
<td>0.660</td>
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<td></td>
<td></td>
<td>1.209</td>
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<td>2.389</td>
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<td>0*</td>
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<td>0.678</td>
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<td>2.076</td>
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<td></td>
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<td>0.6182</td>
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<td>1.406</td>
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</table>
Table 6.2 summarizes the results of the direct shear tests conducted on Bentomat ST sample in unfrozen condition. The Bentomat ST sample at 20% moisture content under 4.152 psi yields the highest value of shear stress of 2.669 psi when compared to all the other conditions on Bentomat ST. It is observed that there is no change in the peak shear stress of the sample when adhesion is considered and when adhesion is not considered. Highest interface friction angle value of 34.8° was observed at 20% moisture content when adhesion is not considered. It is also observed that the values of interface friction angle are relatively higher for the samples with zero adhesion than for the samples with adhesion.

Table 6.2 Results of the Direct Shear Tests conducted on Bentomat ST (Unfrozen)
<table>
<thead>
<tr>
<th>BFIX330NWL</th>
<th>Moisture Content (%)</th>
<th>Shear Stress (psi)</th>
<th>Unit Weight (psi*ft/ft²)</th>
<th>4.152 psi</th>
<th>2.569 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>35%</td>
<td>2.569</td>
<td>1.082</td>
<td>1.453</td>
<td>2.545</td>
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<tr>
<td>50</td>
<td>50%</td>
<td>0.961</td>
<td>1.369</td>
<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>65%</td>
<td>0.873</td>
<td>1.361</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>80%</td>
<td>0.871</td>
<td>1.292</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>20%</td>
<td>1.077</td>
<td>1.686</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>35%</td>
<td>1.082</td>
<td>1.453</td>
<td>2.545</td>
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</tr>
<tr>
<td>50</td>
<td>50%</td>
<td>0.961</td>
<td>1.369</td>
<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>65%</td>
<td>0.873</td>
<td>1.361</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>80%</td>
<td>0.871</td>
<td>1.292</td>
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<td></td>
</tr>
</tbody>
</table>

*Forced Condition

Table 6.3 summarizes the results of the direct shear tests conducted on BFIX330NWL sample in unfrozen condition. The BFIX330NWL sample at 35% moisture content under 4.152 psi yields the highest value of shear stress of 2.569 psi when compared to all the
other conditions on BFIX330NWL. Highest interface friction angle value of 32.6° was observed at 20% moisture content when adhesion is not considered. It is also observed that the values of interface friction angle are relatively higher for the samples with zero adhesion than for the samples with adhesion.

Table 6.3 Results of the Direct Shear Tests conducted on BFIX230NSL (Unfrozen)

<table>
<thead>
<tr>
<th>Moisture Content ( % )</th>
<th>Normal Stress (psi)</th>
<th>Adhesion ( C )</th>
<th>Tan φ</th>
<th>Interface Friction angle, φ (degrees)</th>
<th>Peak Shear Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.038</td>
<td>0.2671</td>
<td>0.553</td>
<td>28.9</td>
<td>0.833</td>
</tr>
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<td></td>
<td></td>
<td>1.427</td>
</tr>
<tr>
<td></td>
<td>4.152</td>
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<td></td>
<td></td>
<td>2.559</td>
</tr>
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<td>35</td>
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<td>0.1931</td>
<td>0.5715</td>
<td>29.8</td>
<td>0.792</td>
</tr>
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<td></td>
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<td>1.372</td>
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<td>4.152</td>
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<td></td>
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<td>2.569</td>
</tr>
<tr>
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<td>0.5419</td>
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<td>0.824</td>
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</tr>
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<td>0.5493</td>
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<td>1.212</td>
</tr>
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<td></td>
<td></td>
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</tr>
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<td>0.5645</td>
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<td>0.745</td>
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<td>2.076</td>
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<td>0.6387</td>
<td>32.6</td>
<td>0.833</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>1.427</td>
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<td>0.6335</td>
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<td>0.792</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>1.372</td>
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<td></td>
<td></td>
<td></td>
<td>2.569</td>
</tr>
</tbody>
</table>
Table 6.4 summarizes the results of the direct shear tests conducted on BFIX330NWL sample in unfrozen condition. The BFIX330NWL sample at 20% moisture content under 4.152 psi yields the highest value of shear stress of 2.764 psi when compared to all the other conditions on BFIX330NWL. Interface friction angle values at zero adhesion are relatively higher than the interface friction angle values when adhesion is considered. The sample at 20% moisture content when adhesion is not considered yielded highest interface friction angle value of 34.6°.

Table 6.4 Results of the Direct Shear Tests conducted on BFIX330NWL (Unfrozen)

<table>
<thead>
<tr>
<th>Moisture Content ( % )</th>
<th>Normal Stress (psi)</th>
<th>Adhesion ( C )</th>
<th>Tan φ</th>
<th>Interface Friction angle, φ ( degrees )</th>
<th>Peak Shear Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.038</td>
<td>0.2941</td>
<td>0.5948</td>
<td>30.7</td>
<td>0.912</td>
</tr>
<tr>
<td></td>
<td>2.076</td>
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<td></td>
<td></td>
<td>1.528</td>
</tr>
<tr>
<td></td>
<td>4.152</td>
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<td></td>
<td></td>
<td>2.764</td>
</tr>
</tbody>
</table>
Table 6.5 summarizes the results of the direct shear tests conducted on Bentomat ST sample in both frozen and unfrozen conditions under a normal stress of 2.076 psi. We observed that the peak shear stress value of the sample when subjected to 4 freeze-thaw

<table>
<thead>
<tr>
<th>Level</th>
<th>Dry Density</th>
<th>Water Content</th>
<th>Peak Shear Stress</th>
<th>Critical State Shear Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>1.038</td>
<td>0.1592</td>
<td>0.576</td>
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</tr>
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<td></td>
</tr>
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<tr>
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<td>4.152</td>
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</tr>
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<td>1.038</td>
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<tr>
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<td>4.152</td>
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<tr>
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<tr>
<td></td>
<td>4.152</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Forced Condition
cycles was relatively higher than that of the samples at 1 and 6 freeze-thaw cycles. It is evident that there is no significant difference in the resulting peak shear stresses when the sample is subjected to freezing and when it is not subjected to freezing. Henceforth, we can say that the effect of freezing temperature on the geosynthetic interface in a capping system of a landfill is negligible.

Table 6.5 Results of the Direct Shear Tests conducted on Bentomat ST (Frozen and Unfrozen)

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Number of Freeze-Thaw</th>
<th>Moisture Content ( % )</th>
<th>Frozen Peak Shear Stress (psi)</th>
<th>Unfrozen Peak Shear Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentomat ST</td>
<td>1</td>
<td>50%</td>
<td>1.31</td>
<td>1.369</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>50%</td>
<td>1.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>50%</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>80%</td>
<td>1.29</td>
<td>1.292</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>80%</td>
<td>1.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>80%</td>
<td>1.22</td>
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</tr>
</tbody>
</table>
References


2011, from <a href="http://science.jrank.org/pages/47787/landfill-techniques.html">landfill techniques - Early landfills and their problems, Modern landfills, The future of landfills, Fig. 1</a>


Rate on Internal Shear Strength of a Reinforced Geosynthetic Clay Liner.

*Geosynthetics International*, 6 (3), 219-239.


32. BENTOMAT Geosynthetic Clay Liners (GCL) (2009). Retrieved December 10,
2009, from CETCO Lining Technologies:


35. GSE BentoLiner NSL Geosynthetic Clay Liner; Product Data Sheet. (n.d.). Retrieved November 2010, from GSEworld:


Appendix:

Test on a *Bentomat DN* sample for moisture content:

The Bentomat DN sample is from CETCO Lining Technologies. On inquiring of the manufacturer, it was found that the dry weight of the clay in the sample at 0% moisture is 0.844 lbs/sq.ft.

A Bentomat DN sample that weighed 36 gms was placed in an oven for 48 hrs. at 78\(^\circ\) C. The sample was weighed at regular intervals in that 48 hrs. period. The weight of the sample after 48 hrs. was 32.6 gms.

Weight of water in the soil = 36 - 32.6 = 3.4 gms

Percentage of water in the sample = \((3.4/36)\times100 = 9.4\%\)

Percentage of water to be added to the sample = 20 - 9.4 = 10.6 \%

Area of the sample = 8.5” * 17” = 1 sq.ft.

Weight of clay in 1 sq.ft of sample = 1 * 0.844 = 382.832 gms

Weight of water to be added to the sample = 382.832 * (10.6/100) = 40.58 gms

Similarly, for 35\% of water:
Percentage of water to be added to the sample = 35 - 9.4 = 25.6%

Weight of water to be added to the sample = 382.832 * (25.6/100) = 98 gms

For 50% of water:

Percentage of water to be added to the sample = 50 - 9.4 = 40.56%

Weight of water to be added to the sample = 382.832 * (40.56/100) = 155.28 gms

For 65% of water:

Percentage of water to be added to the sample = 65 - 9.4 = 55.6%

Weight of water to be added to the sample = 382.832 * (55.6/100) = 212.86 gms

For 80% of water:

Percentage of water to be added to the sample = 80 - 9.4 = 70.6%

Weight of water to be added to the sample = 382.832 * (70.6/100) = 270.28 gms

Test on a Bentomat ST sample for moisture content:

The Bentomat ST sample is from CETCO Lining Technologies. On inquiring of the manufacturer, it was found that the dry weight of the clay in the sample at 0% moisture is 0.848 lbs/sq.ft.

Two Bentomat ST samples that weighed 51.6 gms and 54.1 gms were placed in oven for
48 hrs. at 78° C. The samples were weighed at regular intervals in that 48 hrs. period. The weight of the samples after 48 hrs. was 45.4 gms and 48.1 gms.

Weight of water in the soil = 51.6-45.4 = 6.2 gms

Weight of water in the soil = 54.1-48.1 = 6.0 gms

Average weight of water in the soil = (6.2+6.0)/2 = 6.1 gms

Percentage of water in the sample = (6.1/51.6)*100 = 11.8%

Percentage of water to be added to the sample = 20-11.8 = 8.2 %

Area of the sample = 8.5” * 17” = 1 sq.ft.

Weight of clay in 1 sq.ft of sample = 1*0.848 = 384.646 gms.

Weight of water to be added to the sample = 384.646 * (8.2/100) = 31.54 gms

Similarly, for 35% of water:

Percentage of water to be added to the sample = 35-11.8 = 23.2 %

Weight of water to be added to the sample = 384.646 * (23.2/100) = 89.24 gms

For 50% of water:

Percentage of water to be added to the sample = 50-11.8 = 38.2 %

Weight of water to be added to the sample = 384.646 * (38.2/100) = 146.93 gms

For 65% of water:
Percentage of water to be added to the sample = 65-11.8 = 53.2%

Weight of water to be added to the sample = 384.646 * (53.2/100) = 204.63 gms

For 80% of water:

Percentage of water to be added to the sample = 80-11.8 = 68.2%

Weight of water to be added to the sample = 384.646 * (68.2/100) = 262.33 gms

Test on a BFIX230NSL sample for moisture content:

The BFIX230NSL sample is from Gundle/SLT Environmental, Inc. (GSE). On inquiring of the manufacturer, it was found that the dry weight of the clay in the sample at 0% moisture is 0.776 lbs/sq.ft.

The BFIX230NSL sample that weighed 95.6 gms was placed in oven for 48 hrs. at 78°C. The sample was weighed at regular intervals in that 48 hrs. period. The weight of the sample after 48 hrs. was 88.4 gms.

Weight of water in the soil = 95.6 - 88.4 = 7.2 gms

Percentage of water in the sample = (7.2/95.6)*100 = 7.5%

Percentage of water to be added to the sample = 20-7.5 = 12.5%

Area of the sample = 8.5” * 17” = 1 sq.ft.

Weight of clay in 1 sq.ft of sample = 1 * 0.776 = 351.99 gms ≡ 352 gms
Weight of water to be added to the sample = 352 * (12.5/100) = 44 gms

Similarly, for 35% of water:

Percentage of water to be added to the sample = 35-7.5 =27.5 %

Weight of water to be added to the sample = 352 * (27.5/100) = 96.8 gms

For 50% of water:

Percentage of water to be added to the sample = 50-7.5 =42.5 %

Weight of water to be added to the sample = 352* (42.5/100) = 149.6 gms

For 65% of water:

Percentage of water to be added to the sample = 65-7.5 =57.5 %

Weight of water to be added to the sample = 352 * (57.5/100) = 202.4 gms

For 80% of water:

Percentage of water to be added to the sample = 80-7.5 =72.5 %

Weight of water to be added to the sample = 352 * (72.5/100) = 255.2 gms

Test on a BFIX330NWL sample for moisture content:

The BFIX330NWL sample is from Gundle/SLT Environmental, Inc. (GSE). On inquiring of the manufacturer, it was found that the dry weight of the clay in the sample at 0%
moisture is 0.798 lbs/sq.ft.

The BFIX330NWL sample that weighed 73.2 gms was placed in oven for 48 hrs. at 78\(^\circ\) C. The sample was weighed at regular intervals in that 48 hrs. period. The weight of the sample after 48 hrs. was 67.9 gms.

Weight of water in the soil = 73.2 - 67.9 = 5.3 gms

Percentage of water in the sample = \((5.3/73.2)\times100 = 7.24\%\)

Percentage of water to be added to the sample = 20 - 7.24 = 12.76\%

Area of the sample = 8.5”\(^2\) * 17” = 1 sq.ft.

Weight of clay in 1 sq.ft of sample = 1 * 0.798 = 440.438 gms

Weight of water to be added to the sample = \(440.438 \times \frac{12.76}{100} = 51.2\) gms

Similarly, for 35\% of water:

Percentage of water to be added to the sample = 35 - 7.24 = 27.76 \%

Weight of water to be added to the sample = \(440.438 \times \frac{27.76}{100} = 122.27\) gms

For 50\% of water:

Percentage of water to be added to the sample = 50 - 7.24 = 42.76 \%

Weight of water to be added to the sample = \(440.438 \times \frac{42.76}{100} = 188.33\) gms

For 65\% of water:
Percentage of water to be added to the sample = 65-7.24 = 57.76 %

Weight of water to be added to the sample = 440.438 * (57.76/100) = 254.4 gms

For 80% of water:

Percentage of water to be added to the sample = 80-7.24 = 72.76 %

Weight of water to be added to the sample = 440.438 * (72.76/100) = 320.46 gms