EFFECT OF CREEP AND TEMPRATURE CYCLING ON THARPARKAR SAND AND HDPE GEOMEMBRANE INTERFACE SHEAR STRENGTH

By

Faizan Iqbal

NUST- 2017-MS-Geotech-00000206905

A thesis submitted in partial fulfilment of the requirements for the degree of
Master of Science in Geotechnical Engineering

NUST Institute of Civil Engineering (NICE)
School of Civil and Environmental Engineering (SCEE)
National University of Sciences and Technology (NUST)
H-12 Sector, Islamabad, Pakistan
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TO

MY BELOVED PARENTS

WHO GAVE ME A LOT OF SUPPORT

AND

ENCOURAGEMENT

ACKNOWLEDGEMENT

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Abstract:

In past thirty years, geosynthetic products have been used extensively in civil engineering applications due to their numerous advantages. The most common type of geosynthetics is geomembrane that is used primary as an impervious boundary for liquid and gasses. In district Tharparkar Pakistan where temperature rises to 50 C in summers, different international and national organization are constructing small scale reservoirs using HDPE geomembrane to counter drought affect by harvesting rainwater. The HDPE geomembrane used in construction of landfill and water reservoirs shows viscoelastic behavior to the applied loads and temperature over a period in the form of creep or stress relaxation. Effect of creep, cyclic loading and temperature are critical factors that should be evaluated carefully, because soil geomembrane interfaces usually from weak planes may cause failures. In this study, the 71 direct shear tests were carried out in in the laboratory by subjecting geomembrane samples under different temperature and sustained loading to evaluate the effect of creep, cyclic loading and temperature on Tharparkar sand and HDPE geomembrane. The results showed that the interface friction angle increases up to 5.5 % under sustained loading of 50 KPa for 7 days due to penetration of sand particles into the membrane, resulting in increase of contact surface area. In addition, friction angle decreases with the increase in number of loading and temperature cycles because cycled shearing effected the surface texture i.e., effecting polished surface of smooth HDPE geomembrane. This thesis presents the methods of test performed, results obtained, discussion of the results, findings and recommendation for the future studies.

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LIST OF SYMBOLS / ABBREVIATIONS

$\emptyset$	Angle of internal friction
c	Cohesion
τ_{a} :	Material shear strength at point of contact.
Ac	Real contact area between two materials
$E(t)$	Time dependent or creep modulus.
E_o	initial modulus.
γ	Unit weight
σ_o	Constant stress applied during the test
$A_c(t)$	Time dependent contact area
W	Applied Load
R	Mean radius of curvature
$E'(t)$	Time dependent Composite modulus of elasticity
T_g	Glassy Temperature
T_m	Melting Temperature
ε	Strain
$\acute{\varepsilon}$	Strain Rate
τf	Shear Strength
σ_f	Normal Stress
Tg	Glassy Temperature
Tm	Melting Temperature
SGR	Reference Geomembrane Samples
SGT	Geomembrane Samples subjected to 50 C
SGL	Geomembrane Samples subjected to 5 C

Chapter 1

1. Introduction

1.1.Background:

Geomembranes are extensively used in the geotechnical, environmental, hydraulic, and transportation sectors as barrier layers with low permeability. These geomembrane barriers can efficiently reduce the infiltration of fluids into the engineered structures. The basic functions of geomembrane consist of separation, moisture barrier and reinforcement (G. Koerner & Koerner, 2006). In design of geomembrane lined slide slopes of landfill and water reservoirs the interface friction angle is critically important (Bilgin & Shah, 2010). High density polyethylene (HDPE) is the most common material used to produce HDPE Geomembranes and can be classified as a viscoelastic material that has temperature and time dependent properties (Bilgin, 2011). Placement of different materials that have different properties adjacent to one another creates an interaction zone between them. This zone is referred to as the interface (Karademir & Frost, 2011). The interface between the Geomembrane and soils is slightly weak and thus comprises critical failure planes (Bilgin & Shah, 2010). Geomembranes are made up of polyethylene and it exhibits viscoelastic behavior in response to the loads during its lifetime in two forms: (1) Material creep when a continuous load is applied for a period. (2) Stress relaxation when a continuous strain is applied (Bilgin, 2011).

The interface friction angle between the soil and HDPE is a most important issue in the analysis and design of geotechnical engineering projects where HDPE materials are used. Due to the critical failure planes between the Geomembrane and soils in slopes of landfills, it is very critical to obtain the interface strength properties precisely in order to have safe and sustainable design (G. Koerner & Koerner, 2006). Interface friction angle can be obtained using direct shear test same as shear strength of sand and geomembrane interface. Studies of the soil-Geomembrane interface shear strength began in the early 1980’s. After a failure of a large landfill in California, USA, several researchers have conducted extensive studies to find out the reason of the collapse. This collapse hit when a large mass of waste slide along the interface with the geosynthetics layer (Jogi, 2010).

1.2.Problem Statement:

Over the past 10 years, district Tharparkar of Pakistan is fronting drought like situation, considers one of least developed regions of Pakistan portrayed by cultural and religious diversity (Sindh Drought Needs Assessment Report 2019.). The Natural Disasters conducted Sindh Drought Needs Assessment (SDNA) in different districts of Sindh. To counteract drought by rain water harvesting these agencies are constructing small scale water reservoirs with catchment area using HDPE geomembrane.

The creep is very important in finding out the life and strength of reservoirs because soil Geomembrane usually from weak planes may cause failure (Bilgin & Shah, 2010). Due to the viscoelastic behavior of HDPE, the soil particles will penetrate the surface of the Geomembrane and causes considerable difference in the properties, specifically the interface friction angle (Bilgin, 2011). Due to the viscoelastic behavior of membrane the temperature and cycling loading effect on HDPE geomembrane also plays a significant part in calculating interface shear strength. The interface friction angle increases with the increase in interface temperature (Karademir & Frost, 2011).

Over the past few years, several research using direct shear tests have been performed by different researchers to determine soil geomembrane interface shear strength, with several factors being considered throughout these tests, but none of the research is available on Tharparkar sand. Thus, at present, considering the vast construction of water reservoirs in District Tharparkar using HDPE geomembrane, the analysis of effect of creep, cyclic loading and temperature on interface shear strength is important to improve life and strength of reservoirs with catchment areas.

1.3.Aim and Objectives:

The aim of this research study is to observe the effect of creep, cyclic loading and temperature on the Tharparkar sand and HDPE geomembrane interface shear strength. This aim can be achieved by executing the following objectives:

1. To investigate the index soil properties of Tharparkar sand (e.g. particle sieve analysis, density, moisture content)

2. To implantation of the direct shear test on both conditions; sand-sand and sand-geomembrane materials using different loads, temperature and time for repetitive cycles to determine the shear strength parameters (friction angle and shear strength).
3. To assess the cyclic effect of loading and temperature on Tharparkar sand and HDPE geomembrane interface shear strength.
4. To evaluate the effect of creep on Tharparkar sand and HDPE Geomembrane interface shear Strength.

1.4.Scope:

The scope of this research will be limited to evaluate the effect of creep, cyclic loading and temperature effect on Tharparkar sand and HDPE Geomembrane interface shear Strength. The interface friction angle ‘δ’, between the sand and HDPE geomembrane is a major factor in the analysis and design of geotechnical engineering projects. The sand geomembrane interface may show low frictional angle and shear resistance and it might be a possible cause of failure. Therefore, the precise evaluation of the interface shear strength of sand and geomembrane is required. The laboratory tests can provide an efficient method to calculate the shear behavior of sand geomembrane interface shear strength. The interface friction angle should be calculated accurately to avoid failures of structures.

1.5.Research Layout

The following is the overall structure of this report:

Chapter 1: The introduction scope and aims are presented in this chapter.

Chapter 2: Literature Review of interface friction angle between Sand and geomembrane.

Chapter 3: Material Description, testing methodology and calculations.

Chapter 4: Analysis and discussion of testing results,

Chapter 5: Summary and Conclusion.

Chapter 2

2. Literature Review

2.1. Overview of Geosynthetics

The term Geosynthetics consists of two parts. The prefix ‘geo’ refers to the improvement of civil engineering works concerning soil. The suffix ‘synthetics’ refers to the fact that materials that are man-made products. Geosynthetics products are produced from crude oils, rubber, fiber glass and other polymeric materials. The geosynthetic is a generic term and it represents wide range of products produced from polymeric materials which are used in Geotechnical, Transportation, hydraulics and environmental sectors of civil engineering works (G. Koerner & Koerner, 2006). According to (Kumar Shukla & Yin, 2006), In last 4 decades, huge development has been taken in areas of geosynthetic and their application as described in table 2.1.

Table 2.1: Development in Area of Geosunthetic (Kumar Shukla & Yin, 2006)

Decades	**Developments in area of Geosynthetics and their application**
Early Decades	In 1920s, Casagrande proposed for the first time method for soil reinforcement using geosynthetics to increase soil strength (Shukla 2012).The earliest utilization of geosynthetic in strengthening roads was done by South Carolina Highway Department in 1926.
1950s	The wide range of Geosynthetics were produced for use of separation and filter between granular landfill and weak subsoils in coastal projects of Netherlands and USA
1960s	Geotextiles were used as bed for highway and railway track support system in France.

1970s	The needle punched nonwoven geotextile was used first time as a filter for the aggregate downstream drain in the Valcross Dam France
1980s	Use of Geosynthetic (geotextiles) in construction of safe containment of environmental hazardous material was first developed and evaluated in France.
1990s	Various Standards of geosynthetics were published by American Standards for testing materials and other agencies

2.2. Geosynthetics definition types and functions

Geosynthetics is generally described as a two-dimensional product produced from polymeric materials used with soil, rock, earth or other geotechnical related materials as an essential part of a human-made development, structure, or system (R. M. Koerner, 2012). Geosynthetics can be categorized into nine categories as follow (Bathurst, 2005):

1. **Geotextiles:** are constant pieces of woven and nonwoven fiber and are Permeable geosynthetics comprised of textiles only. Geotextiles are used for separation, drainage, reinforcement, filtration, containment and reinforcement applications.
2. **Geomembranes**: are continuous, flexible sheets made from one or more than one synthetic materials and are relatively impermeable. Geomembranes are used as liner or barrier in geotechnical engineering related civil works to contain fluid gas
3. **Geogrids:** Geosynthetic materials comprising of associated parallel sets of meeting open ribs with gaps of adequate measure to permit strike-through of encompassing soil, stone, or other geotechnical material.
4. **Geonets:** Geosynthetic materials comprising of integrals related similar sets of open ribs covering comparative sets at different points for in-plane waste of fluids or gasses. Geonets are frequently covered with geotextile on one or both surfaces and are at that point referred to as recomposite waste materials.

5. **Geopipes:** Solid-walled or perforated polymer pipes used to discharge liquids or gases (including collection of leachate or gases in landfill applications). In some cases, perforated pipes are wrapped with geotextile filters.
6. **Geosynthetic clay liners (GCLs):** Geotextile wrapped GCL is usually sewn, or needle punched with a bentonite core to increase internal shear strength. When hydrated, they can act effectively as a barrier to liquids or gases and are often used in landfill lining applications with geomembranes.
7. **Geocomposites**: A geosynthetic material composed of two or more geosynthetics. Examples include geotextile geonet, geotextile geogrid etc.
8. **Geofoam:** Blocks or panels are made by developing polystyrene foam, which arranges air-filled closed cells at low density. Geofoam is used for warm spacers, as a lightweight filler, or as a compressible vertical layer to reduce the weight of the floor against a rigid wall**.**
9. **Geocells**: They are a medium-thickness three-dimensional system composed of polymer foil strips. These strips are connected to form interconnected units, which are filled with soil, sometimes concrete.

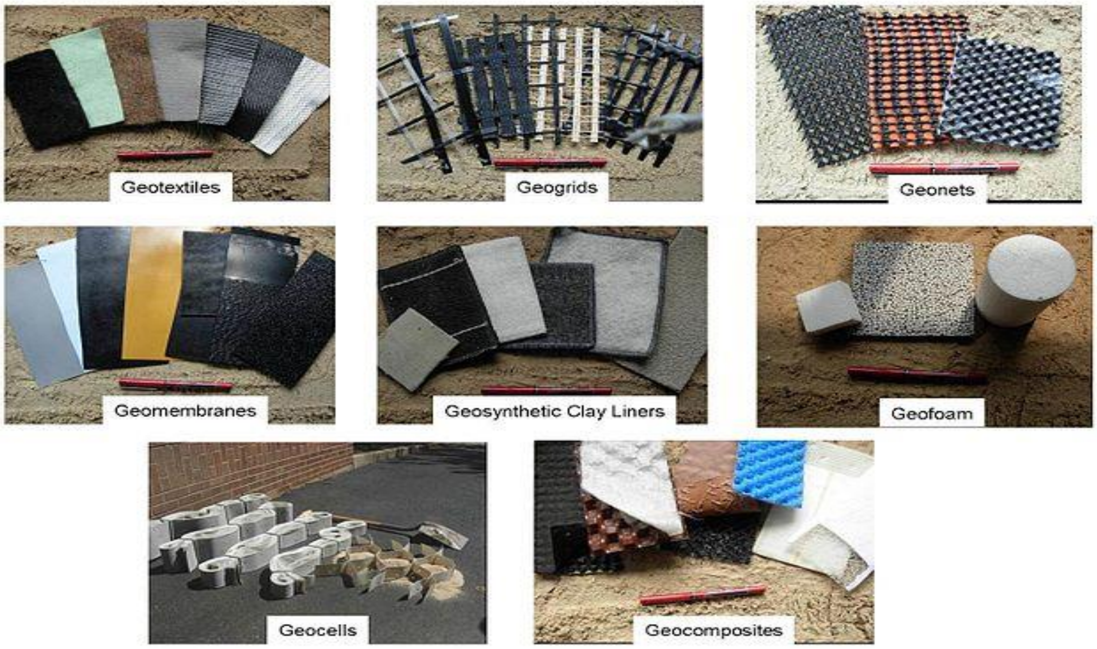


Figure 2.1: Different types of geosynthetic products.

2.3. Functions of Geosynthetics

Geosynthetic materials perform at least one of the following five major functions (Bathurst, 2005):

1. Drainage.
2. Reinforcement.
3. Separation.
4. Containment of liquid or gas.
5. Protection.
6. Filtration

Table 2.2: Functions of geosynthetics products (Bathurst, 2005).

Type	**Functions**					
	Drainage	**Reinforcement**	**Separation**	**Containment of liquid or Gas**	**Protection**	**Filtration**
Geotextile	↗	↗	↗	↗	↗	↗
Geomembrane			↗	↗		
Geogrid		↗				
Geonet	↗					
Geopipes	↗					
GCL				↗	↗	
Geocomposite	↗			↗	↗	
Geoform					↗	
Geocell		↗	↗		↗	

2.4. Geosynthetics Manufacture

Geotextiles are manufactured in different ways using conventional and non-conventional textile procedures. Two steps are involved in production of geotextiles. The first step includes production of basic element of geotextiles i.e., fiber (linear element) from different polymers under specific temperature and pressure. The second step is consists of production of fabrics Planar Structures from fibers (Giroud, 2005). The basic element fiber is a unit of matter having properties including elasticity, quality, highness and high ratio of length to thickness. The basic four types of synthetic fiber are as follows (Kumar Shukla & Yin, 2006):

1. Filaments: Manufactured by extrusion of molten polymer through the die.
2. Staple Fiber: Achieved by reducing fibers to a small length i.e. (2-10cm)
3. Shift Films: Produced by slitting extruded plastic films.
4. Strands: A pack of tape fiber that can be attached with each other.

Geosynthetics are produced by polymerization of synthetic polymer. Some of these polymers are enlisted below,

1. Polypropylene.
2. Polyester
3. Polyethylene
4. polyamide and polyvinyl chloride etc.

Polymer is composed of two Greek words ‘poly’, meaning many, ‘meros’ meaning portions. A polymer is formed from numerous identical molecules, known as monomers, bonded together to produce the material. These small monomers form long chains using a process called polymerization. After the polymerization, the final product is in either a granular or a powder form. Polymers are highly resistant to chemical and biological degradation Synthetics materials can be categorized into three main groups as follows (Nicholson, 2007)

1. Thermosets.
2. Elastomers.
3. Thermoplastics.

There are several factors that can influence the properties of these polymers such as melting flow rate, density, and draw ratio. Table 2.3 lists the raw materials used for manufacturing different types of geosynthetics (Shukla, 2012).

Table 2.3: The raw materials utilized for manufacturing geosynthetics (Shukla, 2012).

Geosynthetics Types	**Raw Material**
Geomembrane	HDPE, LLDPE, PVC, VLDPE, CPE, PP, CSPE
Geotextile	PE, PET, PA, PP
Geogrid	HDPE, PET, PP
Geonet	HDPE, MDPE
Geopipes	PVC, PP, HDPE
Geofoams	XPS, EPS

2.5. Geomembranes

Geomembranes are commonly consisting of as part of the planned barrier structure for current landfills. There are numerous types of geomembranes comprising polyvinyl chloride (PVC), chlorinated polyethylene (CPE), chlorosulphonated polyethylene (CSPE), ethylene propylene rubber (EPDM), polypropylene (PP), linear low-density polyethylene (LLDPE), medium-density polyethylene (MDPE) and the bituminous geomembrane (Rowe & Sangam, 2002) . The most popular type is high density polyethylene (HDPE). It is available in different thicknesses ranging between 30 and 120 mils (0.75-3 mm). The geomembrane is a relatively thin (0.02 to 5 mm) sheet of polymeric material that has a relatively impermeable fluid barrier function ($k \geq 10^{11}$ to 10^{13} cm / sec). (G. Koerner & Koerner, 2006). The choice of geomembrane liner depends on the application in which it will be used. High Density Polyethylene (HDPE) geomembranes are only used for landfill applications, especially for underlining, as they are generally highly resistant to strong leachate components. (Rowe & Sangam, 2002). In common, HPDE geomembranes comprise 96–97.5% of polyethylene tar, 2–3% of carbon dark, and 0.5–1.0% of other added substances such as antioxidants and stabilizers (R. M. Koerner & Soong, 2000). The HDPE geomembranes are used in various civil engineering projects, such as: liners for potable water, liners for solar bonds, liners for water canals, waterproof liners for pipelines, waterproof for earth/ concrete/ rock fill dams, waterproof layer beneath asphalt, and landfills (Rowe & Sangam, 2002).

2.5.1. Common Polymers and Chemical Structures in Geosynthetic products:

Polyethylene (PE):

Chemically represented as C2H4, Polyethylene or PE is a monomer ethylene chemically bonded in the form of a long chain. The chemical structure of C2H4 consist of 2 strong double covalent bond using CH2=CH2 structure. A molecular structure of ethylene is described in the following picture for better understanding of the connection between CH2 molecules. The use of PE is the industries of today are quite vast especially in the geotechnical engineering field where most commonly it is used to produce low- and high-density PE geomembranes. The difference between low and high density PE geomembranes is that low density PE is crystallizable up to 65% in contrast to high density PE at 90% with occasional branching and linear chains (Daniel, 1990) .

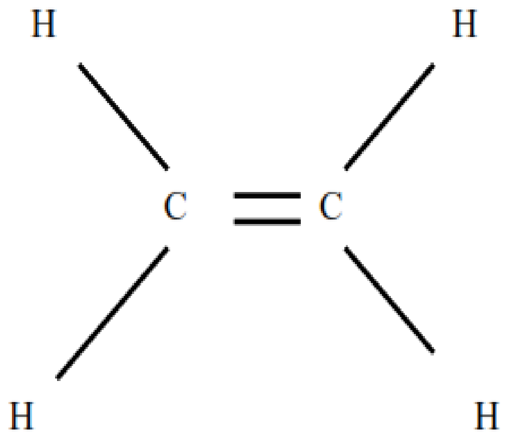


Figure 2.2: Chemical Structure of Ethylene Molecule (Painter & Coleman, 1997)

As described, PE is one of the products of ethylene as a result of polymerization . However, the processes of polymerizations are different in different situations from radical to ion coordination, anionic addition or either cationic polymerization (Daniel, 1990).

Polyvinylchloride (PVC):

The polymer of PVC or polyvinylchloride is similar to PE in structure except the fact that one of the Hydrogen atoms in the molecular structure is replaced by C1 atom. This changes the properties of this ethylene monomer enormously. The chemical structure of PVC is displayed in the following figure for better visualization. The use of PVC in the modern world has been extensive and many of the trivial material like iron and wood have been replaced by PVC products that are more durable and cheaper. The main usage is in drain pipes and fittings that are common in construction. But in recent times, the advancement in chemical structuring of these polymers, the use of PVC in the field of geotechnical engineering has found its way through geomembranes.

The structure of PVC is majorly formed by the polymerization of vinyl chloride that is the basic building material. The benefit is that PVC has crystallinity at 10% while being a good thermoplastic product. The polymer chain of PVC is illustrated in figure 2.3. below for better understanding of the chemical structure (Bilgin, 2011).

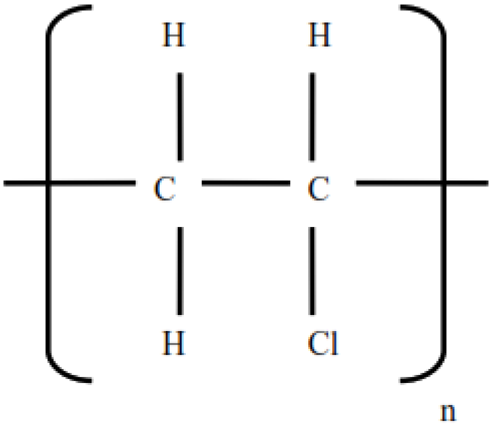


Figure 2.3: Schematic representation of the repeating unit of Polyvinylchloride (Osswald & Menges, 1990)

Polypropylene (PP):

PP or Polypropylene is one of the most used polymer in the geotextile manufacturing consisting of long chain structure of propylene monomer. The molecular structure of PP is also based on the basic molecular structure of ethylene that is illustrated in the figure 2.4. to describe the chemical structure of PP.

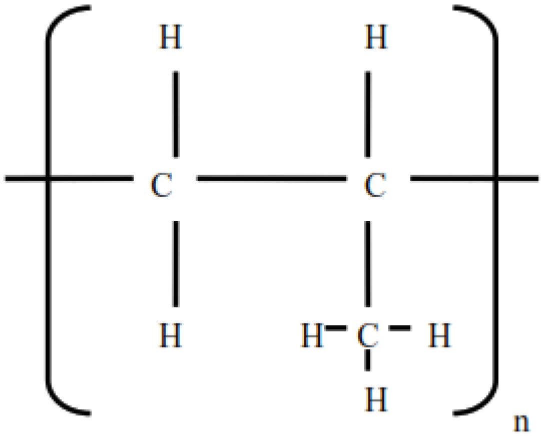


Figure 2.4: Schematic representation of the repeating unit of Polypropylene (Osswald & Menges, 2012).

All the above discussed polymers have been widely used in the local industries today and their application in the field of geotechnical engineering has been certainly increasing. There are many good reasons to this increased usage that are capped by good properties of these polymers to resist against acids, bases, oils & fats, solvents etc. (Daniel, 1990).

Figure 2.5: Arial view of land fill structure. (source: www.eciwv.com)

2.6. Past Research on Soil-Geomembrane Interface

After a failure of a large landfill in California, USA, several researchers have conducted extensive studies to find out the cause of the collapse. This collapse occurred when a large mass of waste slide along the interface with the geosynthetics layer (Jogi, 2010). Creep behavior is among the critical properties of soil geomembrane interfaces. However, there have been very limited studies in this area. Potyondy made a major compromise with interface components in 1961, and he concluded that the strength of the interface is affected by four main variables: moisture content, soil composition, surface hardness, and load. (Zettler et al., 2000). (Bilgin, 2011) performed a study on the effect of time on the contact surfaces at the soil geomembrane interfaces using a theoretic model. He Modified the existing surface contact area model by adding the time dependency of the geomembrane to the model. The results of the study showed that the contact area of the soil-geomembrane interface increases about 250% after 10 years and 300% after 100 years. In other words, the contact stress at the soil geomembrane interface decreases when the contact area increases.

SK Alzahrani (2017) conducted a study on effect of time on soil geomembrane interface shear strength using laboratory testing on Ottawa sand and smooth HDPE geomembrane. The normal stresses used in this research were ranged between 45 and 100 KPa. The results of this study shows that there was increase of approximately 17% of frictional angle after two weeks of soil loading on soil geomembrane interface. According to previous research conducted on sand geomembrane interface shear strength, the following table 2.4. summarizes the result of sand geomembrane interface shear strength.

Table 2.4: Summary of soil-geomembrane interface friction angle.

Soil Type	Geomembrane Type	Interface Frictional Angle (δ°)	Normal Stress (KPa)	Type of Test	References
Ottawa Sand 20/30	HDPE	20	15-100	Direct	Martin et
		19-21	200	Direct	Saxena and
		19	10-100	Direct	Williams and
		15-18	50	Ring	Negussery et al.
		19	3-70	Direct	O'Rourke et
		18-21	5-50	Direct	Fleming et
		18-20	129	Large	Bilgin and Shah

2.7. Contact and Friction Between Surfaces

The Frictional behaviour between geomembrane and soil particles interface and shear mechanism involved has been examined completely by (Dove & Frost, 1999). The frictional force between two solid surfaces is directly proportional to normal force acting at the surface. The proportionality constant ‘μ’ of friction is defined as:

$$\mu = tan\ \alpha = \frac{F}{w} \qquad \text{or} \qquad \mu = tan\ \delta = \frac{\tau}{\sigma} \tag{2.1}$$

Where μ is friction proportionality constant, α is interface frictional angle, f is frictional force, W is weight, τ is shear force and σ is normal force

The above equations 2.1 hold sufficient for several geotechnical engineering explanations however these equations are not valid for material having viscoelastic properties because their friction coefficient varies with change in applied load. The frictional force depends upon two basic components of shear strength, adhesion and plowing.

$$F = F_{\text{adhesion}} + F_{\text{plowing}} \tag{2.2}$$

When harder material comes in contact with softer material, high pressure at contact point will generate which will ultimately cause pure plastic deformation. In plastic deformation area of contact between soil and geomembrane will turn out to be directly proportional to applied load instead of proportional to 2/3 of applied load (Bowden & Tabor, 2001). Past researches of soil geomembrane interface shear strength indicates that the behaviour of deformation is elastic rather than plastic (Dove & Frost, 1999).

2.8. Time Dependent Behaviour of Geomembrane

Geomembranes are subjected to sustain loads throughout their service life. The stress applied on geomembranes having viscoelastic properties is a function of time and applied strain. Because the stress depends upon level of stain produced so this behaviour is called as nonlinear viscoelasticity and can be described as (Bilgin, 2011)

$$\pi = f\ (\mathcal{E}\,, t) \tag{2.3}$$

Where $\mathcal{E}$ is Applied Strain and t is time.

In 1994 Moores stated that when strain is very small i.e. less than 0.01 or 60 percent of stress applied the viscoelastic behaviour of material becomes linear. The time dependent strain can be described as follows (Bilgin, 2011)

$$\varepsilon(t) = \varepsilon_o\, t^{\,n} \tag{2.4}$$

where (ε_o) initial strain at one point, t is time and n is power law exponent

The normalization of strain in above equation can be done by applied stress σ_0, which ultimately results in equation form of creep, that is independent of initial modulus applied stress. So, for linear viscoelastic material creep modulus can be calculated as,

$$E(t)=E_o t^{-n} \tag{2.5}$$

$E(t)$ is time dependent or creep modulus and E_o is initial modulus.

The creep modulus for linear viscoelastic material can also be calculated from stress obtained from stress relaxation test.

$$E(t) = \frac{\sigma o}{\varepsilon(t)} \tag{2.6}$$

where σ_o is constant stress applied during the test and $\varepsilon(t)$ is time dependent strain measured during the test.

Above equation of creep modulus implies that the creep modulus is independent of level of stress agrees with the linear viscoelastic theory.

2.9. Effect of Time on Soil-Geomembrane Contact Surfaces:

The modulus of geomembrane due to its viscoelastic nature will differ with time under the continuous loading and results in increase of contact area of soil geomembrane contact surface as shown in Figure 2.6. Figure indicates the soil particles and geomembrane before applying the load and the instant penetration of soil particles in geomembrane and as a result effect of creep will begin resulting increase in contact area of soil geomembrane. This theory was based on an belief that the surface of the geomembrane is flat during the loading phase. However, the surface of a geomembrane is not perfectly smooth in reality.

Since the behaviour of geomembrane is elastic (Bilgin, 2011) suggested the change in equation by including the effect of time as,

$$Ac(t) = \pi \left(\frac{3WR}{4E'(t)}\right) \tag{2.8}$$

Where $A_c(t)$ is time dependent contact area, W is Applied Load, R is Mean radius of curvature and $E'(t)$ is Time dependent Composite modulus of elasticity.

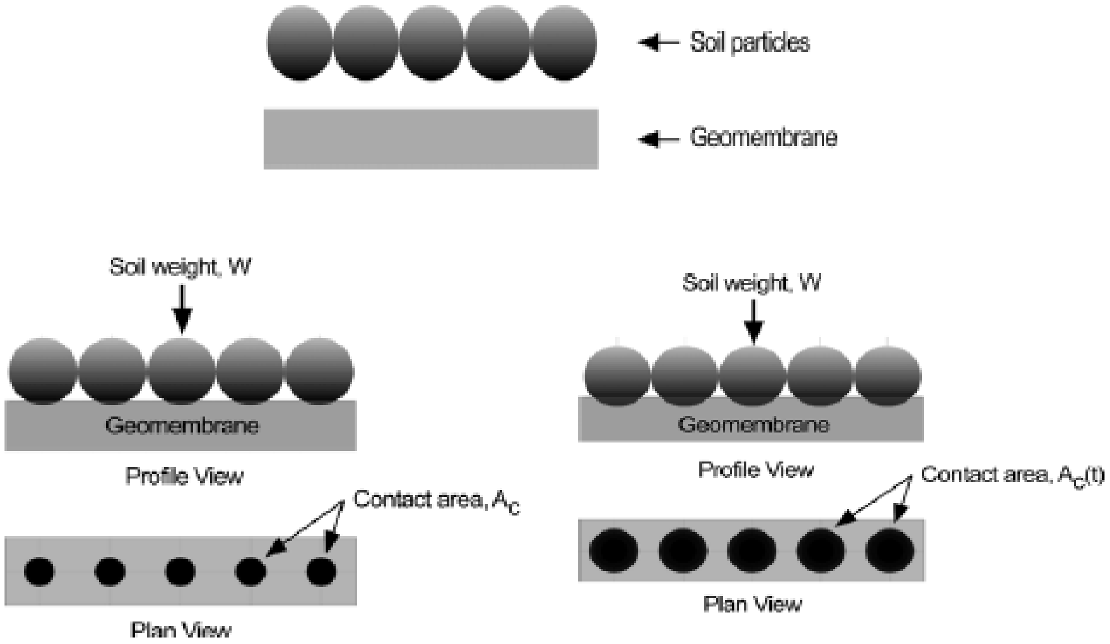


Figure 2.6: Creep effect on Soil Geomembrane Interface.

2.10. Effect of temperature on soil geomembrane interface shear strength

The properties of HDPE geomembrane are very vulnerable to temperature deviations because they are formed by polymeric material. The temperature has a significant effect on engineering properties of geomembrane such as hardness, tensile and strength. Increase in temperature results in decrease in tensile strength and hardness (Karademir & Frost, 2011). The HDPE geomembrane manufacturers don’t advised continuous temperature more than 57^0C for HDPE and 46^0C for LLDPE. The increase in temperature beyond 57^oC in HDPE geomembrane can start the reduction of antioxidants existing in geomembrane and ultimately leading to initiate oxidation of the polymer and lastly leading to loss in stress, crack resistance and decrease in service life of geomembrane (Rowe & Sangam, 2002). The HDPE geomembrane by weight percentage comprised of 0.5 – 1 % of antioxidant , 2 – 3 % of carbon black and 96 – 97 % of polyethylene resin (Zettler et al., 2000). The main function of adding of antioxidant in manufacturing of HDPE geomembrane is to decrease the effect of polymer degradation during manufacturing and reduction of oxidation reaction during early stages of service life. The process of degradation of HDPE geomembrane was researched by many researchers and in general considered to comprised of following three stages (Hsuan & Koerner, 1998):

1. Depletion stage (Oxidization of antioxidants).
2. Induction stage (Initiation of polymer degradation).
3. Degradation stage (Reduction in fundamental physical properties).

In the first stage, the antioxidants in the geomembrane begin to oxidize (Koerner 1998). The time period of Phase 1 is very important because active antioxidants can protect the geomembrane from degradation. In the second stage, the polymer began to degrade, but the engineering properties of the polymer did not change significantly, even though the maximum oxidation of the antioxidant was . In the third stage, the engineering properties of the geomembrane will undergo considerable changes until the service life of the geomembrane is reached. Table 2.5 shows the service life of HDPE geomembrane in a landfill lining system replicated in the laboratory at a temperature of 20 to 60°C. The estimated service life of HDPE geomembrane based on a 50% reduction in tensile strength at different temperatures (Jafari et al., 2014).

Table 2.5: Estimated service life on different temperatures (Rowe 2005)

Sr #	Temperature	Service Life In years
1	20	565 - 900
2	30	203 - 315
3	35	130 - 190
4	40	80 - 120
5	50	35 - 50
6	60	15 – 20

2.11 Glass Transition Temperature and Melting Temperature:

The effect of temperature on different polymers like Polyvinylchloride (PVC), Polypropylene (PP) or High Density Polyethylene (HDPE) has various influence in the Glass Temperature (Tg) and also on the Melting Temperature (Tm). The Tm is the temperature at which the material converts into rubbery from glassy and continues to convert into melting stage with increase in temperature. It is also known as the Phase Change stage. The Tg on the other hand is the temperature at which the movement of the polymer material changes. The movement change in the glassy stage is lesser as there is not adequate room for movements of the polymer chains and when moving to rubber stage, the mobility changes. Underneath the glassy temperature, the polymers are only able to react to the stretching of bonds due to the fact that secondary bonds between hydrogen and van der Waals bonds binds the molecules in long chains. This is affected by the stages as the glassy stage has least room for significant change than the rubbery stage. That’s why, in the glassy stage, the molecular movement is hindered and thus giving the material a brittle breaking instead of a flexible bend in the rubbery stage (Nielsen & Landel, 1994). However, in contrast, the influence of secondary bonds in such condition above the Tg is lower when contrasted to temperature below Tg. This is due the fact that free volume also increases with increase in temperature and thus affecting the material properties (Li, 2000) . Thus gives the molecules more space to adapt the heighted movements. figure 2.7. shows that transition zone of change from glassy to rubbery:

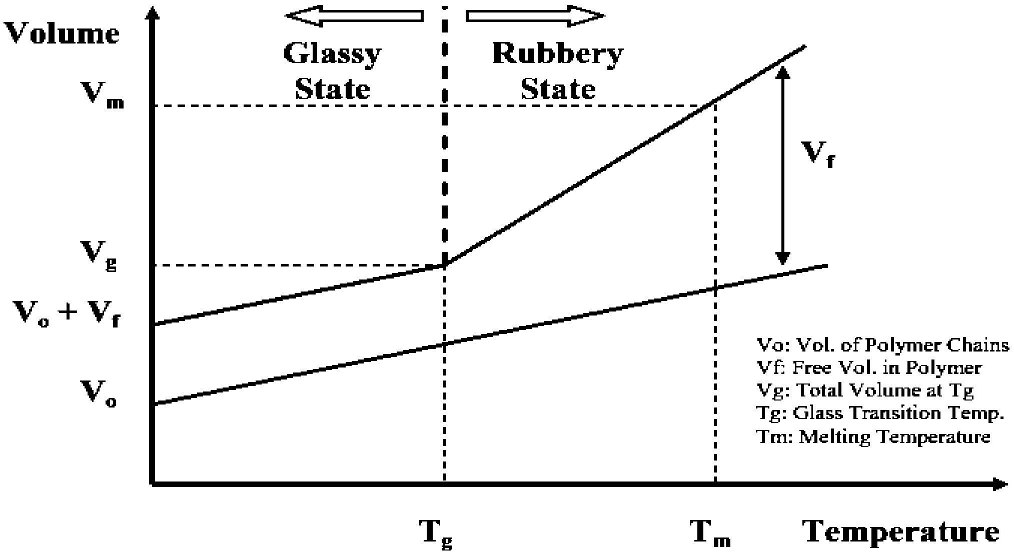


Figure 2.7: Volume Change of Polymer with Temperature Change (Dowling, 2007).

2.12 Stiffness (i.e. Modulus) and Temperature:

The relationship between stiffness and temperature is constant as from the below figure 2.9 and it can be seen that when temperature is less than Tg, the modulus remains constant. However, when temperature goes beyond the Tg, the stiffness factors significantly drops as the material shifts to the rubbery stage. The rubbery point of the material occurs at Tm and for different materials, this can vary as per the properties of the material. A similar scenario is also observed between time and modulus. Until a specific time, the modulus remains unchanged but eventually it drops dramatically as the polymers changes that state from glassy to rubbery. The initial glassy stage provides the material properties of a solid and when in rubbery stage, the properties shift to match the elastic material properties. That is why, when the modulus drops dramatically, in small amount of time after the state change and increasing temperature, the structure collapses and the material is no longer able to hold the original solid or rubbery shape and eventually converts to liquid before burning fully to ashes (Painter & Coleman, 1997).

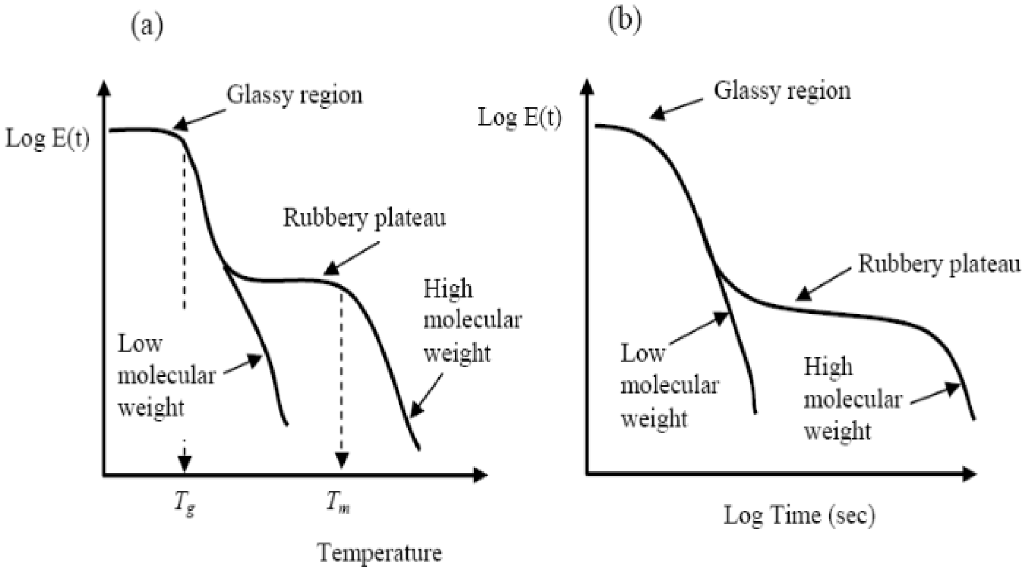


Figure 2.8: Graphic representation of the modulus as a function of Temperature and Time (Painter & Coleman, 1997)

2.13 Stress Relaxation and Temperature:

Depending on the time and temperature, the stress relaxation of polymers can vary. By definition, itis described as the time that is taken by the polymer to release the stress in order to return to original state. The relation with temperature for stress relaxation is inverse as increasing temperature can cause decreases stress relaxation (Osswald & Menges, 2012). Depending on the properties or elasticity of the polymer, the stress release time can vary from a few seconds to even days in some cases. For materials that have a longer stress release time, this means that their internal energy is higher and stress dissipation is lower than others. To lengthen the relaxation time in polymers, the crystallinity process plays the part. In polymers, when temperature is above the Tg, the stress release is rapid and easy as the molecules are active enough to release and dissipate the stress. However, at lower temperature, all polymers show similar lengthy relaxation time. In the glassy polymers, the relaxation is quite short, in fact non existing as the absorption of external energy makes the shatter at once rather than having a ductile failure in rubbery state (Osswald & Menges, 2012). In the geotechnical field, the effect of temperature on the stress relaxation of polymers is important to consider. This can be exemplified by the case of polypropylene where fibers of this polymers can significantly lose their internal strength if they are exposed to thermal induced relaxation times (R. Koerner, 1990)

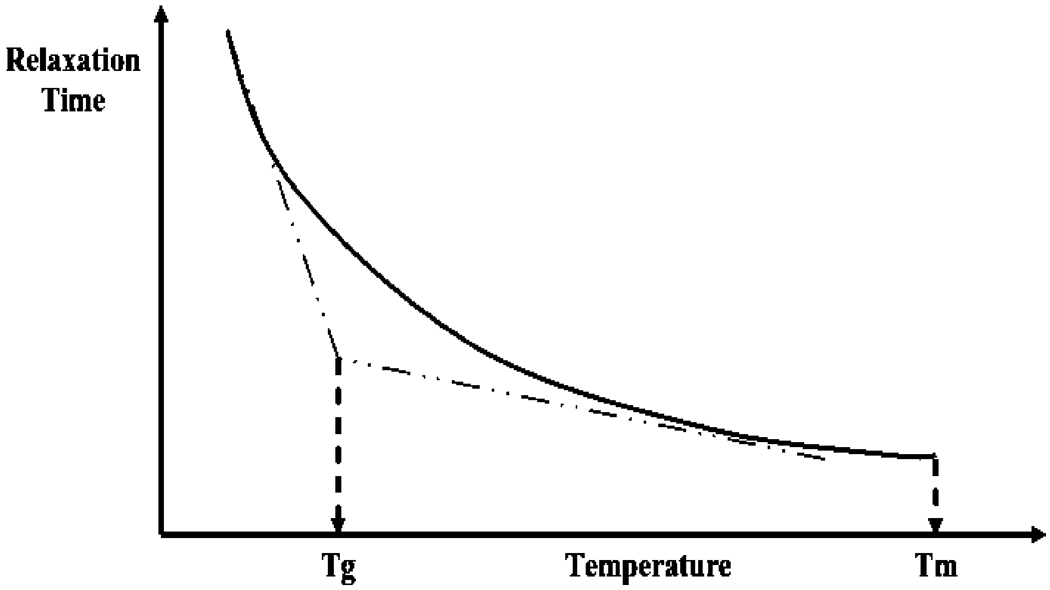


Figure 2.9: Relaxation Time in Polymeric Materials and Temperature (Nielsen & Landel, 1994).

2.14 Temperature Effects on Mechanical and Durability Properties of Polymers:

The relation between mechanical properties and temperature is significant to understand when utilizing polymers on vast scales. Hardness, tensile strengths, stress relaxation time, modulus are such examples that are highly affected by the impact of temperature change.

Polymers can easily change their shape from glassy to rubbery and eventually to liquid stage when temperature keeps rising. That's why it is important to ponder the effect of temperature as well as realize the temperature limits beyond which permanent deformations can hinder the actual use of the polymer (Karademir & Frost, 2011)

2.14.1 Creep and Temperature:

An increment in inside temperature (i.e., energy) of a polymeric test, or an increase within the temperature of the testing conditions will result in an increment in the coefficient of friction between polymers. The estimate and shape of a test can change the results of friction testing between polymeric specimens. In common, polymers show both elastic and plastic distortion. The plastic distortion makes arrangement of the chains relative to the applied force direction within the polymer structure. In addition, plastic deformation tends to increase the contact area between the materials at the interface and greater flexibility of the surface; in this way, the measured coefficient of friction increases. The increased surface pliability comes about in a more pliable, pliable, or more versatile polymeric material surface than that at moo temperatures. The distinction within the surface pliability of the polymeric fabric at tall temperatures as compared to that at moo temperatures can be credited to less flexible (i.e., inflexible), more fragile polymer fabric properties at low temperature conditions that comes about within the polymeric material possessing a less pliable and compliant polymer interface surface in conjunction with counter face material component. Furthermore, the softer and adaptable material properties of the polymer as well as the moldable and more flexible surface characteristics of the polymeric material at higher temperatures permit for a more prominent region of contact and interaction between it and the other counter face interface component since it does not have the surface depressions of the polymer existing at lower temperatures due to inflexible and intractable material surface properties which diminish the contact range creating at the interface during the course of shearing. Moreover, as shearing advances, the higher surface pliability of the polymer at the interface permits it to implant into by the counter face material, coming about within the improvement of larger frictional shear resistance. Consequently, the higher polymer flexibility and the bigger surface pliability of the polymeric fabric at higher temperatures empowers the shear strength increasing mechanisms examined here to create more promptly that accounts for the greater friction mobilized at high temperatures. At low temperatures, heat produced at the interface due to shearing is less effectively disseminated by the polymer than by other materials. However, as the temperature of the polymeric material increases, this produced heat due to friction testing can more effectively be scattered by the polymer resulting in higher interfacial frictional resistance existing between the interface materials. In in this way, obtaining higher coefficient of contact within the tests (Daniel, 1990).

Creep behaviour is defined as a time-dependent deformation process where the stress is less than the strength of the material (Nielsen & Landel, 1994). The typical tensile creep behaviour of is shown in Figure 2.10, where the creep strain is represented by a solid line and the creep rate is represented by a dashed line. Creep behavior can be divided into three stages: primary creep, secondary creep and tertiary creep. In the primary (or transition) stage, after an instantaneous elastic response to the applied stress, as the strain rate decreases with time, the strain continues to increase. In the second (or steady state) stage, the strain (ε) increases linearly with time, resulting in a constant strain rate (έ), so a plateau area is observed between the strain rate and the strain (ε) or on the time chart. The third stage is described by the rapid increase in strain (ε) and strain rate (έ) leading to creep failure. Similarly, the compression creep behaviour in the primary and secondary creep stages shows similar behavior to the tensile creep. However, in the third stage (the final stage), the creep strain rate (έ) decreases instead of creep strain (ε) increasing. Furthermore, creep rupture does not occur in compression behaviour, because the material behaves as a complete solid material compared to tensile behaviour (Dowling, 2013).

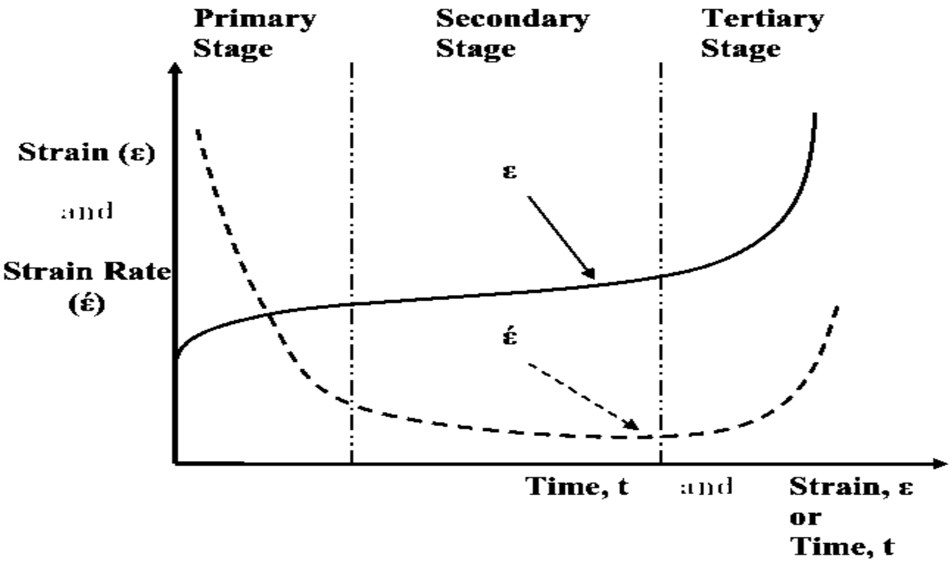


Figure 2.10: Relation Between Creek and Temperature (Nielsen and Landel, 1994).

The mechanism of creep in all polymers is majorly controlled by the temperature and load factor. Thus the effect of temperature in affecting the polymer's creep behavior is significantly observable. By description, creep is the movement of molecules thus with increased temperature, room for movement expands. The deformation in such cases is critical as when the polymer is subjected to high static loads and high temperatures, the deformation of lengths and angels of the chemically connected bonds gets disturbed. The problem doesn't end here as the deformation occurrence is one thing that disruption of the bond structure but when such change happens, atoms adjust to the change and permanently takes the changed shape up and leaving the material with permanent deformation (Roylance, 1996). Similar is the case with long duration static loads that push the chain structure of bonds to eventually lose shape and break into an amorphous region which again crystalizes as atoms move to adjust the change.

2.14.2 Fatigue and Temperature:

Fatigue occurs in polymers when a cyclic load and unloading of a pressure is induced. Certain considerations in such cases focus on the load itself, the time of loading, the relative size of the sample compared to the load and most importantly, the temperature of the environment and the material when the load cycle occurs (Daniel, 1990). On other hand, the loading and unloading cycle frequency is also an important factor as illustrated by the fatigue curve graph illustrated in the following figure 2.11.

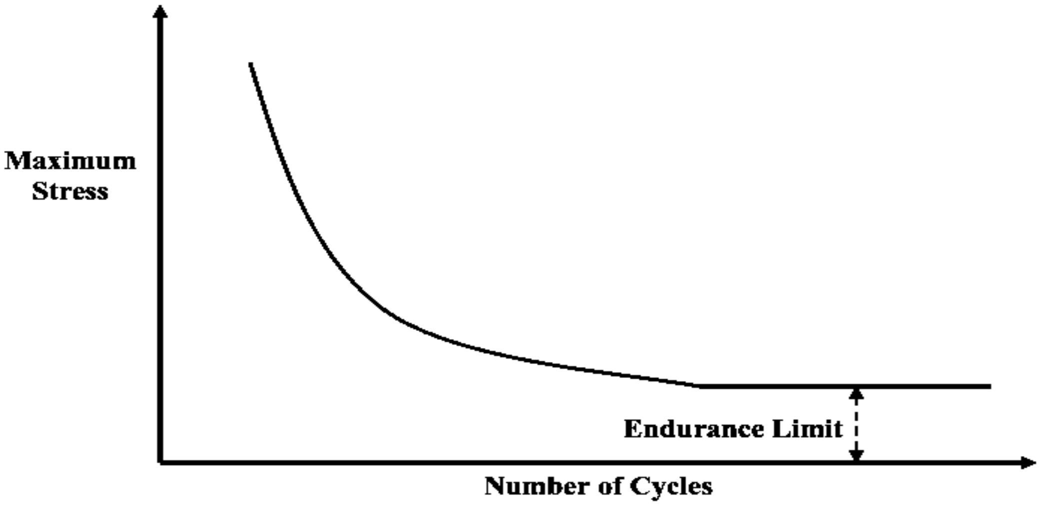


Figure 2.11: Fatigue Curve for a Typical Polymer (Nielsen and Landel, 1994).

The duration of unloading and the extent is directly linked to the lifetime and durability of the polymer in terms of their fatigue reaction. If the time provided to the polymer to recover from the previous loading, allowing it to release the absorbed stress then the chances of polymer to return and evade a fatigue are quite higher as compared to opposite conditions (Nielsen & Landel, 1994). This shows that in such cases, the plastic deformation is less if cycles are moderated effectively. This is also observed in tensile strength testing where it shows that polymers have a better life, durability and lesser fatigue when the temperature is less, load is reduced and time of loading and impact is also reduced. This summarizes that polymers can have decreased lifetime and increased chance of fatigue with increased temperature, greater loading weights and increased unloading time.

2.14.3 Mechanical Damping and Temperature:

When a polymer is stressed, the energy that gets converted into heat energy is called the mechanical damping. The sum of the remaining energy is thus put to the elastic or plastic deformation. The relation of temperature to the damping behavior of polymers is critical to understand. Damping is normally lower in the glassy state but increases as the polymer shifts to a rubbery state. However, a peak is observed during the phase change. For polymers, it is desired that they should have high mechanical damping properties to get a better reduction of vibrations and also increased coefficient of friction (Dowling, 2013).

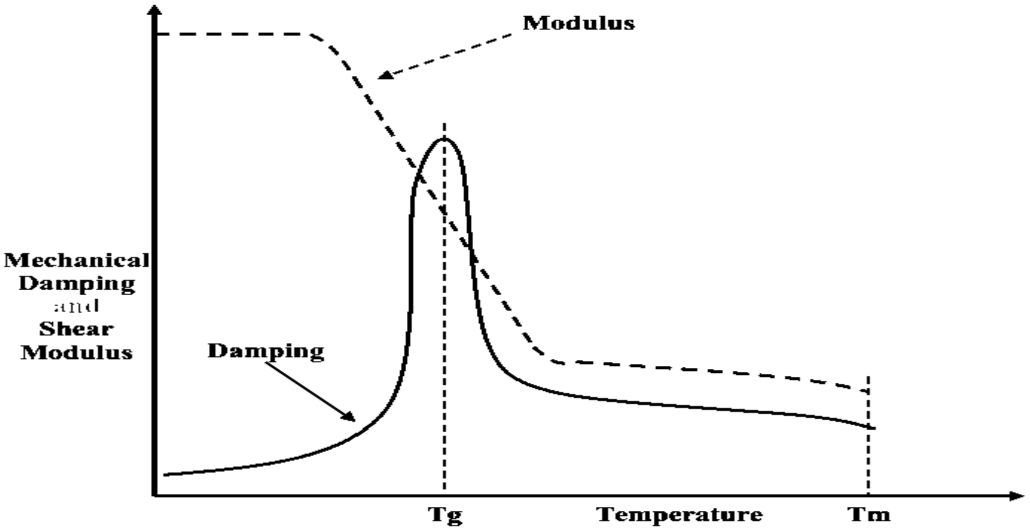


Figure 2.12: The General Mechanical Damping and Shear Modulus Behavior of a Polymer with respect to Temperature (Dowling, 2013).

2.14.4Impact Strength and Temperature:

The ability of the polymer to absorb a sudden shock of loading is called the impact strength or impact resistant capability (Daniel, 1990). The relation between temperature and impact strength of polymers is direct. A rubbery polymer has a greater ability to dissipate the energy around the free spaces and due to elastic properties, absorb a good amount of energy. However, in glassy polymers, the reaction is different and opposite as they don’t have room to adjust the incoming gush of energy and thus often shatter. Temperature directly controls the rubbery behavior of polymers and thus also affects the shock absorption. However, too much temperature can negatively affect the polymer as the polymer can take permanent deformation too.

2.15 Tensile Creep Behaviour of Geosynthetics:

Similar to polymers, geosynthetics are also known for depicting viscoelastic properties. Under constant loading can affect the tensile creep behavior that can induce damage to structural items. The degree of the creep strain varies with the temperature of the material itself and the amount of the loading as well as the type of polymer and fabricating process of the geosynthetics. The dependents in such cases are temperature, the loading and the material properties of the geosynthetics used. Thus, to have a safeguard, the creep reduction factor is calculated prior to allow the material a factor of safety (FS). The variation of the reduction factor is due to polymer type. Geotextiles, made from base polymer types such as HDPE and PP, have relatively large reduction factors, since they are within the rubbery state and show the typical physical properties of rubbery polymer state (i.e. polymer chains promptly experience plastic flow under tensile stretch at micro-level and the polymeric fabric exhibit plastic deformation under tension constrain with ease) at normal surrounding conditions (i.e. -10 °C < T < 50 °C) to which these geosynthetics are commonly uncovered in most broad geotechnical applications (G. Koerner & Koerner, 2006).

2.17 Tensile Strength Properties and Temperature:

Tensile Stress and Strain test is the most common mechanical test categories generally used for polymers. There are two variables involved in test: rate of change in length/width and rate of change in area of cross section. The test assessment setup must be the same for all polymers tested to be capable to produce a post-test comparison on the results obtained by experiment. The results can shift enormously for the same polymer depending on boundary conditions and test arrangement as a result of the differences of chain and molecular structure found inside the wide range of polymers. Additionally, the tensile and yield are profoundly variable within the detailed test results of the same polymer due to changing test conditions specified over. Furthermore, the compression properties of polymers are generally different than the tension properties. Temperature covers a notable impact on tensile properties of polymers as shown in figure 2.13. Since polymers are anisotropic materials and extremely susceptible to both temperature alter and strain rate. So, as temperature increments in a polymeric fabric, a continuous development of the fabric happens, coming about in more free volume as well as weakening of the bonding strengths which shape the polymer structure and constitute the arrange of polymer chains holding the fabric together. For example, a lessening in van der Waals strengths happens between atoms resulting in less internal quality with increasing temperature which is reflected in a decreased maximum tensile quality. This often goes with an increment within the strain that the polymer can sustain without breaking. Figure

2.14 outlines ordinary tensile test comes about of polymers in different states which were tried to failure with a direct strain rate (Daniel, 1990).

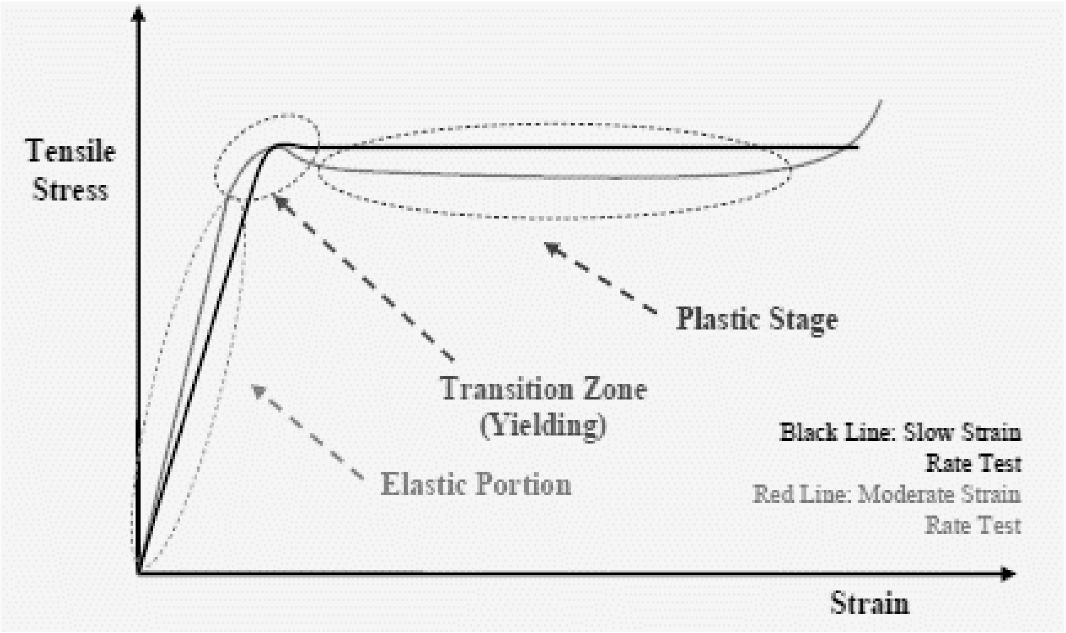


Figure 2.13: Tensile test for crystalline polymer (Daniel, 1990).

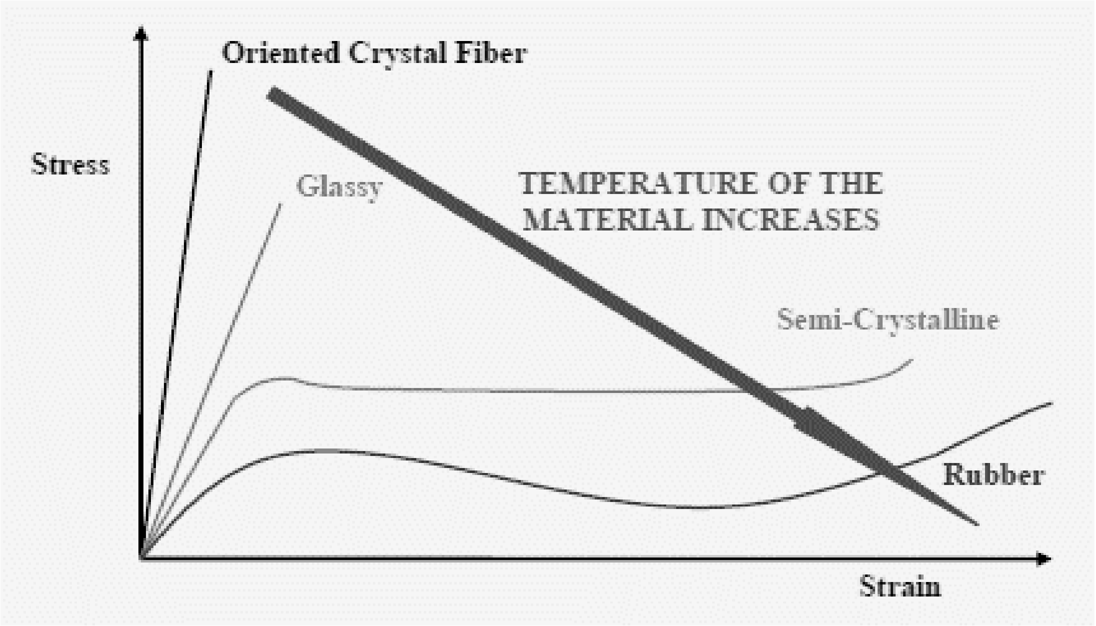


Figure 2.14: Tensile test for different state of polymer tested till failure (Daniel, 1990).

As shown in Figure 2.15, the tensile behavior of a polymer is strongly related to the state of the fabric which depend on its temperature. Polymers are brittle at the least temperatures. As the temperature increases, they ended up more tough, until they reach brittle-ductile transition over which polymers got to be adequately ductile so that they can show necking behavior which is obviously seen within the yielding zone of the direct strain rate test in Figure 2.14. Further increases in temperature lead to a rubber-like behavior as illustrated in Figure 2.15. Moreover, the type of behavior a polymeric material shows when tested depends on the strain rate of expansion in ductile tests. For illustration, if extremely high strain rates are utilized, a polymer can show brittle behavior at nearly any temperature (Dowling, 2013).

2.18 Previous Interface Shear Strength Tests on Geosynthetic Composite Systems at Various Temperatures:

(Akpinar & Benson, 2005) conducted a study to evaluate whether temperature affects needlepunched non-woven polypropylene geotextile (GT) and two smooth high-thickness polyethylene geomembranes (GMS) and finished product (GMT). Shear strength of the interface. Use a dual interface shear device (DISD) enclosed in a mild temperature chamber for testing, with a temperature range of 26°C to 33°C, a normal stress of 7.5 to 49.5 kPa, and a displacement speed of 0.9 to 1.5 mm/min., A slight change in interface resistance is observed within the temperature range considered. Regardless of the displacement rate, a temperature increases of 33°C causes the bounce interface friction point of the GMS-GT interface to increase by 2.91, and the bounce interface friction point of the GMT-GT interface to increase by 2.31. A comparative change in the friction point after the peak is observed.

2.19 Effect of surface hardness on soil geomembrane interface shear strength.

The resistance of plastic materials to indentation is defined as the material’s hardness as described by the ASTM 2240 (2005). It dependence however circles around different materialistic properties including viscoelastic and stiffness properties. The effect of hardness on polymer properties was observed by (O’Rourke et al., 1990). When a study was conducted for shear interface study between different sand polymers. Different polymers were part of this experimental study including HDPE and PVC in the shape of pipes and geomembranes. To capture the surface of the material before and after the application of stress, the Scanning Electron Microscope or SEM was utilized. The study found that there was a significant relation between hardness and interface strengths of the geomembranes and as the hardness increased, the interface strength was affected by a steep decrease. It was also observed that when the materials were observed for interface strengths, the hard material like HDPE showed a sliding movement of sand particles while in the soft material case of PVC, a round and rolling motion of sand particles was visible. Another research conducted by (Dove & Frost, 1999) also contributed to the effect of hardness and interface strengths where a relation between normal strength, interface strength and hardness of material was observed. Under the observation of different interfaces in this study, it was uncovered that with initial increase in the normal stress, the initial friction actually decreases. What happens in this stage is that the sand particles distribute the normal stress and thus the interface friction decreases to a certain limit. After reaching the ultimate normal stress for non-transfer of friction, the particles start to dissipate the normal stress through individual surface contact. The relation in this stage is mainly regulated by the hardness of the material as normal stress transforms to critical stress. When the normal stress is lower than critical stress, the sliding action without any significant damage to the surface is the primary translation of stress. However, as the normal stress passes over the critical stress limit, the particles between the interface not only slide but also plow the surfaces. This is due to the increase in the stress that hinders the present movement to confine the mobility and these particles plunge into the material surface and scratch the surface in this translation. But when this happens, the force required to move the plowed sand particles is now increased due to increase in the interface friction. According to (Dove & Frost, 1999) the increase of interface friction was observed to be greater and significant in the softer polymers like geomembranes and on the other hand, insignificant in the hard polymers like HDPE. Thus according to the summary of their results, the interface friction becomes a factor or surface hardness and shearing distance. To further explore the interface friction and properties, (Dove & Frost, 1999) used the image analysis technique to observe the shearing distribution from the void ratio differences when sand particles were undergoing surface friction. The report identified that when round and angular shaped sand particles were observed directly adjacent to the geomembranes, the friction was dependent on the surface roughness. A zone two particle diameter (2D50) surface variation was observed for smoother and softer geomembranes and with the increase in surface hardness, the size of the affected zone increased to 6D50.

The experiment used the quantification method for the geomembrane based on the normal stress, shear displacement and also the shape and angularity of the particles. The topography of the surface can be easily used to measure the shear interface between the geomembranes as the zones are quite significant and with increase in hardness, the observation becomes easier. The strength of the interface in such experiments is directly linked to the soli particle’s angularity and size as it describes the plowing capability of the particles between the interfaces and under stress. When sliding along the surface, the work required is lower but when plowing into the surface, the particle has to displace the material of the membrane that requires significant effort. Therefore, the plowing strength increment is the increment in strength of the particles and can be clearly observed by the topography of the zone. However, what this actually comes to conclude and describe for the application purpose of the geomembranes is that plowing can result in voids and pores that significantly affects the permeability and durability of the geomembranes.

2.20 Effect of surface hardness on soil geomembrane interface shear strength.

The roughness of the surface of the geomembrane is one of the most important factors affecting the friction angle of the interface between the geomembrane and the geomembrane. The measurement of the surface roughness of the geomembrane is related to the morphology of the surface of the soil particles encountered when the geomembrane is in contact with the interface. The interfacial shear strength of a textured geomembrane is greater than that of a smooth geomembrane (Dove & Frost, 1999). To observe the effect of surface texture on interface shear strength, a series of direct shear tests were performed on the soil geomembrane using an improved direct shear device (Williams et al., 1987). They noted that the failure mechanism of the smooth geomembrane is basically the rolling of particles restricted by the slippage of the interface. However, the cut surface of the rough geomembrane moves to the adjacent ground, resulting in a higher interface friction point. The surface roughness of the material can be subdivided into macroscopic morphology and microscopic morphology.

The macroscopic morphology are the ones visible to human eye whereas the microscopic morphology is visible only at the microscopic level with the help of a few instruments (Dove & Frost, 1999). Moreover, (Stark & Poeppel, 1994) used torsional direct shear test to observe the failure envelops for smooth and textured geomembrane by shearing them against nonwoven geotextile at normal loading up to 400 KPa. The results obtained from shear testing reported that there was approximately 300 to 400 percent increase in interface friction angle by using textured geomembrane instead of smooth geomembrane. The increase in interface friction angle by using textured geomembrane is very critical to be noted during designing of geosynthetic composite systems and slopes.

According to (Dove & Frost, 1999), the peak interface angle increases rapidly with increasing a small amount of surface roughness, until the critical surface roughness value is greater than the critical surface roughness value , and the rate of increase of the friction angle decreases. Similarly, the residual interface friction angle ratio of also increases with increasing surface roughness and begins to decrease when the critical value of surface roughness is exceeded. However, it is observed that the friction angle patterns of the residual and peak interface are the same, but the mechanism of the friction point of the residual interface is different, so the critical roughness and the residual friction angle value are less than the maximum friction angle. This is attributed to the fact that the remaining mass is basically the work of macroscopic surface roughness, and almost all micro-textures discharged during displacement are close to peak intensity, which means that the basic value of surface roughness is basically the residual strength performance represents and tears the fibers of the geotextile, so the strength may be a function of the quality of the geotextile itself.

2.21 Shear Box Size

(Vieira et al., 2013) used simple and large-scale direct shear tests to study the shear strength of the sand geomembrane interface. The test results of simple and large-scale direct shear tests are relatively similar. In other words, the type of test used to obtain the interface friction angle and the interface shear strength of the sand geomembrane interface has no significant effect on the test results.

Chapter 3

3. Methodology

3.1. Introduction:

Methodology of this research is represented by the following flow chart. After Collection of the soil sample from Tharparkar Sindh and geomembrane from manufacturer the sample were brought in lab where index properties and direct shear test were performed. After performing the laboratory tests the obtained results were used to find the calculate the effect of temperature cycling and creep on sand geomembrane interface shear strength.

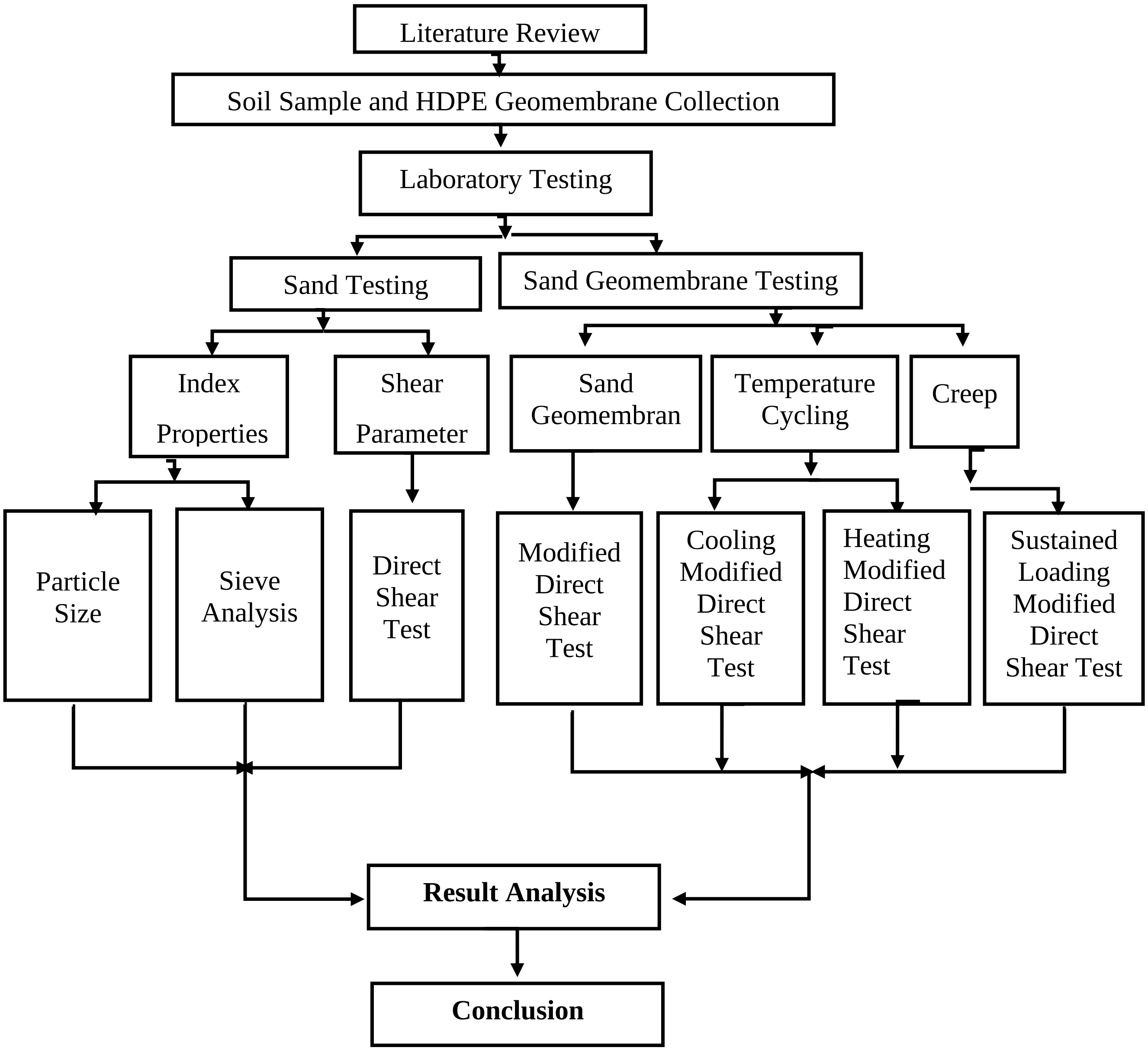


Figure 3.1:Conceptual Framework

3.2.Study Area:

The study was based on the area of district Tharparkar Sindh. The district Tharparkar facing drought like situation from last few years, and the reign is considered to be one of least developed regions of Pakistan which is described by cultural and religious diversity (*Sindh Drought Needs Assessment Report - 2019*). The Natural Disasters Consortium (NDC) conducted Sindh Drought Needs Assessment (SDNA) in different districts of Sindh. To counter drought by rain water harvesting these agencies are constructing small scale water reservoirs with catchment area using HDPE geomembrane.

Figure 3.2: Site Images

3.3.Materials

1. Tharparkar Sand

Tharparkar Sand was used in this research. The index properties i.e. Particle size and specific gravity were calculated using sieve analysis.

2. Geomembrane

The smooth HDPE geomembrane having thickness of 1.5 mm was used in this research which being the same as the one at Tharparkar . The following table 3.1 shows the physical properties of geomembrane provided by manufacturer.

Table 3.1: Properties of HDPE Geomembrane

Sr #	**Properties**	**Units**	**Values**	**Test Method**
1.	Thickness	mm	1.5	D 5199
2.	Density	g/cc	0.94	D 1505
3.	Tear Resistance >	N	187	D 1004
4.	Puncture Resistance >	N	480	D 4833
5.	Shear Crack Resistance >	hr	300	D 5397
6.	Carbon Black Content	%	2 - 3	D 1603
7.	Tensile Properties (Each Direction)			
•	Yield strength	KN/m	22	D 6693
•	Break strength	KN/m	40	Type IV
•	Yield Elongation	%	12	
•	Break Elongation	%	700	
8.	Oxidation Induction Time (OIT) >			
•	Standard OIT	min	100	D 3895

•	High Pressure OIT	min	400	D 5885
9.	Over aging at 85 C Retained after			
•	Standard OIT	%	55	D 3895
•	High Pressure OIT	%	80	D 5885
10.	UV Resistance High Pressure OIT	%	50	D 5885

3.4. Particle Size Distribution:

To determine the soil gradation between and No. 200 sieves, soil particle size distribution was performed in accordance with ASTM standard D-6913. Since the maximum particle size is equal to or less than 4.75mm, method B will be used with single sieve set arrangement. The sieve arrangement from top to bottom will be 4.75mm (No.4), 2.00mm (No.10), 850μm (No.20), 425μm (No.40), 250μm (No.60), 150μm (No.100), 106μm (No.140) and 75μm (No.200). Sample of 200g will be taken according to the standard for each test which will be oven dried and then placed over the sieving set and mechanically shaken. After the specimen has been shaken, record the percentage passing (PP_N) in grams for each Nth sieve using Eq. 3.1.

$$PP_N = 100 \times \left(1 - {}^{CMR_N}\!/_{S,\,M_d}\right) \tag{3.1}$$

Where PP_N is the Percentage passing through the Nth sieve, CMR_N is the cumulative mass retained on the Nth sieve in g or kg, S, M_d is the dry mass of the specimen in g or kg

3.5. Direct Shear Test

The interface frictional angle between Tharparkar sand and HDPE geomembrane at different loading and times were determined using modified direct shear apparatus. Since the failure plane is already known and fixed so direct shear test is more reliable in case of finding out interface friction angle than triaxial compression test. The direct shear test was performed in accordance with ASTM 3080. This method involves finding maximum shear stress against failure at constant normal stress of 50, 100, 200 KPa. The frictional angle of soil can be calculated by calculating tangent of a graph between normal stress on x-axis and shear stress on y-axis and its y intercept is called as cohesion of soil. The Columns shear strength equation is than used to find shear strength.

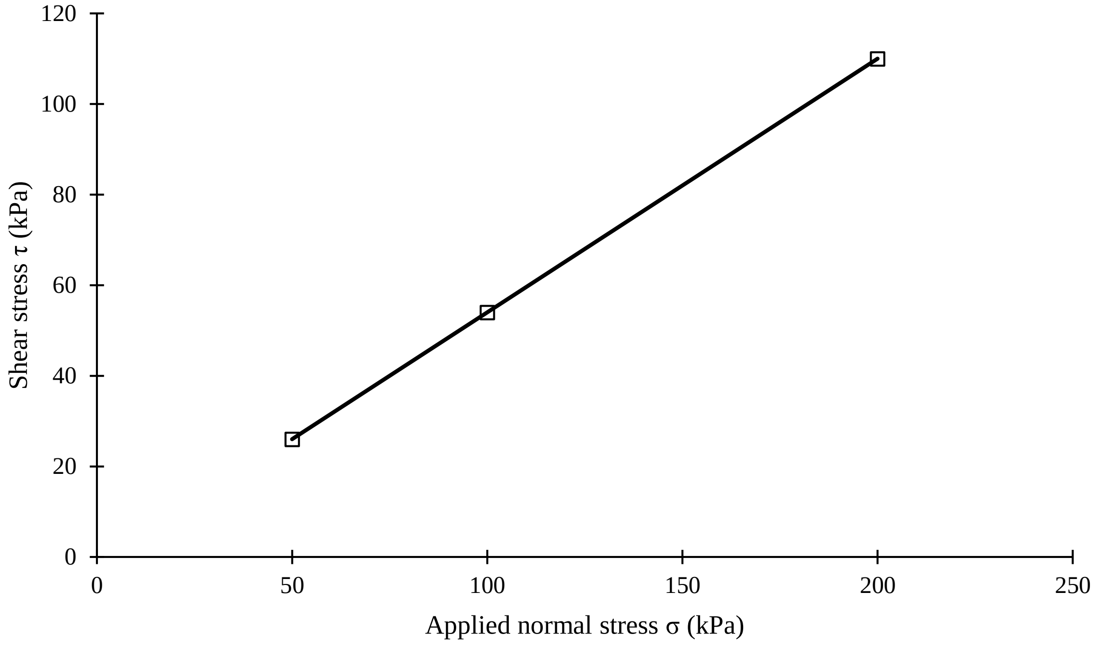


Figure 3.3: Normal vs Shear Stress

$$\tau f = c + \sigma_f \tan \emptyset \tag{3.2}$$

Where τf is the shear strength of soil at failure, c is the cohesion of soil.

3.6. Modified Direct Shear Test Apparatus

To evaluate the effect of creep and interface frictional angle between Tharparkar sand and HDPE geomembrane, modification in conventional direct shear box were required and made according to ASTM D 5321 the minimum dimension of direct shear box must be greater than or equal to 300 mm for determining the interface frictional angle between sand and geomembrane (Markou & Evangelou, 2018). According to (R. Koerner, 1990) recommends to use 100 mm square box for geomembrane against sand, silts and clays. O'Rourke et al., 1990), compared the results of the contact between Ottawa sand and smooth HDPE geomembrane, and found that the values of the interface friction angles were 60 mm, 100 mm, 280 mm, and 305 mm2 shear box were almost similar. The summary of test performed to find sand geomembrane interface frictional angle by using different size of shear boxes are given in the table 3.2.

Table 3.2: Previous interface friction angle obtained using different size of shear box.

Soil Type	Geomembrane Type	Interface Frictional Angle (δ°)	Normal Stress (Kpa)	Dimension of Shear Box (mm)	References
Otawa Sand 20/30	HDPE	20	15-100	100 x 100 mm	Martin et al. (1984)
		19-21	200	280 x 280	Saxena and Wang (1984)
		19	10-100	305 x 305	Williams and Houlihan(1987)
		18.5	50	60 Dia	Negussery et al. (1989)
		19	21 - 69	60 x 60	O'Rourke et al. (1990)

The size of direct shear box is appropriate for testing if it complies with the following two condition (O'Rourke et al., 1990)

1. For Each plane dimension of the shear box should be greater than or equals to 100 times the mean grain size (D50) of the sand to be tested.
2. The min and maximum shear must be occurred displacement equals to at 2- 5 % of the shear box dimension which characterizes peak an appropriate level of deformation with respect to boundary effect.

Based on above mentioned information it was decided to use conventional direct shear box for finding out the interface frictional angle between Tharparkar sand and HDPE geomembrane. The assembly of modified shear box is illustrated in figure 3.4

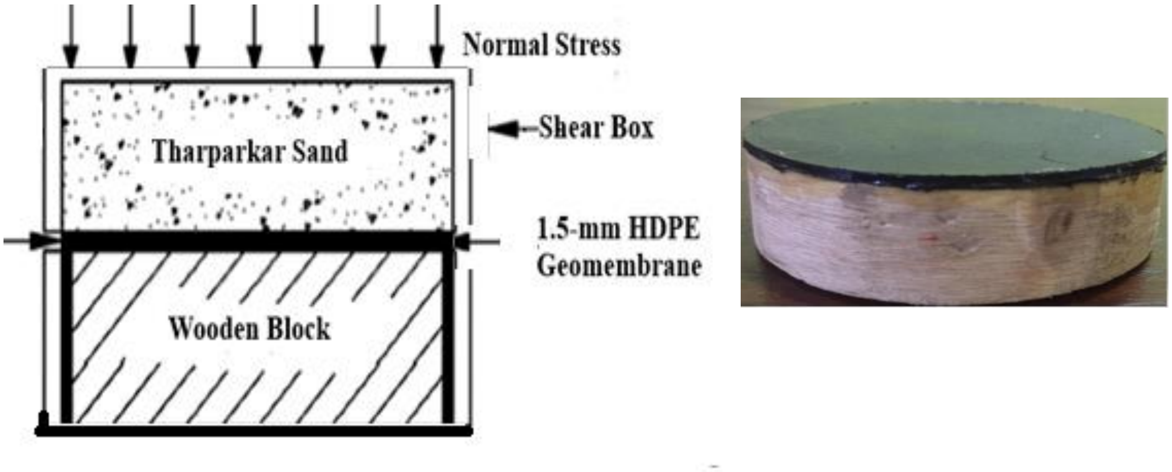


Figure 3.4: Assembly of Direct Shear Box

The HDPE geomembrane samples were attached on a wooden block having rough surface. The wooden block comprised of geomembrane at the surface was placed in the lower shear box. Whereas Tharparkar sand was then placed at the upper shear box to evaluate the interface friction angle between sand and geomembrane. The same modified direct shear test was also used by Koerner and other researchers and has been successfully used for evaluation of interface friction angle between soil and geomembranes. It is also assumed that sand and geomembrane are placed on the top and bottom of the shear box, respectively, which will give basically the same results as the normal test setup (Markou & Evangelou, 2018).

3.7. Testing Procedure:

The HDPE geomembrane having thickness of 1.5mm having 100 percent virginity was used for finding out the effect of temperature and creep on sand geomembrane interface shear strength. The values of normal stresses were selected to simulate the actual normal stresses in the field. The direct shear test were divided into 6 groups with respect to temperature and creep conditions as shown in table 3.3.

Table 3.3 Testing Methodology

Group	**Testing Material**	**No. of Sample**	**Temperature**	**Normal Stress Applied (kPa)**	**No. of Cycle**	**Applied Load Time**
1	Sand - Sand	3	20 C	50, 100, 200	0	Instantaneous
2	Sand - Geomembrane	3	20 C	50, 100, 200	3	Instantaneous
3	Sand - Geomembrane	3	50 C	50, 100, 200	3	Instantaneous
4	Sand - Geomembrane	3	5 C	50, 100, 200	3	Instantaneous
5	Sand - Geomembrane	3	5 C	50, 100, 200	3	Instantaneous
6	Sand - Geomembrane	2	20 C	50	0	7 Days

Group 1, direct shear tests were performed on three samples of Tharparkar sand and their average frictional angle was determined. Whereas Group 2, three cycles of direct shear test was carried out on three samples of Tharparkar sand and HDPE geomembrane to determine interface friction angles right after the normal stress was applied on the sample. Group 3, in all three cycles, three HDPE geomembrane samples were placed in oven at 50 C for one hour and then placed at room temperature for one hour before direct shear testing. Similarly Group 4, in all three cycles three HDPE geomembrane samples were placed in cooling apparatus at 5 C for one hour and then at room temperature for one hour before direct shear testing. In group 5, same three samples that were previously tested for heated temperature were again placed at 5 C for one hour and then at room temperature before testing. Finally, group 6 was tested after 7 days of applied normal stress of 50 KPa on the sample to determine the effect of creep. The following procedure were followed to perform the test:

1. Wooden block were cut at the size of 60 mm diameter in accordance to the size of lower shear box.
2. HDPE geomembrane was than attached at surface of wooden block with the help of glue and the geomembrane samples were closely inspected to eliminate abrasion on the surface.
3. Wooden block consisting of HDPE geomembrane on top surface was placed at lower part of shear box.
4. The upper part of shear box was placed on the top of geomembrane and fixed with the alignment screws.
5. The weight of Tharparkar sand that was calculated using density was poured into upper part of shear box.
6. Porous plate was then placed at the top of sand.
7. Loading plate was placed at the top of porous plate and diagonal screws were tightened.
8. The horizontal and vertical gauges were initialized to zero and applied normal load.
9. Remaining two screws were tightened and vertical load was applied.
10. After applying vertical loads all screws were removed and motor was started.
11. Reading of shear load, horizontal and vertical deflection were noted during the test.

Chapter 4

4. RESULTS AND DISCUSSION

4.1. Introduction:

This chapter presents the results of direct shear tests that were conducted in the laboratory using the modified direct shear apparatus. Natural sand sample from area Mithi Tharparkar Sindh around the constructed water reservoir was selected for the study..

4.2. Results of Direct Shear Testing.

The results obtained from direct shear testing for all the groups are presented below in table 4.1 and 4.2.

Table 4.1: Interface frictional angle results

Group	**No. of Cycle**	**Sample**	**Temperature**	**Friction Angle**	**Average Friction Angle**
1	i)	SS 1	20	32.8	32.9
		SS 2	20	33.0	
		SS 3	20	32.9	
2	i)	RSG 1 (1)	20	29.1	29
		RSG 2 (1)	20	29.3	
		RSG 3 (1)	20	28.7	
	ii)	RSG 1 (2)	20	28.1	28.9
		RSG 2 (2)	20	30.6	
		RSG 3 (2)	20	28.2	
	iii)	RSG 1 (2)	20	28.1	28.6
		RSG 2 (2)	20	29.5	
		RSG 3 (3)	20	28.2	
3	i)	SGT 1 (1)	50	27.9	28.3
		SGT 2 (1)	50	29.2	
		SGT 3 (1)	50	27.7	
	ii)	SGT 1 (2)	50	27.4	27.8
		SGT 2 (2)	50	28.3	
		SGT 3 (2)	50	27.7	
	iii)	SGT 1 (3)	50	27.4	27.5
		SGT 2 (3)	50	28.1	

		SGT 3 (3)	50	27.0	
4	i)	SGL 1 (1)	7 C	56.0	
		SGL 2 (1)	7 C	28.2	
	ii)	SGL 1 (2)	7 C	29.4	28.8
		SGL 2 (2)	7 C	28.2	
	iii)	SGL 1 (3)	7 C	28.8	28.6
		SGL 2 (3)	7 C	28.4	
5	i)	SGTL 1 (1)	7 C	27.2	27.0
		SGTL 2 (1)	7 C	26.9	
		SGTL 3 (1)	7 C	27.1	
	ii)	SGTL 1 (2)	7 C	27.0	26.7
		SGTL 2 (2)	7 C	26.4	
		SGTL 3 (2)	7 C	26.6	
	iii)	SGTL 1 (3)	7 C	26.8	26.5
		SGTL 2 (3)	7 C	26.4	
		SGTL 3 (3)	7 C	26.5	

Table 4.2: Shear Stress Results

Group	**No. of Cycle**	**Sample**	**Max Shear Stress at 50 KPa**	**Max Shear Stress at 100 KPa**	**Max Shear Stress at 200 KPa**
1	i)	SS 1	26.3	59.0	123.0
		SS 2	28.0	61.0	125.3
		SS 3	27.7	60.3	124.7
2	i)	RSG 1 (1)	25.7	58.3	109.3
		RSG 2 (1)	26.3	59.0	110.3
		RSG 3 (1)	25.0	57.0	107.0
	ii)	RSG 1 (2)	25.3	58.0	105.3
		RSG 2 (2)	25.7	58.3	114.3
		RSG 3 (2)	24.7	56.7	105.0
	iii)	RSG 1 (2)	25.0	58.7	105.0
		RSG 2 (2)	25.3	57.0	110.0
		RSG 3 (3)	24.7	56.0	105.0
3	i)	SGT 1 (1)	25.7	57.3	105.0
		SGT 2 (1)	25.0	58.0	109.0
		SGT 3 (1)	25.0	56.0	103.7
	ii)	SGT 1 (2)	24.7	57.0	102.3

		SGT 2 (2)	24.3	57.3	105.0
		SGT 3 (2)	24.3	56.0	103.0
	iii)	SGT 1 (3)	24.0	56.7	101.7
		SGT 2 (3)	24.0	57.3	104.0
		SGT 3 (3)	23.7	56.0	100.0
4	i)	SGL 1 (1)	25.3	59.0	110.3
		SGL 2 (1)	26.7	57.0	107.0
	ii)	SGL 1 (2)	25.0	58.3	109.6
		SGL 2 (2)	26.3	56.7	106.7
	iii)	SGL 1 (3)	24.7	56.0	107.0
		SGL 2 (3)	25.0	58.7	106.0
5	i)	SGTL 1 (1)	24.0	56.0	101.0
		SGTL 2 (1)	24.3	57.0	100.3
		SGTL 3 (1)	23.0	55.7	99.7
	ii)	SGTL 1 (2)	23.7	55.7	100.0
		SGTL 2 (2)	24.7	57.0	99.3
		SGTL 3 (2)	22.7	55.0	97.8
	iii)	SGTL 1 (3)	23.3	55.7	99.0
		SGTL 2 (3)	24.3	56.0	98.7
		SGTL 3 (3)	23.6	55.7	98.3
6	i)	SGC 1	27.0		
	ii)	SGC 2	27.3		

4.3. Effect of Heated Temperature Cycling on Interface Friction angle of Tharparkar Sand and HDPE Geomembrane:

To determine the effect of heated temperature on interface shear strength between Tharparkar sand and HDPE geomembrane, direct shear tests for three cycles were conducted using three HDPE geomembrane samples that were placed in oven at 50 C (maximum temperature observed physically on site in last three years) for one hour and then at room temperature for one hour before testing. Figure 4.1 shows the comparison of interface frictional angle between the HDPE geomembrane and sand samples that are subjected to heated temperature (i.e. SGT) and samples that are not subjected to temperature (i.e. SGR). The average friction angle of three samples of SGR were 29, 28.9 and 28.6 on cycle one, two and three respectively. Whereas, average friction angle of three samples of SGT were 28.3, 27.8 and 27.5 on cycle one, two and three respectively. Table 4.3 shows the percentage difference of friction angles of SGR and SGT. The percentage difference of friction angle between SGR and SGT was 2.6, 4 and 3.8 percent on cycle one, two and three respectively. The decrease in friction angle of SGT in cycle one is only due to the increase in temperature which effected the chemical and physical properties of geomembrane. Whereas, the percentage difference of 4 and 3.8 of cycle two and three respectively are due to the cyclic effect of temperature and loading on geomembrane. It is evident from the figure 4.1 that friction angle was decreased with the increase in number of cycles because cycled shearing effected the surface texture i.e. effecting polished surface of smooth HDPE geomembrane (Hanson et al., 2015). However, if the testing was conducted in temperature controlled direct shear test i.e. at 50 C, the friction angle may increase because of decrease in surface hardness and increase in surface area of geomembrane (Karademir & Frost, 2011).

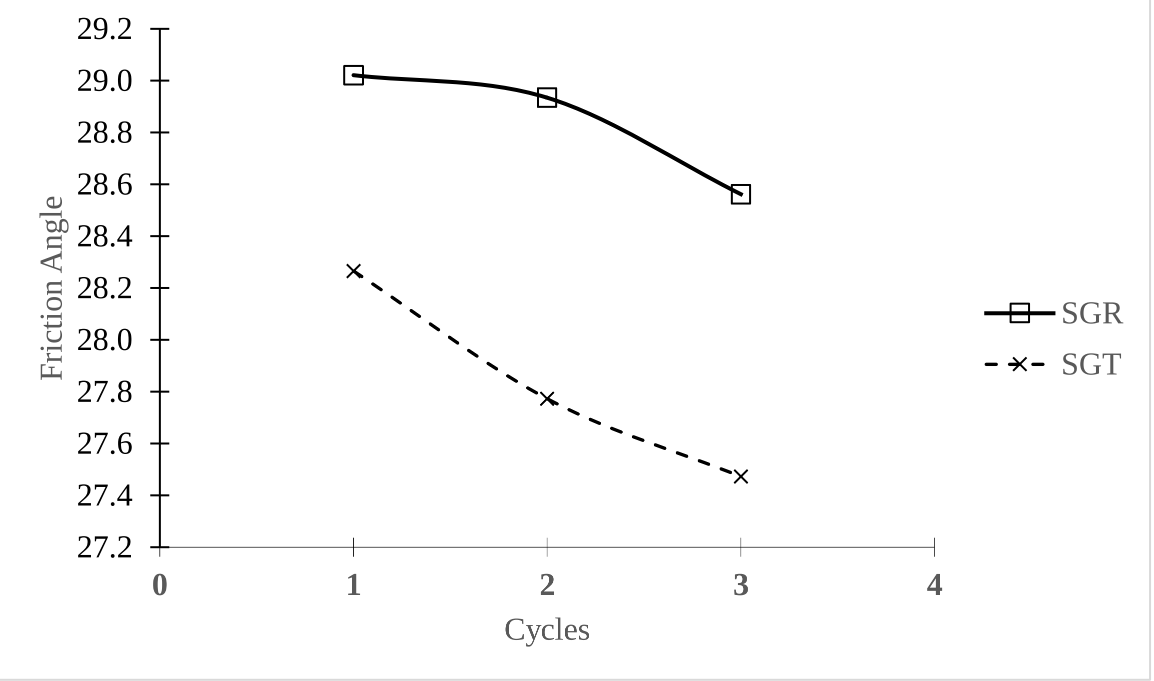


Figure 4.1: Comparison of interface friction angle between SGR & SGT

Table 4.3. Percentage difference of interface friction angle between SGR & SGT

Cycles	SGR	SGT	Difference %
1.0	29.0	28.3	2.6
2.0	28.9	27.8	4.0
3.0	28.6	27.5	3.8

4.4. Effect of Cold Temperature Cycling on Interface Friction angle of Tharparkar Sand and HDPE Geomembrane:

Similarly, To determine the effect of cold temperature on interface shear strength between Tharparkar sand and HDPE geomembrane, direct shear tests for three cycles were conducted on the three HDPE geomembrane which were placed at 5 C (minimum temperature observed physically on site) for one hour and then at room temperature for one hour before testing. In addition, three HDPE samples that were tested before for heated temperature were also tested at 5 C to stimulate the actual field condition in lab. Figure 4.2. shows the comparison of interface frictional angle between the HDPE geomembrane samples that are subjected to cooled temperature i.e. SGL and SGR . Whereas, Figure 4.3. shows the comparison of interface friction angle between HDPE geomembrane samples that were tested before for heated temperature and then again are subjected to cooled temperature i.e. SGTL. The average friction angle of three samples of SGL were 28.9, 28.7 and 28.6 on cycle one, two and three respectively. Whereas, average friction angle of three samples of SGTL were 27, 26.7 and 26.5 on cycle one, two and three respectively. Table 4.4 shows the percentage difference of friction angles of SGR and SGL. Whereas, Table 4.5 shows the percentage difference of friction angles of SGR and SGTL. It is evident from figure 4-3 that there is not any significant change in friction angle between SGR and SGL, which indicates that cooled temperature i.e. 5 C did not affect any chemical or physical properties of geomembrane. Thus, the percentage difference of 6.8, 7.8 and 7.1 percent on cycle one, two and three respectively between SGR and SGTL is only due to the cyclic loading because of cycled shearing that effected the surface texture i.e. effecting polished surface of smooth HDPE geomembrane (Hanson et al., 2015).

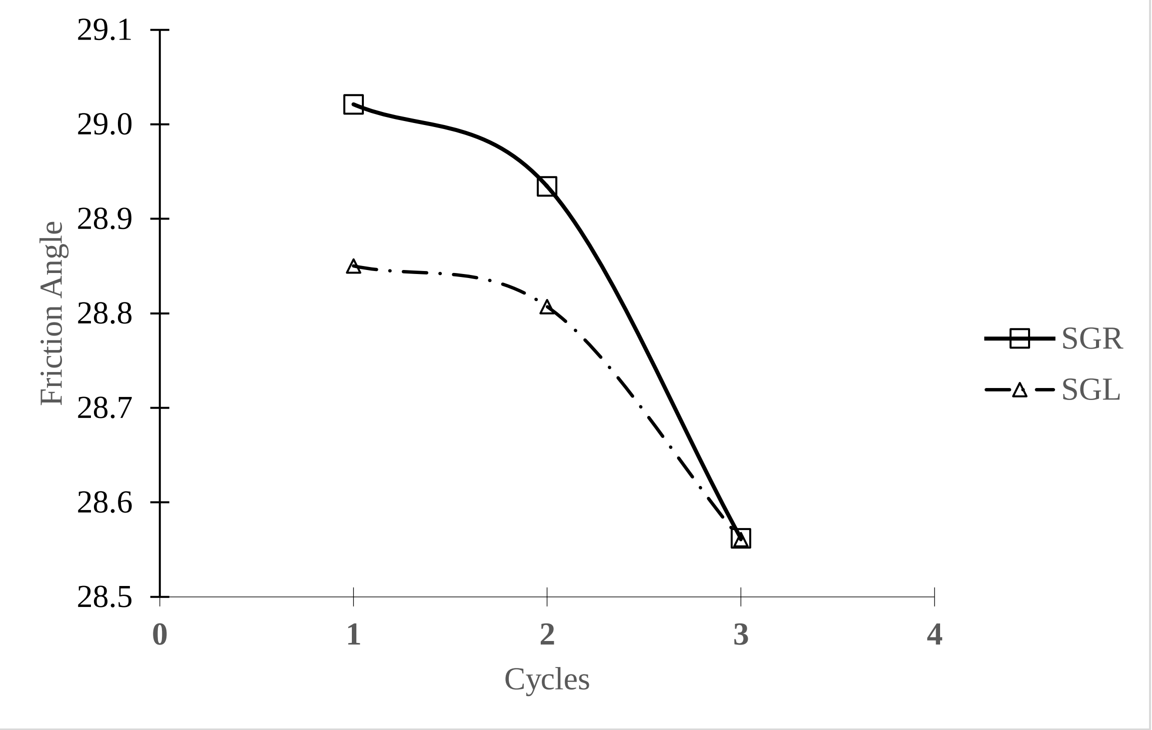


Figure 4.2: Comparison of interface friction angle between SGR & SGL

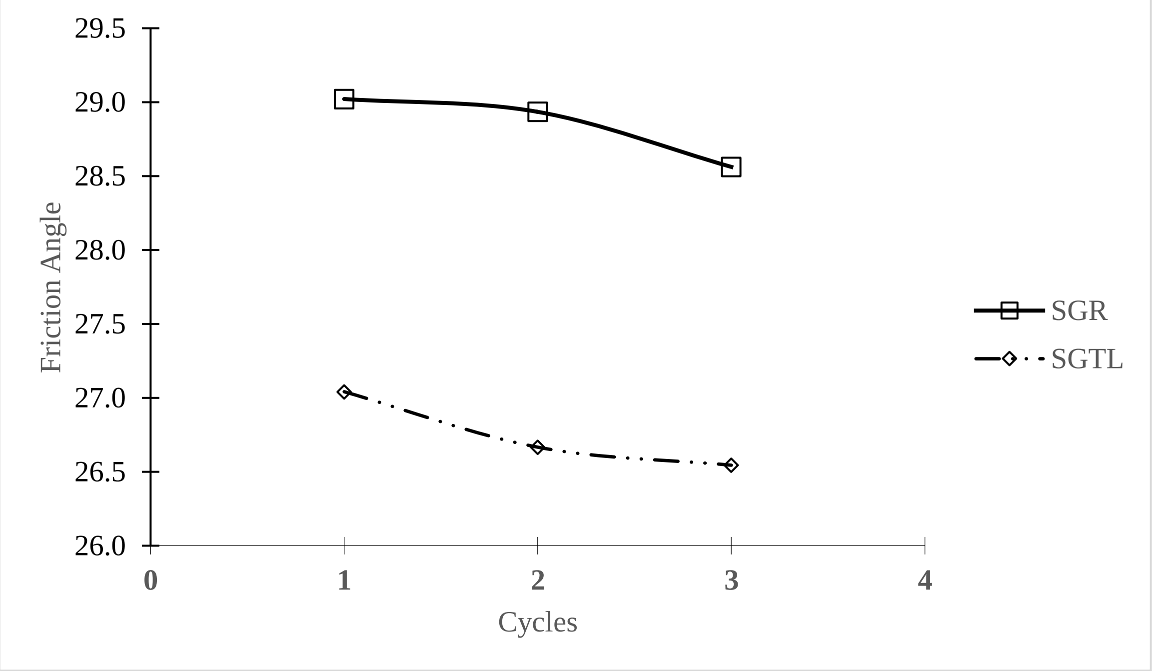


Figure 4.3: Comparison of interface friction angle between SGR & SGTL

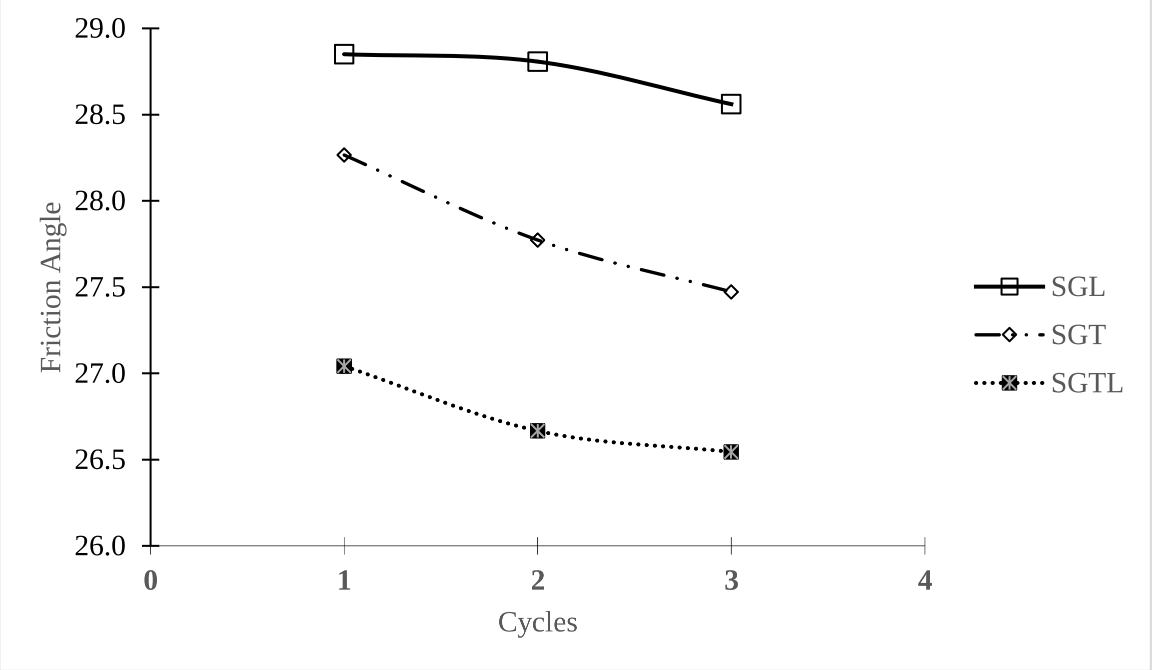


Figure 4.4: Comparison of interface friction angle between SGT, SGL & SGTL

Table 4.4 Percentage Difference of Interface Friction Angle Between SGR & SGL

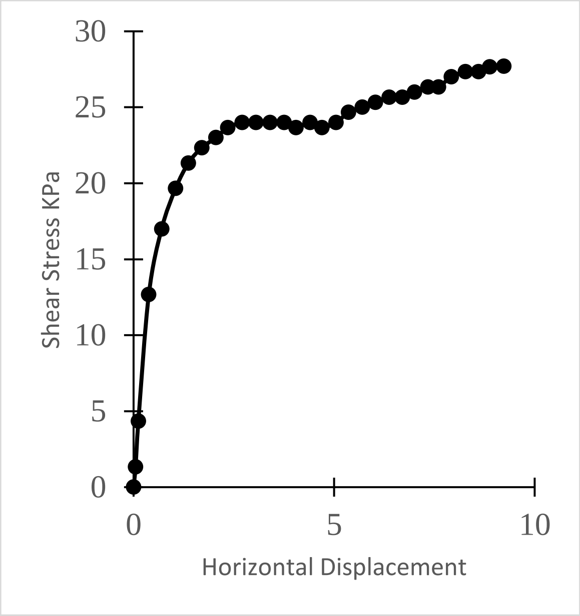
Cycles	SGR	SGL	Difference %
1.0	29.0	28.9	0.6
2.0	28.9	28.8	0.4
3.0	28.6	28.6	0.0

Table 4:5 Percentage Difference of Interface Friction Angle Between SGR & SGTL

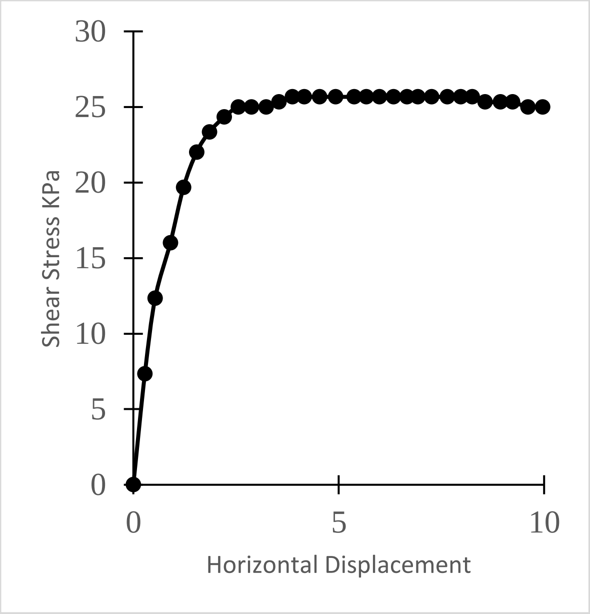
Cycles	SGR	SGTL	Difference %
1.0	29.0	27.0	6.8
2.0	28.9	26.7	7.8
3.0	28.6	26.5	7.1

4.5. Effect of Creep and on Interface Shear Strength of Tharparkar Sand and HDPE Geomembrane:

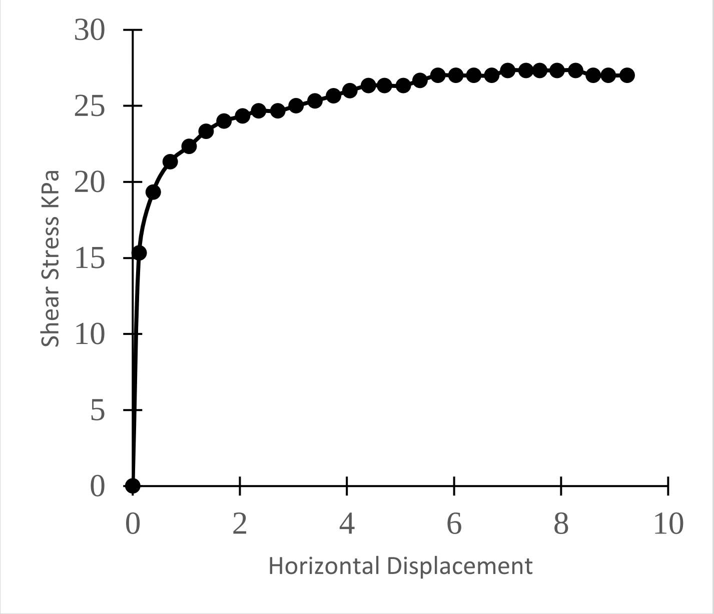
To evaluate the effect of creep on interface shear strength of Tharparkar sand and HDPE geomembrane the direct shear test was conducted after applying normal stress of 50 KPa for 7 days on two samples of HDPE geomembrane i.e. SGC. Figure 4.5 (a, b and c) shows the interface shear resistance of SS, SGR and SGC samples that are subjected to sustained loading of 50 KPa for 7 days. Whereas, Figure 4.6. shows the comparison of shear stress obtained at normal stress of 50 KPa between the HDPE geomembrane samples that are subjected to loading of 50 KPa for 7 days i.e. SGC , SGR and SS were 27.2, 25.7 and 27.3 KPa respectively. The increase in shear stress of SGC was due to the effect of creep. It is known that due to the viscoelastic nature of geomembrane, application of normal load for a 7 days allowed sand particles to penetrate into the surface of HDPE geomembrane. Thus the contact area between sand particles and HDPE geomembrane will increase and shear stress will increase as well. (Bilgin, 2011)



(a)



(b)



(C)

Figure 4.5: Interface shear stress at normal stress of 50 KPa (a). SS, (B) SGR, (c) SGC.

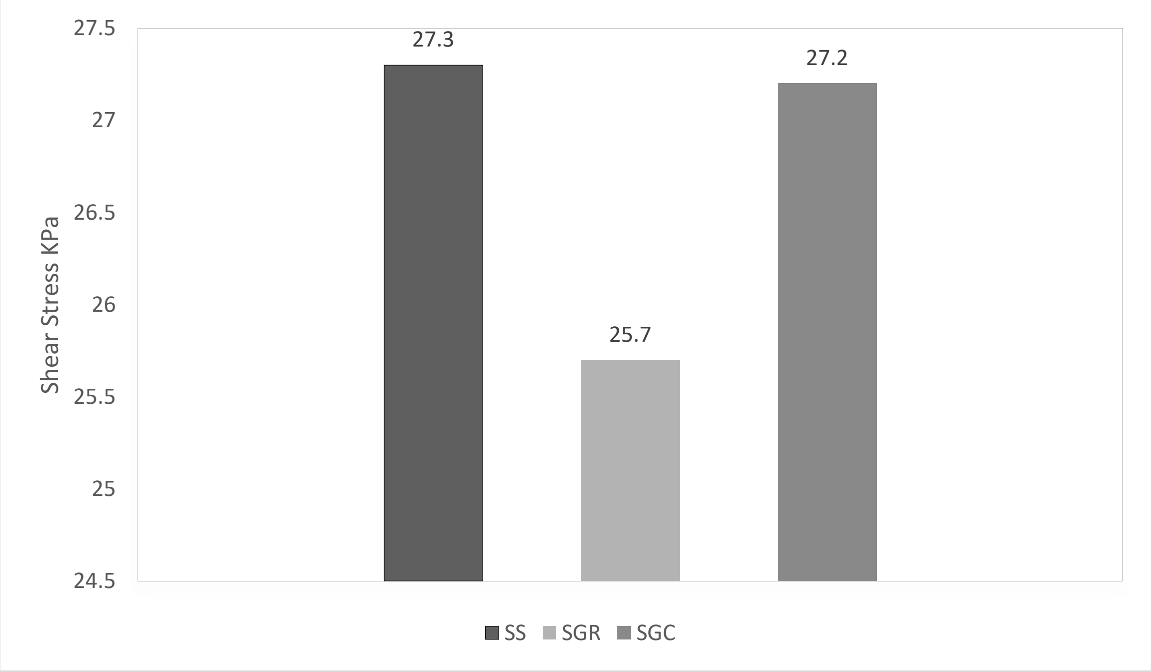


Figure 4.6: Comparison of interface shear stress at normal stress of 50 KPa between SSR, SGR & SGC

Chapter 5

5. Conclusions & Recommendations

The present study addresses the effect of temperature cycling and creep on interface shear strength of HDPE geomembrane and Tharparkar sand. The effect of temperature and creep should be considered in design of slope landfill structures. The conclusion drawn are discussed in the section below.

5.1. Conclusions:

Geomembranes are broadly utilized within the geotechnical, environmental, hydraulic, and transportation sectors as barrier layers with low permeability. The shear strength of the soil geomembrane interface is critical to the proper design of the side slopes of the geomembrane lining of landfills, reservoirs and canals. Geomembranes are viscoelastic material that has temperature and time dependent properties. The interface between the Geomembrane and soils is somewhat weak and thus constitutes critical failure planes. Due to the critical failure planes between the Geomembrane and soils in slopes of landfills, it is very important to obtain the interface strength properties accurately in order to have safe and sustainable design. Considering the viscoelastic behavior of geomembrane, effect of temperature cycling, and creep was determined using direct shear testing. following conclusion have been drawn from the study:

1. The interface friction angles obtained from direct shear test using HDPE geomembrane samples that are subjected to heated temperature of 50 C are less than HDPE samples that are tested without subjection to temperature.
2. The interface friction angles obtained from direct shear test using HDPE geomembrane samples that are subjected to cooled temperature of 5 C are approximately equal to HDPE samples that were tested without subjection to temperature.
3. It is noted that with the increase in number of cycles, the interface friction angle tends to decrease.

4. Considering all the direct shear test performed, the results shows that there was increase of approximately 5.5 % of friction angle after 7 days of sustained loading of 50 KPa at sand geomembrane interface.

5.2. Recommendations

For future studies, HDPE geomembrane of having different thickness can be studies on different loads and temperature for more than three cycles. This would help in determining the detailed behavior of geomembrane. The temperature controlled direct shear testing should be used to stimulate the actual field condition in lab and for close monitoring of effect of temperature on interface friction angle during the test. In addition, effect of cyclic loading and temperature on chemical and physical properties of geomembrane should be studied in detail to for better understanding of behavior of interface friction angle.

Chapter. 6

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