A mini project report on

"GEOSYNTHETIC CLAY LINERS: AN OVERVIEW OF CURRENT RESEARCH, TRENDS AND INNOVATIONS"

Submitted in Partial Fulfillment of the Requirement for the Award of the Degree of

MASTER OF TECHNOLOGY

In

CIVIL ENGINEERING

(*With specialization in Geotechnical Engineering***)**

of

Assam Science & Technology
University Session: 2023-2025

By

MAUSOM KALITA

Roll No. PG/C/23/08

ASTU Reg No. 230620062006

Under the guidance of

Dr. MALAYA CHETIA

PROFESSOR

DEPARTMENT OF CIVIL ENGINEERING
ASSAM ENGINEERING COLLEGE
JALUKBARI, GUWAHATI

CERTIFICATE OF SUPERVISION

This is to certify that the work presented in this report entitled **— “GEOSYNTHETIC CLAY LINERS: AN OVERVIEW OF CURRENT RESEARCH, TRENDS AND INNOVATIONS”** is carried out by Mausom Kalita, Roll No: PG/C/23/08, a student of M.Tech 3rd semester, Department of Civil Engineering, Assam Engineering College, under my guidance and supervision and submitted in the partial fulfillment of the requirement for the award of the Degree of Master of Technology in Civil Engineering with specialization in Geotechnical Engineering under Assam Science and Technology University.

Date:

Place:

Dr. MALAYA CHETIA

Professor, Department of Civil Engineering,

Assam Engineering College,

Jalukbari, Guwahati-781013

CERTIFICATE FROM HEAD OF THE DEPARTMENT

This is to certify that the mini project report entitled **"GEOSYNTHETIC CLAY LINERS: AN OVERVIEW OF CURRENT RESEARCH, TRENDS AND INNOVATIONS"** has been submitted by Mausom Kalita, Roll No: PG/C/23/08, a student of M.Tech 3rd Semester, Geotechnical Engineering (Civil Engineering), Assam Engineering College, in partial fulfillment of the requirements for the award of the degree of Master of Technology in Geotechnical Engineering of Assam Science & Technology University.

Date :

Place :

DR. JAYANTA PATHAK

Professor and Head of Department

Department of Civil Engineering

Assam Engineering College, Guwahati – 781013

DECLARATION

I hereby declare that the mini project "**GEOSYNTHETIC CLAY LINERS: AN OVERVIEW OF CURRENT RESEARCH, TRENDS AND INNOVATIONS**" in partial fulfillment of the requirement for the award of the degree of " MASTER OF TECHNOLOGY" in Civil Engineering (With specialization in Geotechnical Engineering), submitted in the Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13 under Assam Science & Technology University, is a real record of the work carried out in the said college for six months under the supervision of Dr, Malaya Chetia, Professor, Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13. Do hereby declare that this project report is solemnly done by me and is my effort and that no part of it has been plagiarized without citation.

Date : MAUSOM KALITA

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Date: Dr. MALAYA CHETIA

Professor, Department of Civil Engineering

Assam Engineering College, Jalukbari, Ghy-13

ACKNOWLEDGEMENT

I would like to express my sincere appreciation to my supervisor Dr. Malaya Cheta, Professor, Department of Civil Engineering of Assam Engineering College for his extensive support and encouragement throughout the project work. I am highly indebted for her guidance and constant supervision as well as for providing necessary information regarding the project work. Working under her has indeed been a great experience and inspiration for me.

This project would not have been possible without the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

I express my gratitude to Dr. Jayanta Pathak, Professor and Head of Department of Civil Engineering, Assam Engineering College and also towards the entire fraternity of the Department of Civil Engineering, Assam Engineering College.

Date:

Place:

MAUSOM KALITA

M.Tech, 3rd Semester

Geotechnical Engineering

Department of Civil Engineering

Assam Engineering College, Jalukbari, Ghy-13

ABSTRACT

Geosynthetic clay liners (GCLs) are advanced hydraulic barriers manufactured to prevent fluid movement and are often utilized in landfill applications and other containment systems. These liners are smaller in thickness and more efficient in terms of installation and manufacturing, which makes them extremely relevant in the current construction market. Proper quality assurance and control are crucial for GCLs which are dependent on many aspects such as material, bonding type, shear strength, chemical compatibility etc. This study purports to critically review the existing literature to report the current research, trends and innovations in the fields of GCLs. This review is divided into three sections. The first section documents the current overview of GCLs, the second section deals with the chemical compatibility of GCLs. Lastly, the third section presents an overview of shear strength and stability studies in the present literature. The overview of GCLs presents the advantages of GCLs over traditional compacted clay liners (CCLs), manufacturing methods and materials. The chemical compatibility chapter discusses the compatibility of chemicals present in leachate for the GCL and their transport mechanism. The shear strength and stability part discusses the factors influencing the Shear properties of GCLs and stability aspect of installation of GCLs.

Table of Content

List of figures

List of tables

Chapter 1

Introduction

1.1. Introduction:

Geosynthetic Clay Liners (GCLs) are sophisticated composite materials commonly employed in environmental and civil engineering projects, especially for waste management and containment systems. These liners are constructed by sandwiching a layer of bentonite clay between two geosynthetic sheets, which are typically composed of geotextiles or geomembranes. These outer layers perform both structural and functional roles in the liner system.

GCLs have their roots in 1962, when Arthur G. Clem filed a patent application for prefabricated moisture-impervious panels that fused corrugated paperboard and bentonite clay.[2] Arthur J. Clem applied for a patent in 1982 for what is now known as a GCL, which was a combination of geotextile, adhesive, and bentonite clay.[3] Arthur J. Clem founded Clem Environmental Corp. that same year in order to start manufacturing his innovation.[4] GCLs, as a distinct class of geosynthetics, seem to have been used as a geomembrane backup in solid waste containment in the United States in 1988.In order to attach the clay between two geotextiles—one above (the cover textile) and one below (the carrier textile)—the product was called Claymax, which is bentonite combined with an adhesive. Around the same period, Bentofix, a distinct product made in Germany, was created by sandwiching bentonite powder between two geotextiles and then joining the three components with a needle punch. Shear strength, a crucial characteristic for installation on slopes, was provided by the

Engineering function of geosynthetic clay liner is to act as a hydraulic barrier for water or some other liquid, leachate or sometimes other gases. They are used as a replacement of either compacted clay liner or geomembrane. These three materials can be used as a composite manner to augment the traditional liners.

Geosynthetic clay liner is an efficient lining material in terms of cost efficiency and ease of installation and better quality control and assurance compared to traditional lining materials available. Average thickness of GCL is 7mm and provides better protecting against wet/dry and freeze thaw cycles. GCLs offer equivalent or lower rates of release of fluids and chemicals than Compacted Clay Liners (CCLs).

Compared to traditional lining systems, GCL technology enables installation on steeper slopes (sometimes up to 2H:1V or greater). This capability removes the need to create two impoundments with level slopes, which shortens the facility's operating life by reducing the containment capacity.

1.2. Motivations of study:

GCLs are composite materials widely used in containment applications, where their unique properties play a vital role in modern engineering practices. GCLs create reliable barriers that prevent the migration of contaminants through soil and groundwater. GCLs exhibit low hydraulic conductivity due to the swelling properties of sodium bentonite, creating a highly effective waterproof barrier. This functionality reduces the need for traditional clay liners and offers a more lightweight and flexible alternative.

Another motivation stems from the advancements in materials science that improve GCL performance. Innovations such as polymer-modified bentonites are being developed to enhance the GCL's chemical resistance and hydraulic performance when facing aggressive leachates. New GCL characteristic and performance improvement is being researched worldwide. Worldwide a many research in going on in this field.

The objective of this study is to review the current trends and research in the field of installation, materials and design of GCLs.

Chapter 2

Literature Review

(Herlin & Von Maubeuge, 2002)	Geosynthetic Clay Liners (GCLs) are a sealing product used in landfills, fuel storage facilities, dams, canals, rivers, and lakes. Made of high swelling sodium bentonite sandwiched between geotextiles, GCLs offer low hydraulic conductivity, volume advantages, and reduced construction costs. They are used in various sectors of the environmental industry, protecting groundwater and the environment.
Kong et al. (2017)	This paper provides an overview of modern geosynthetic clay liner (GCL) in landfills, discussing its performance, critical properties, and future research perspectives, offering a comprehensive overview of GCLs.
Petrov and Rowe (1997)	The study examines the effects of permeant, static confining stress, hydrating medium, and degree of bentonite hydration on geosynthetic clay liner (GCL) tests. Results show that higher salt concentrations in the hydrating fluid increase hydraulic conductivity. GCLs permeated with 0.6 and 2.0 M NaCl solutions were more permeable than those initially hydrated with water. The study also highlights the importance of maximizing overburden stress before GCL hydration.
Lake (2000)	The type of manufacturing process for Geosynthetic Clay Liners (GCLs) can affect the final bulk ion ratio of a GCL produced after heating. The hydrostatic conductivity is related to the diffusion coefficients, and a constant stress applied to the sample mitigates increases in diffusion coefficients. The bentonite component of GCL and various bentonite additives can improve sorption. A field study examined the performance of a geomrmbrane-i Ghl) cornpacted clag (CCL) composite liner for a landfill leachate lagoon, finding that the GM component did not perform well as a barrier.
Lee and Shackelford (2005)	The study evaluates hydraulic conductivity of two geosynthetic clay liners (GCLs) with different bentonite

	qualities. GCL-HQB has higher sodium montmorillonite, plasticity index, and cation exchange capacity compared to GCL-LQB. However, GCL-HQB's conductivity is lower when permeated with CaCl2 solutions, making it more susceptible to chemical attack.
Marr et al. (n.d.)	his paper provides guidance to design stable slopes using Geosynthetic Clay Liners (GCLs) in liners or co- vers for the varying combinations of conditions that may develop due to the shape of the containment facility
Sawada et al. (2019)	This study compares seismic performance of earth dams with and without geosynthetic clay liners (GCLs). The panel is installed parallel to the dam's slope, reducing the risk of a weak plane. The benched installation method showed half the same seismic deformation.
Daniel et al. (1998)	Field test plots with geosynthetic clay liners (GeLs) were constructed to assess slope stability, despite slide incidents in two plots and one in unreinforced GeL components.
Suzuki et al. (2017)	This study investigates the properties of geosynthetic clay liners (GCLs) used for widening embankments and minimizing water leakage. Results show that the shear strength of the interface between soil and geotextiles varies based on soil type, geotextile type, and submergence period. GCLs have minimal influence on embankment instability.

Chaptet 3

Overview of GCLs

3.1. General Overview of GCLs:

Research on geosynthetic clay liners (GCLs) has grown rapidly in recent decades, with numerous laboratory investigations and field tests examining their hydraulic conductivity, chemical compatibility, water-swelling and self-healing capacity, diffusion, gas migration, and shear strength. These properties are affected by various factors, such as structural types, permeant solution, hydration condition, confining pressure, and environmental factors. It is crucial to assess GCL properties on a site-specific basis. GCLs are widely used in landfills and other geotechnical applications, but they can face problems in complicated environments like moisture-cycles, freeze-thaw cycles, thermal cycles, and long-term exposure to solar radiation. Polymer-treated technology has shown potential for future GCL applications, as the addition of superabsorbent polymers can improve hydraulic performance and self-healing capacity. Further study is needed on the microstructure and macro behaviors of polymer-bentonite composites.

3.2. Advantages of geosynthetic clay lines over compacted clay liners:

Geosynthetic clay liners are in many cases advantageous than compacted clay liners. Although GCLs requires experienced quality control on site, CCLs are highly labour intensive. for large construction advantages GCLs are far advantageous than CCLs since material cost and transport is more efficient in case of GCLs due to low thickness than CCLs. GCLs also shows self healing properties.

Table-1 difference in GCLs and CCLs(source: Herlin, B., & Von Maubeuge, K. (2002))

Characteristics	GCLs	CCLs
Materials	Bentonites, adhesives, geotextiles and geomembranes	Native soils, bentonite admixs
Thickness	About 7 mm	Typically 300mm to 900mm
Hydraulic conductivity	About 10^{-9} cm/sec	About 10^{-7} cm/sec
Construction deployment	Rapid and simple installation	Slow and complicated process of construction
Regarding manufacturing quality control	Relatively simple, straight forward common sense procedure	Complex quality control and assurance procedures requiring detailed knowledge of clay soils and moisture compaction relation
Vulnerability to damage due to desiccation	When dry no concern but when wet desiccation may occur but self heal when rewetting	CCLs are nearly saturated and can desiccate during construction, upon rewetting there is little self healing occurs.
Avalibility of materials	Materials can be easily shipped to and location	Suitable materials not always available, may require extensive transportation.
Typical installed cost	Approx. 10$ per sq. meter for large site	Highly variable, can go upto 50$ in large constructions.
Experience	Began its use in 1986	Been in use for long time

3.3. Materials and Manufacture of GCLs:

GCLs comprises of a layer of bentonite sandwiched between two layers of geotextile or geomembrane. The thickness of GCLs is typically 5 to 12 mm. Geotextile is needlepuched(NP) through the bentonite layer. According to the geosynthetics adopted, GCL is divided into two categories, (i) GT-GCL (geotextile encased GCL) and (ii) GM-GCL (geomembrane supported GCL).

Geo-textile(GT):

Geotextiles are permeable fabrics consisting mainly of materials such as polypropylene and polyester. Depending on their manufacturing method, they may be woven or non woven, based upon the type of application they are intended for. Woven and non woven fabrics have different production methods. While non woven geotextile fabrics comprise fibres, filaments or other elements that are joined together randomly, in the case of woven fabrics, these yarns, fibres or filaments are intertwined.

Figure 1: Geotextile sheet (source: https://texdelta.com/en/blog/geotextile-fabric-uses-and-applications/)

Bentonite Powder:

Bentonite is a very soft plastic clay consisting predominantly of montmorillonite, a fine particle-sized hydrous aluminum silicate and member of the smectite group. Most bentonites are formed by the alteration of volcanic ash and rocks after intense contact with water. Bentonite presents strong colloidal properties and increases its volume several times when coming into contact with water, creating a gelatinous and viscous substance. Its specific properties include swelling, water absorption, viscosity, and thixotropy. sodium bentonite is commonly used for GCLs because of their low permeability and high swelling potential.

Geo-membrane:

A geomembrane is an extremely low-permeability synthetic membrane liner or barrier that can be used with any geotechnical-related material to control fluid (liquid or gas) migration in man-made projects, structures or systems. Geomembranes are made from relatively thin, continuous polymer sheets, but they can also be made by impregnating geotextiles with asphalt, elastomers or polymer sprays, or as multi-layer asphalt geocomposites. Continuous polymer sheet geomembranes are by far the most common. Geomembranes are synthetic materials made from flexible polymer sheets. They are typically made from materials such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP) or polyvinyl chloride (PVC).

Figure 2:Geo-membrane (source: https://www.bpmgeosynthetics.com/wp-content/uploads/2023/12/BPM-Geomembrane-Liner.jpg)

Needle-puncing (NP):

Because of the intricate tangling of the geotextile fibers, needlepunching—the most popular technique for creating nonwoven geotextiles—produces a mat with exceptional strength. However, a subsequent needlepunching procedure that extracts fibers from the top nonwoven geotextile and embeds them in the carrier geotextile is used to create needlepunched GCLs. In addition to creating a link between the two geotextiles, this procedure fixes the bentonite in place permanently, preventing it from moving within the GCL's plane during installation and as operational conditions alter.

While needlepunched staple fiber nonwovens are utilized for the cover layer, the carrier layer can be any geosynthetic that enables the fibers from the cover layer to be anchored via needlepunching, such as a woven, nonwoven, or nonwoven reinforced with woven scrim. To secure the bentonite in place and reinforce the otherwise weak (when hydrated) layer of clay, the geosynthetics are needlepunched together through its thickness.

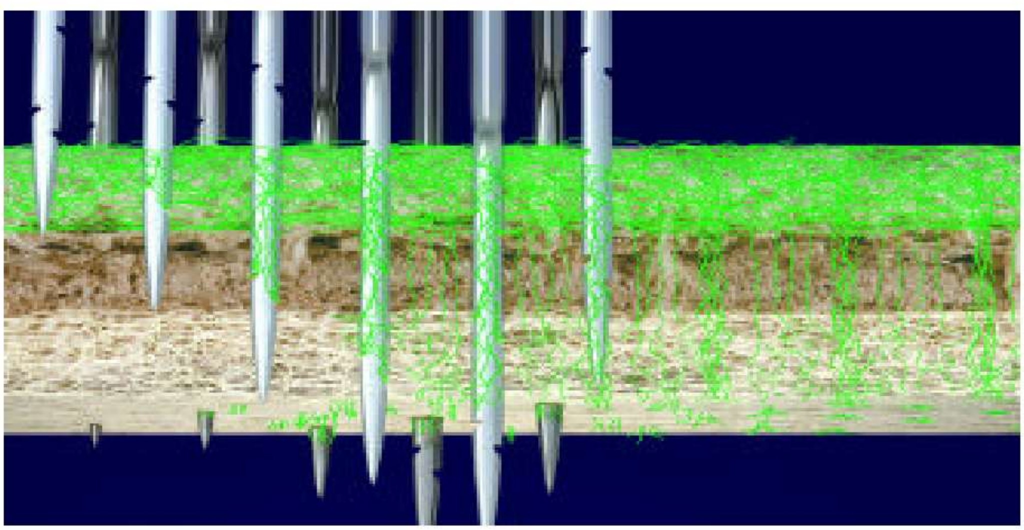


Figure 3: Needle punching in geosynthetic clay liner (source: Herlin and Von Maubeuge (2002))

3.4.Applications of geo-synthetic clay liner:

For landfill liners:

Geosynthetic clay liners (GCLs) are widely recognized as effective materials used in landfill applications, primarily for their impermeability and engineering properties. The primary purpose of GCLs is to control leachate flow, ensuring that toxic substances do not infiltrate groundwater sources. By effectively minimizing permeability, GCLs are essential in managing the risks associated with waste containment. Leachate is a liquid that results from the decomposition of waste and can contain a variety of toxic compounds, making its containment critical to environmental protection.

The figure below shows the use of GCL in landfill construction.

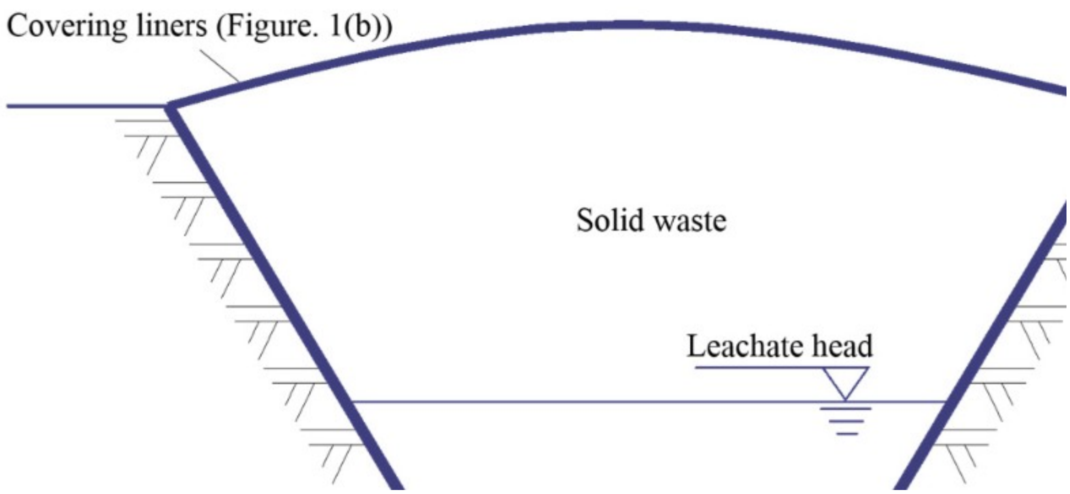


Figure-4(a) use of GCL in landfill structure

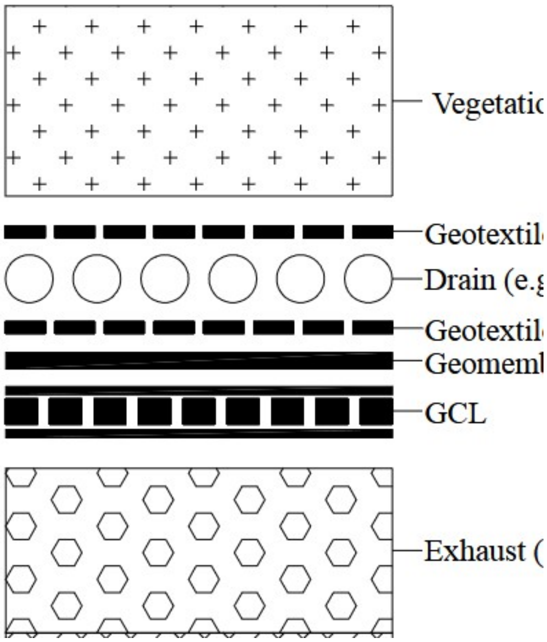


Figure-4(b) GCL in covering liner

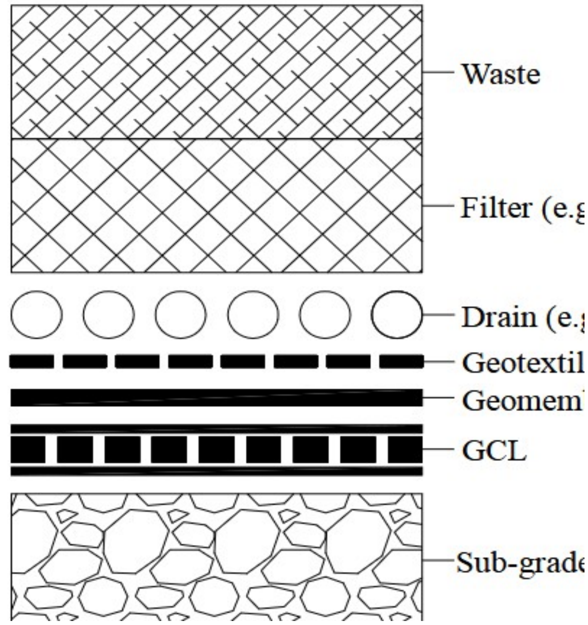


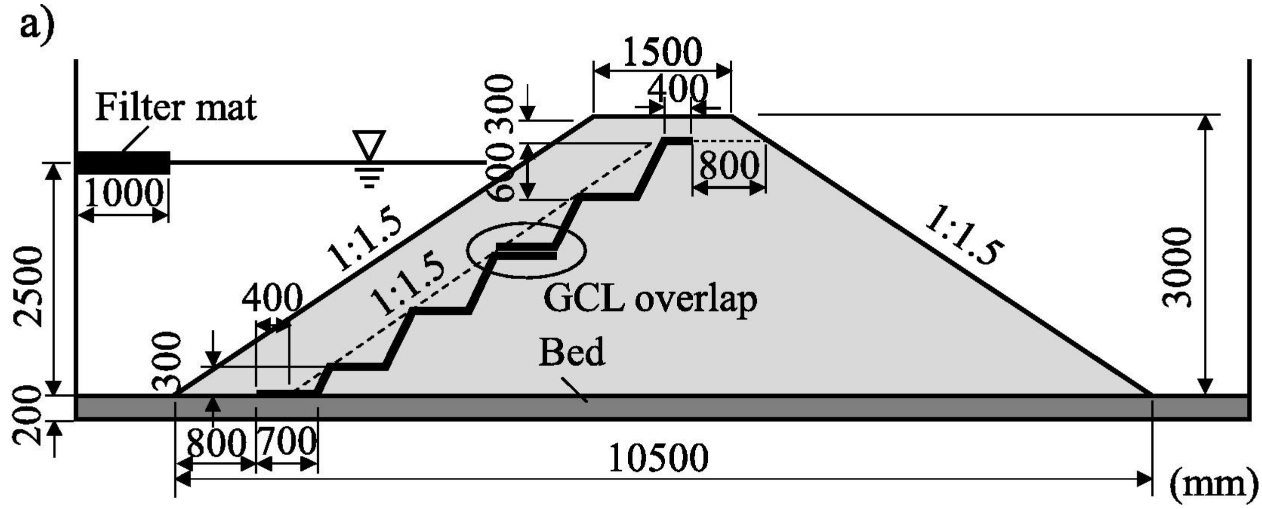
figure-4(c) GCL in bottom liners

Image source: State-Of-The-Art Review of Geosynthetic Clay Liners (Kong et al. (2017))

Roles of GCLs in Dam Engineering:

The primary function of geosynthetic clay liners in dams is to provide an impermeable barrier that prevents water seepage through the dam structure. This is particularly important in earthen and rock-fill dams, where controlling water flow is critical to ensure structural integrity and prevent erosion. GCLs help control seepage flow by minimizing the potential for hydraulic failures, enhancing the overall stability of the dam.

Geosynthetic clay liners (GCLs), used to repair small earth dams, are typically installed with the GCL panel placed parallel to the upstream slope of the dam or on the surface of benches cut into the upstream side of the earth dam fill. While the former requires less earthwork, leading to a more cost-effective and rapid construction, it can potentially introduce a plane of weakness if the interface shear strength between the GCL and the cover soil is less than the shear strength of the cover soil. The inclusion of benches in the upstream slope of an earth dam can potentially be an effective strategy for reducing the significance of this preferential failure plane, resulting in an increased seismic performance during earthquakes.



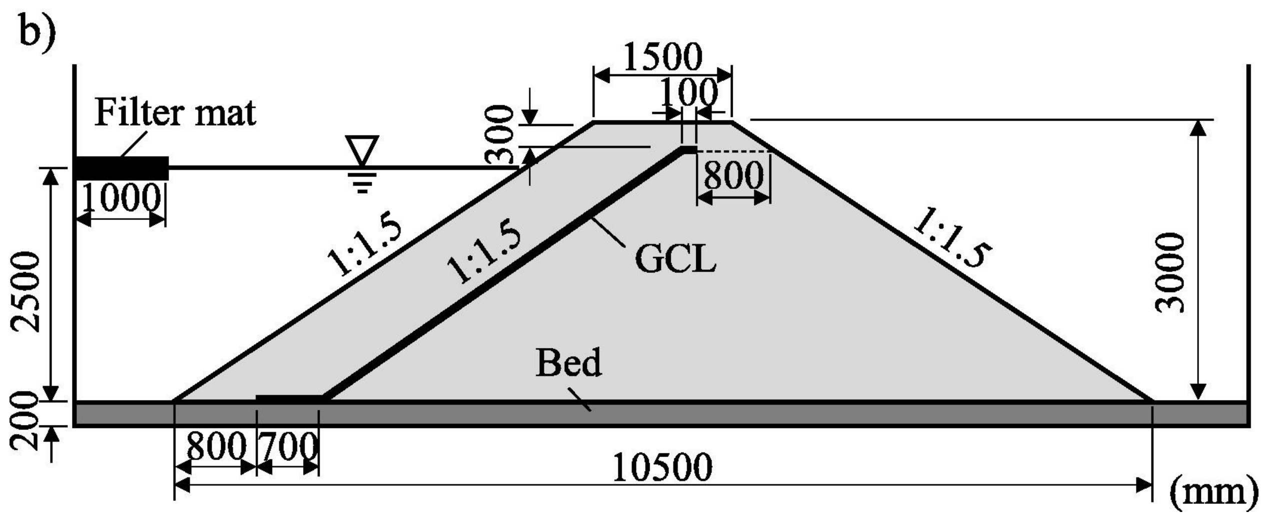


Figure 5: GCLs in earth dam on upstream side. (a) with bench cut, (b) without bench cuts (image source: Sawada et al. (2019))

Use of GCLs in embankment:

Geosynthetic clay liners (GCLs) are used in embankments to widen them and to reduce water leakage. GCLs are also used in other construction projects to control water movement and contamination.

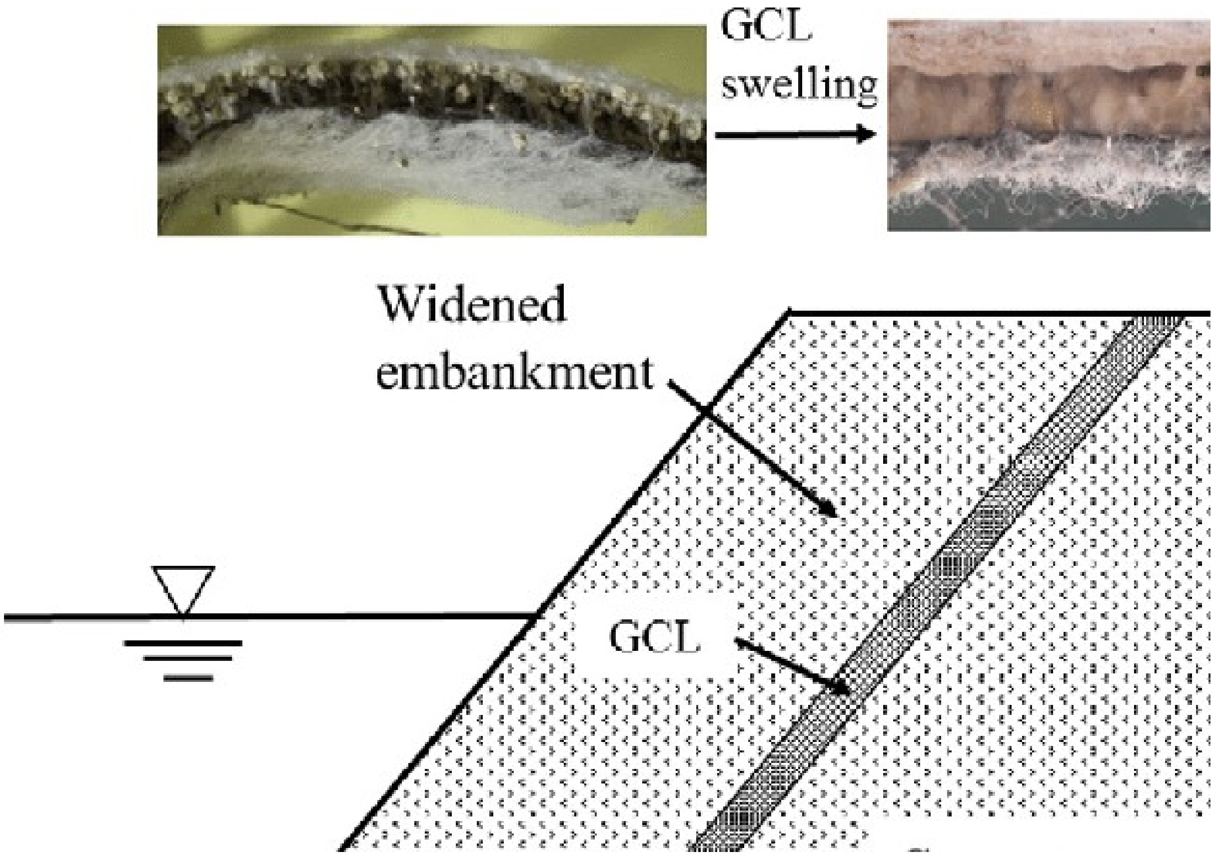


Figure 6: use of GCL in widening of embankment (image source: Suzuki et al. (2017))

Chapter 4

Chemical Compatibility of GCLs

4.1. Chemical compatibility of GCLs by hydraulic conductivity testing and factors affecting its performance (Petrov & Rowe, 1997):

Petrov & Rowe in 1997 performed an extensive series of laboratory tests on a needle-punched geosynthetic clay liner including 1D confined swelling test and index tests and hydraulic conductivity tests. The conclusion they drawn upon result of these tests are:

Effect of concentration of permeant solution on hydraulic conductivity of GCL:

Water-hydrated GCLs exposed to aqueous saline solutions showed significant increases in hydraulic conductivity, ranging from negligible to significant. The increase was attributed to increased double-layer and c-axis contraction and a more open-structured, flocculated soil fabric, which increased the effective pore space and hydraulic conductivity.

The hydraulic conductivity decreased as the confining tension increased and varied by roughly one order to one and a half orders of magnitude for a given salt content. Differences in void ratios led to a significant variation in hydraulic conductivity values, with GCLs with lower void ratios showing a smaller effective pore space for permeant migration.

Higher concentrations of NaCl solutions in GCL resulted in smaller final void ratios, but this did not compensate for increased double-layer and c-axis contraction, causing hydraulic conductivity to increase by 280 to 420. Conversely, an increase in confining stress from 3 to 110 kPa decreased hydraulic conductivity by an order of magnitude due to a significant reduction in void ratio.The study found that incremental confining stresses can reduce hydraulic conductivity in water-hydrated GCL permeated with NaCl solutions. Higher confining stresses were needed for higher salt concentrations to effectively heal the GCL and achieve a similar conductivity value.

Impact of hydration on hydraulic conductivity:

The impact of hydrating medium on hydraulic conductivity depends on NaCl concentration in solution. For optimal hydraulic properties, GCLs should be well hydrated with fresh water before exposure. The highly flocculated clay fabric with salt solutions had larger hydraulic conductivity values. However, the hydrating fluid was less critical for permeation of lower NaCl concentrations. The lower void ratio of saltwater hydrated GCL produced similar conductivities regardless of the hydration medium.

Prehydration confinement of GCLs before bentonite hydration resulted in lower void ratios and hydraulic conductivity values, up to 3.3 times smaller than posthydration confinement, indicating the significant hydraulic benefits of maximizing overburden before bentonite hydration.

Hydraulic conductivity is influenced by three factors: the GCL void ratio, the permeant salt solution concentration, and the initial clay fabric. Increases in hydraulic conductivity occur for GCLs hydrated with salt solutions and salt concentration. Index tests can estimate compatibility with smectitic-rich soil, but should not replace hydraulic conductivity testing.

A synthetic MSW leachate produced hydraulic conductivity values similar to NaCl concentrations at constant confining stress and void ratio. Index tests suggested a degree of impact similar to NaCl concentrations. Initial hydrating medium did not influence conductivity values at 33 kPa confining pressure, suggesting no potential benefits of a water-hydrated bentonite core. Hydration with water is preferred. More work is needed to evaluate leachates with different chemical constituents and concentrations and the potential benefits of biologically active MSW leachate.

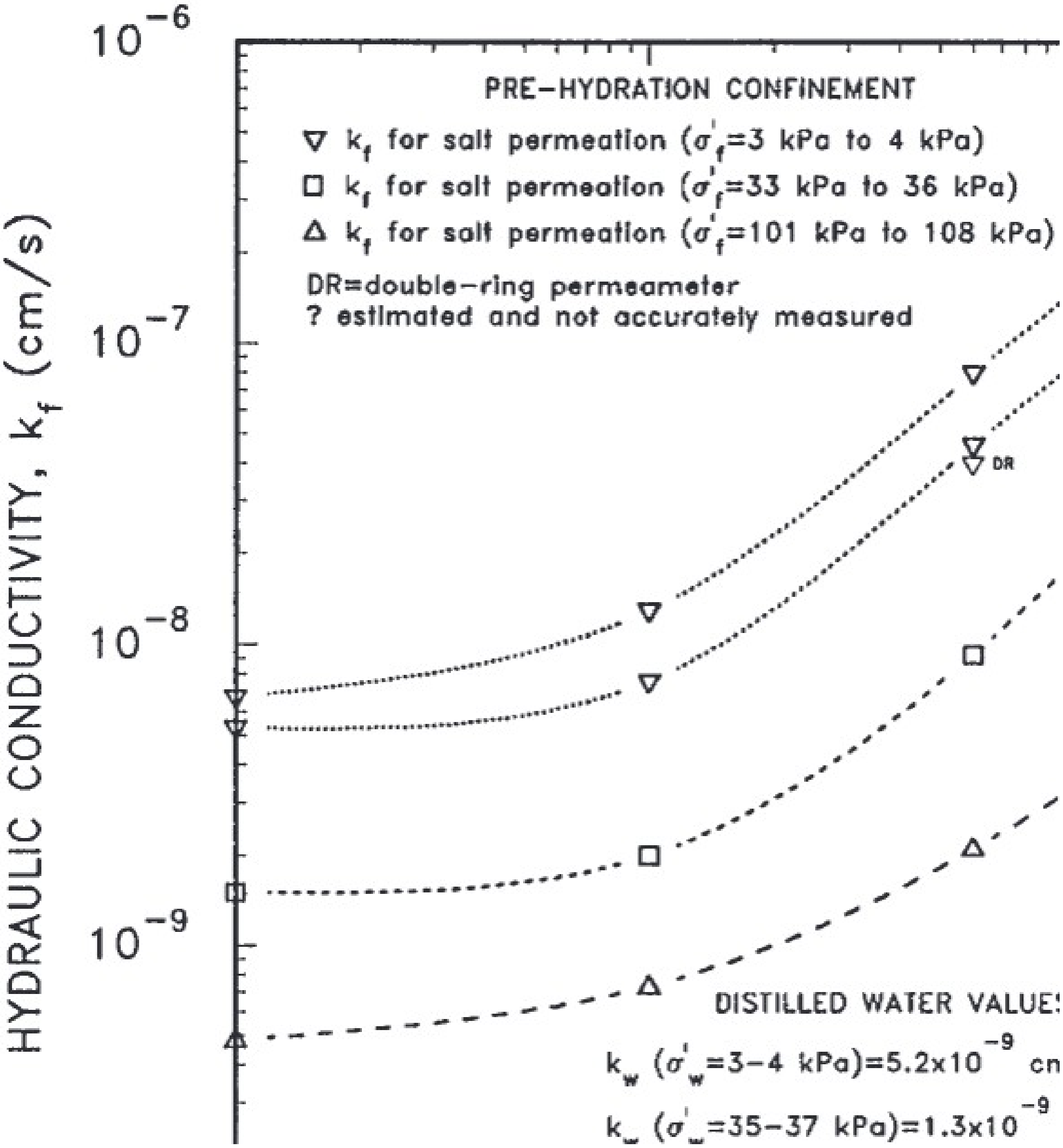


Figure-7(a) Hydraulic conductivity versus NaCl concentration for sequential permeation of varying concentrations of aqueous NaCl solutions at three confining stresses at prehydration confinement. (image source: Petrov and Rowe (1997))

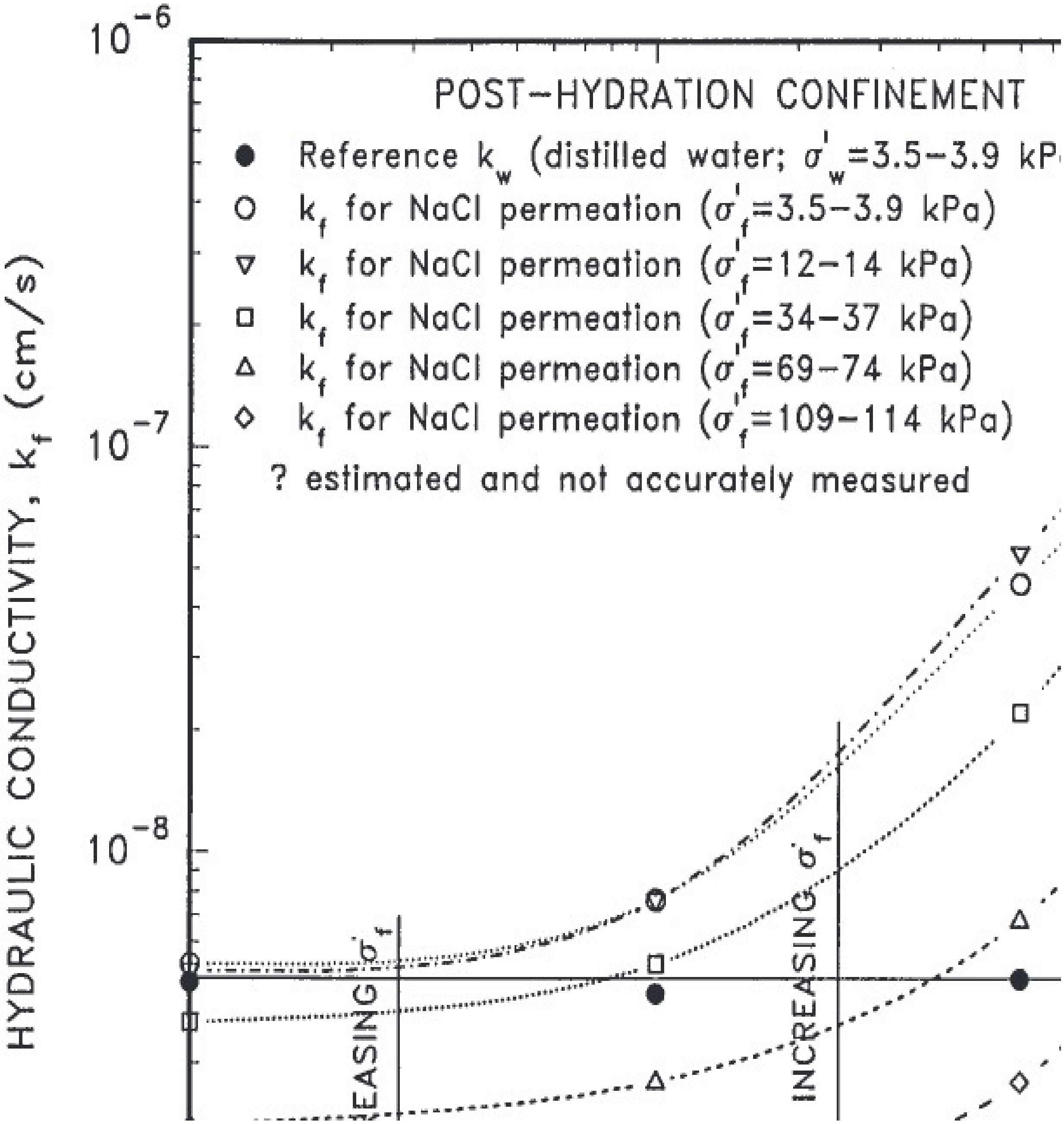


Figure-7(b) The effect of posthydration confinement on the hydraulic conductivity for sequential permeation of varying concentrations of NaCl solutions (Petrov and Rowe (1997))

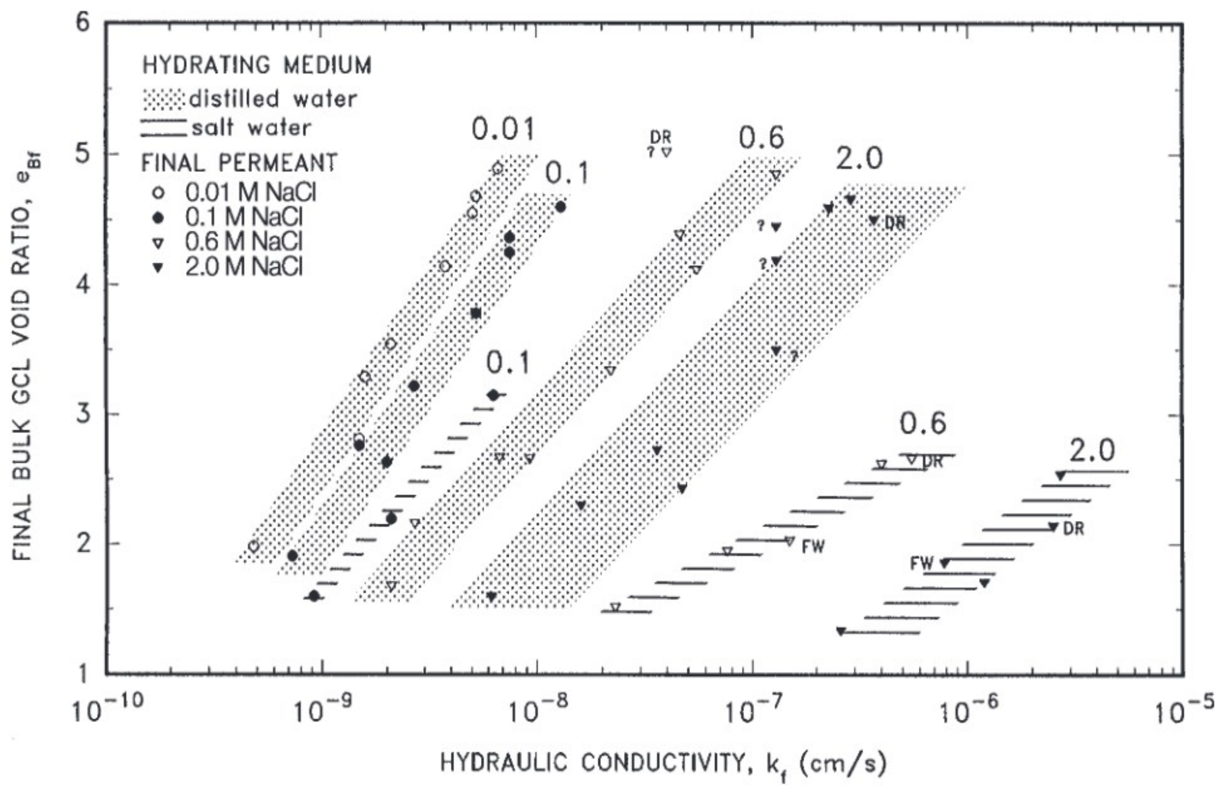


figure 8: Final bulk void ratio versus hydraulic conductivity for permeation of varying concentrations of aqueous NaCl solutions
(SOURCE: Petrov, R. J., & Rowe, R. K. (1997))

4.2. Swelling characteristics of needle-punched thermally treated GCLs (Lake 2000):

(Lake, 2000) shows that at low confining stresses, the GCL with powdered bentonite in the cover geotextile has a high contrast between the void ratio of the surface bentonite and that in the core, which is needle-punched between the core and carrier geotextile.

The study found that needle-punched GCLs swell to similar bulk GCL void ratios at confining stresses above 100 kPa. The type of GCL manufacturing process has a smaller effect on the bulk GCL void ratio when the stress is higher. Thermally treated fibers appear to be more effective at restricting GCL swell height, regardless of stress level. Diffusion tests showed that thermally treated needle-punched GCLs swell to a much lower bulk CGL void and exhibit a lower diffusion coefficient under free swell conditions. Thus, thermally treated needle-punched fibres are more effective in controlling GCL swelling at low confining stresses. (Lake, 2000)

4.3. Contaminant migration through GCLs (Lake, 2000):

Lake, 2000 found in his study that diffusion coefficient of Na^+ (K_d = 0.2 mg/L) is 4.0 x 10^{-10} m^2/s and that for chloride to be 7.0 x 10^{-10} m^2/s. The potassium diffusion coefficient (7.0 x 10^{-10} m^2/s) is within the established range, but the sorption of potassium to the soil in the municipal solid waste leachate tested is relatively high and non-linear.

4.4. Impact of bentonite quality on hydraulic conductivity of geosynthetic clay liner (Lee and Shackelford (2005)):

In this study, The GCL withthe higher quality bentonite (GCL-HQB) is characterized by a greater content of sodium montmorillonite (86 versus 77%), a higher plasticity index (548 versus 393%), and a higher cation exchange capacity (93 versus 64 meq/ 100 g) relative to the GCL with the lower quality bentonite (GCL-LQB). As the permeant liquid, $CaCl_2$ solution of 5 to 500 mM is used.

The hydraulic conductivity of GCL-HQB is lower than GCL-LQB based on ASTM D5084 criteria. However, when specimens are permeated with $CaCl_2$ solutions, the hydraulic conductivity increases as the $CaCl_2$ concentration increases for both GCL specimens. GCL-HQB's hydraulic conductivity values are always higher than

GCL-LQB. The ratios of hydraulic conductivity for GCL-HQB relative to GCL-LQB range from 2.0 to 2.6 for specimens permeated with 5, 10, and 20 mM CaCl 2 solutions, and from about 230, 100, and, 40 for specimens permeated with 50, 100, and 500 mM $CaCl_2$ solutions, respectively.

The higher bentonite quality of GCL-HQB increases its susceptibility to chemical attack upon permeation with $CaCl_2$ solutions. In terms of the time required to achieve chemical equilibrium, specimens permeated with GCL-HQB require longer test durations than GCL-LQB, while shorter test durations are required for GCL-HQB. The pore volume for flow (PVF) required to achieve chemical equilibrium are less dependent on the bentonite quality for the GCLs used in this study. Therefore, the quality of the bentonite in the GCL affects not only the hydraulic conductivity but also the time and PVF required to achieve chemical equilibrium.

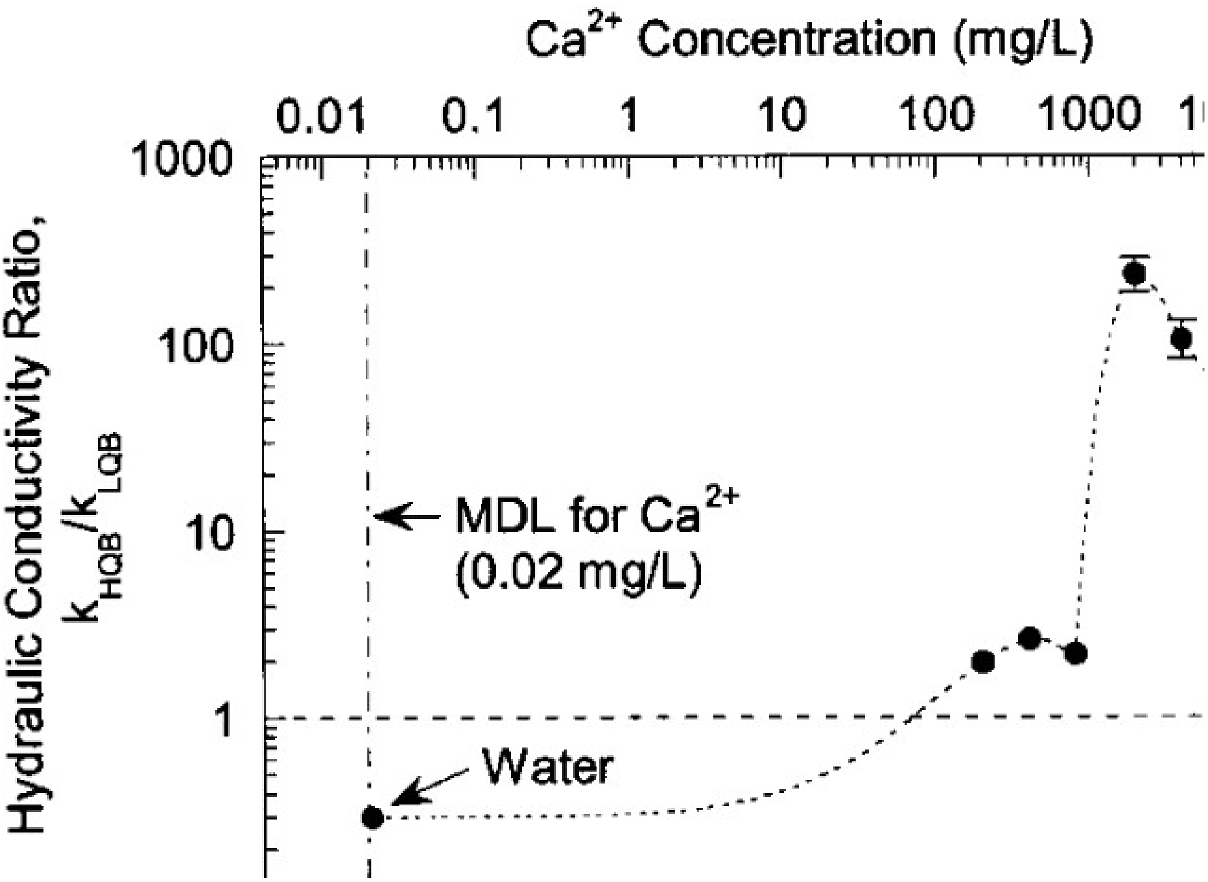


figure 9: hydraulic conductivity ratio (HQ to LQ bentonite) vs $CaCl_2$ concentration in permeant (source: Lee and Shackelford (2005))

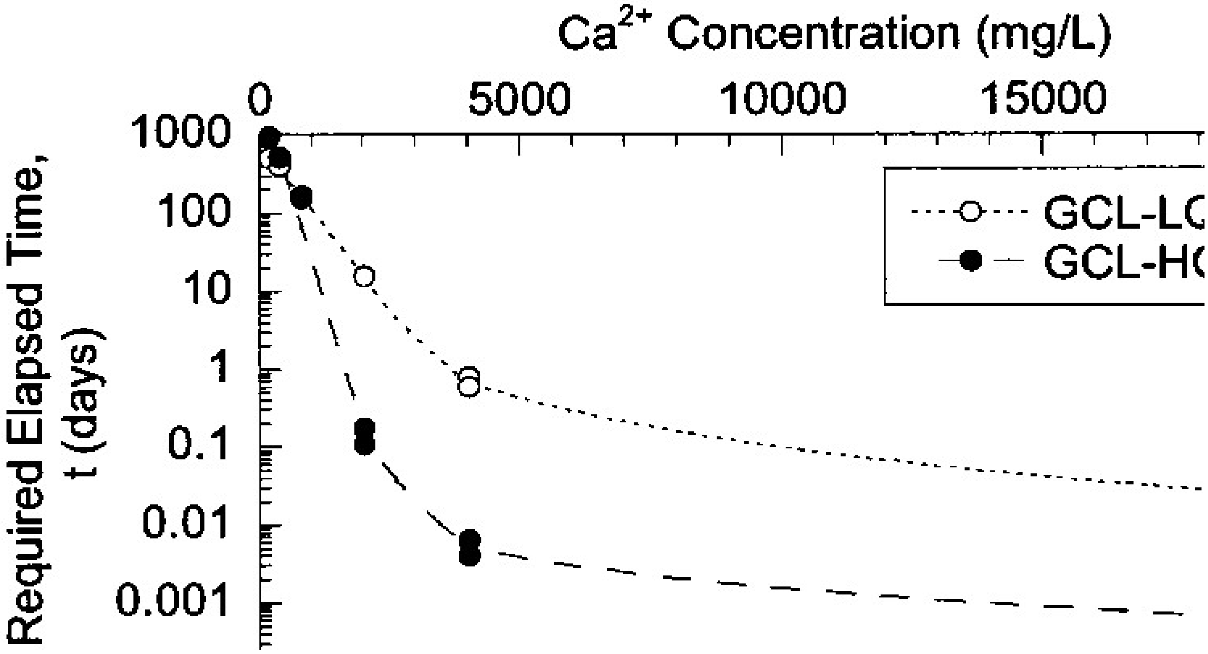


figure 11: plots for elapsed time to achieve chemical equilibrium between influent and effluent vs $CaCl_2$ concentration (source: Lee and Shackelford (2005))

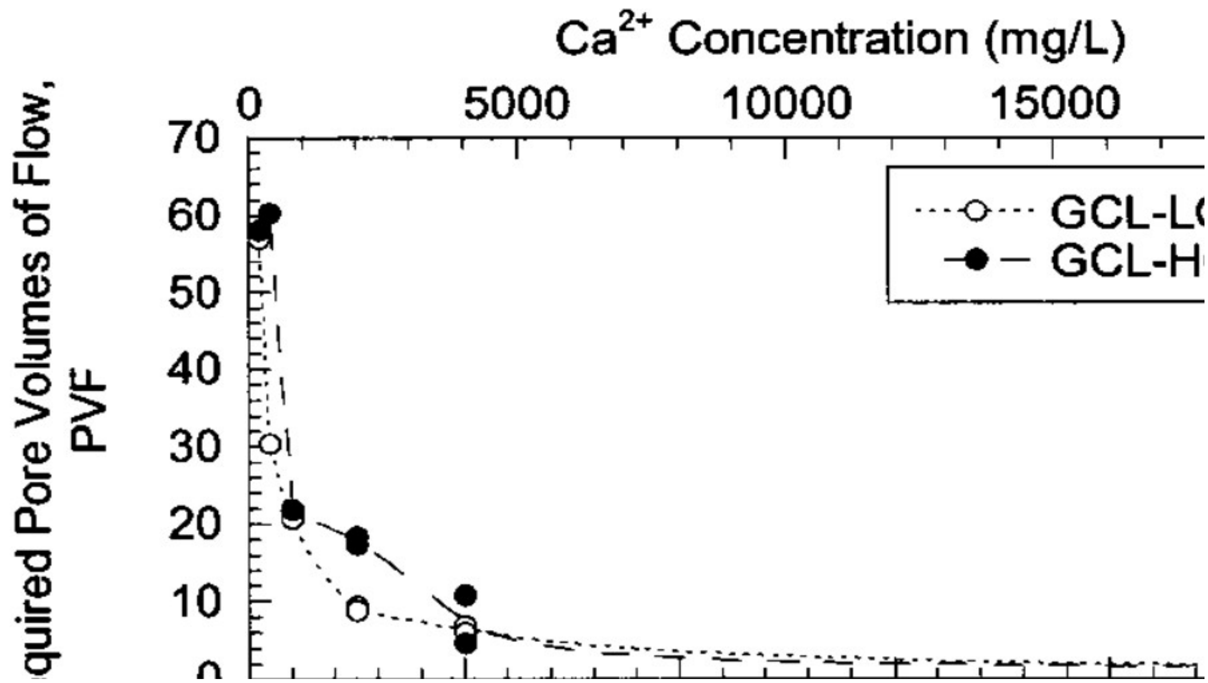


figure 12: Required pore volume of flow vs $CaCl_2$ concentration vs CaCl2 concentration (source: Lee and Shackelford (2005))

Chapter 5

Shear strength and Stability of GCLs

5.1. Internal shear strength of GCL(GRI-GCL5):

GCLs are divided into reinforced and unreinforced types, with reinforced GCLs containing fibers connecting upper and lower geotextiles. The internal shear strength of GCLs is influenced by the fibers that penetrate through the GCL's thickness. The bentonite itself offers limited shear strength. Test Method D 6243 measures the combined contribution of these components, but does not specify essential parameters like normal stresses, saturation conditions, liquid type, consolidation time, shearing rate, and shearing distance.

Shear strength of bentonite:

Bentonite clay, a component of GCLs, has a hydrated shear strength influenced by hydration and normal loading. Olson (1974) work showed that the lower limit of effective shear strength is 35 kPa at 275 kPa. Decreased bentonite percentage increases shear strength but increases permeability. Higher normal loads result in a drained friction angle approaching seven degrees. Site-specific testing is required for high and very high loads.

Internal reinforcement strength:

Reinforced Geotextile Composite (GCL) fibers contribute significantly to the shear strength of a GCL, as they penetrate through the thickness and penetrate the geotextile surfaces. The amount of shear strength added by reinforcement at low strains may also be influenced by fiber anchorage or tensioning. The peel strength test is used to evaluate the consistency of the reinforcement at frequent intervals.

Large strain internal shear strength:

The study reveals that reinforced GCLs have a residual strength beyond peak stress, which is comparable to an unreinforced GCL's peak strength. The strength of a reinforced GCL approaches that of an unreinforced GCL at large shear displacements.

Creep:

Polymeric materials in tension can fail due to sustained load creep at lower stresses than their short-term tensile strength. To handle creep and aging in reinforced soil applications, reduction factors are applied to the peak strength of the materials. A creep reduction factor of three is recommended, based on creep reduction factors for polypropylene fibers in tension. Most internal shear displacement occurs during the first 100 hours of loading, with a minimum slope stability factor of 1.5 applied to 3H:1V slopes.

5.2. Variables Affecting GCL Internal Shear Strength (J.G. Zornberg & J.S. McCartney book chapter – 8):

Effect of normal stress:

Because GCLs are frictional materials, normal stress causes an increase in their shear strength. Additionally, the GCL is strengthened under low normal load thanks to the internal reinforcements. Consequently, the Mohr-Coulomb failure envelope, is commonly used to report the GCL internal peak shear strength for a set of experiments with the same conditioning techniques and shear displacement rate.he Mohr-Coulomb failure envelope, given by:

$$\tau_p = c_p + \phi_p \tan$$

where τ_p is the peak shear strength, c_p is the cohesion intercept, σ_n is the normal stress and ϕ_p is the interface friction angle.

GCL reinforcement:

The peak internal shear strength of reinforced geosynthetic clay liners (GCLs) is significantly higher than that of unreinforced GCLs, with a substantial intercept. The data shows that needle-punched GCLs and thermally-locked GCLs have similar shear strength, while stitch-bonded GCLs have lower shear strength. The difference between needle-punched and thermal-locked GCLs may be explained by the pullout of reinforcements from the woven geotextile during hydration and shearing. Stitch-bonded GCLs have less fiber reinforcement per unit area but are continuous throughout the length of the GCL. The type of fiber reinforcement used in GCLs (needle-punched or stitch-bonded) has minor effect on the residual shear strength of GCL.

Many studies have investigated whether the internal shear strength of needle-punched GCLs varies with the amount of needle punching per unit area of the GCL. The peel strength test (ASTM D6496) has been used as a manufacturing quality control test, and several studies have correlated the peak internal shear strength of needle-punched GCLs with peel strength. Stark and Eid (1996) performed shear strength tests on reinforced GCLs with and without a sodium bentonite component (filled and unfilled, respectively) to find the effect of the reinforcement on the shear strength of reinforced GCLs. The presence of reinforcement may cause an adhesive component in the shear strength failure envelope of the GCL, as the fiber reinforcements provide tensile resistance to the bentonite clay.

GCLdescription	Peak envelope	
	c_p (kPa)	ϕ_p (Degrees)
Reinforced GCLs	40.9	18.0
Unreinforced GCLs	5.0	5.7
Needle-punched GCLs	40.5	19.5
Stitch-bonded GCLs	28.5	5.6
Thermal-locked GCLs	33.2	22.7
W-NW needle-punched GCLs	[illegible]	40.9

table 2: Shear strength parameters for GCL internal peak shear strength (source: J.G. Zornberg & J.S. McCartney book chapter – 8)

Shear Displacement Rate:

Studies have shown that stress-displacement ratio (SDR) affects the peak and large-displacement shear strength of reinforced and unreinforced GCLs under normal stresses. These studies, conducted under relatively low stress, show an increasing trend in peak shear strength with increasing SDR. The reasons for this trend include shear-induced pore water pressures, secondary creep, undrained frictional resistance of bentonite, and rate-dependent pullout of fiber reinforcements during shearing. However, the observed trends are consistent with the generation of shear-induced pore water pressures. Longer testing times may also have an additional effect on the shear strength of the GCL, as specimens tested under low normal stress may swell during hydration, while those tested under high normal stress may consolidate during hydration.

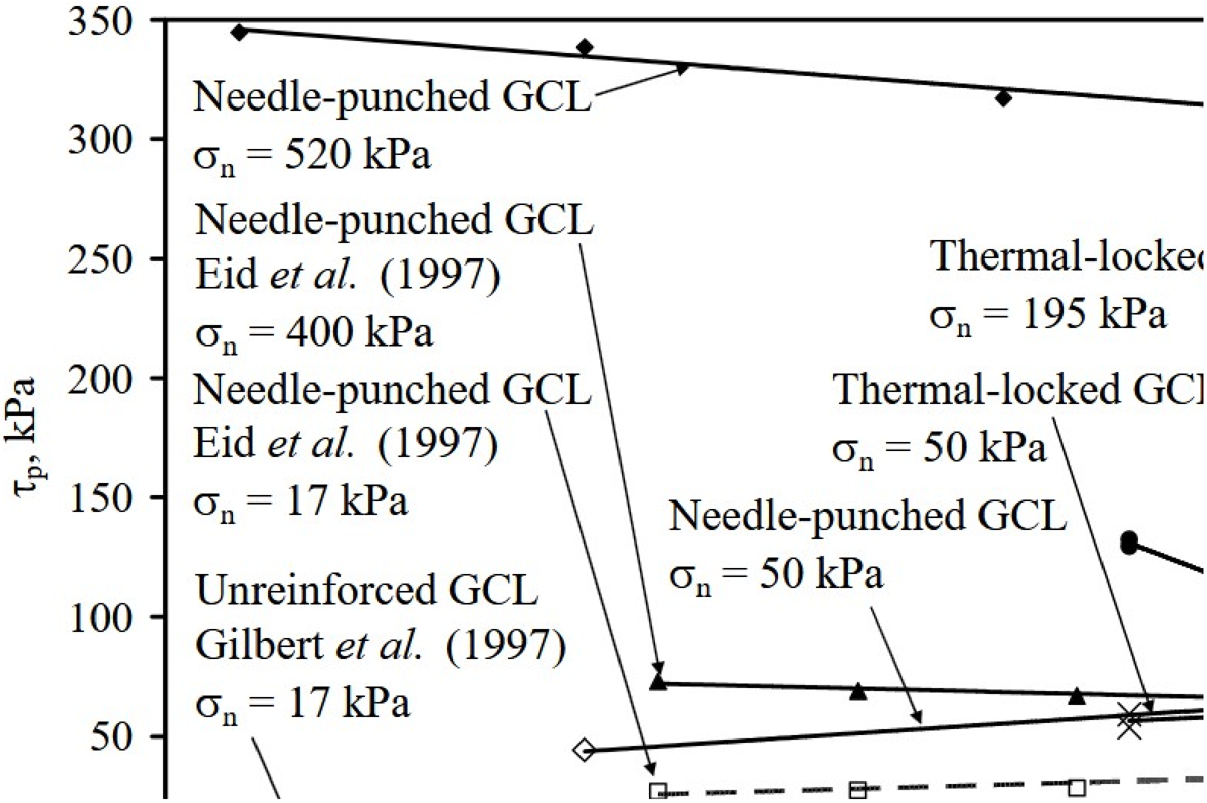


figure 12: Effects of shear displacement rate on GCL internal peak shear strength (source: J.G. Zornberg & J.S. McCartney book chapter – 8)

5.3. GCL-GM Interface shear strength(GRI-GCL5):

The designer of GCLs must consider the interfaces between outer surfaces and adjacent materials, as well as other liner components' shear strengths. Test product-specific materials and apply site-specific conditions according to ASTM D 6243, considering variables like liquid type, saturation, consolidation time, load, displacement rate, and displacement amount.

Shear stress of non-reinforced bentonite GCLs:

GCLs with bentonite bonded to a geomembrane have a critical interface, within or against the bentonite. Hydrated bentonite having varying shear strength depending on normal stresses. A field-placed geomembrane encapsulates the bentonite, resulting in higher shear strength. Emphasis is then transferred to the geomembrane surfaces.

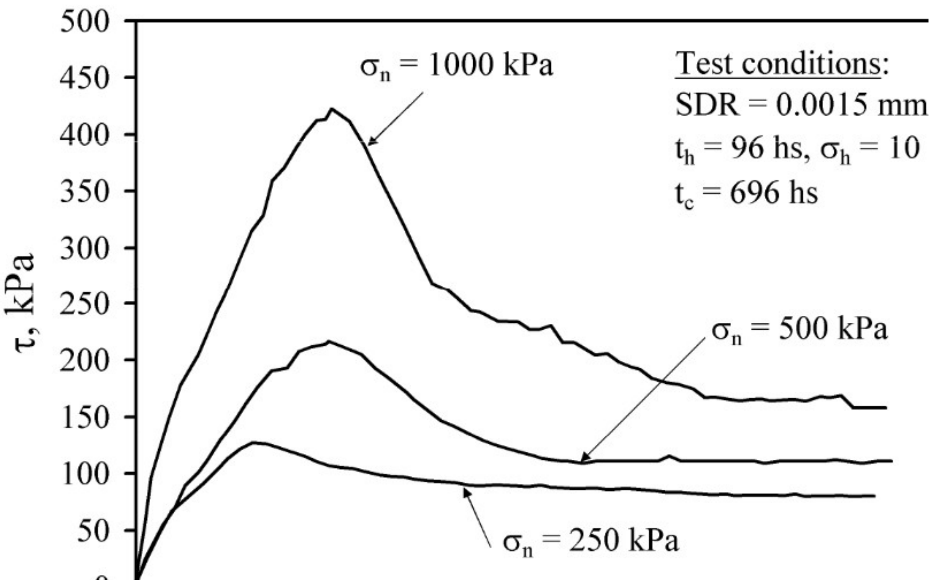


figure 13: Typical shear stress-displacement curves for interfaces between the woven carrier geotextile side of a needle-punched GCL-textured HDPE GM sheared under a slow shear displacement rate under different normal stresses (source: : J.G. Zornberg & J.S. McCartney book chapter – 8)

Interface with woven geotextiles:

Woven geotextile used in GCLs must be evaluated for shearing resistance using site-specific and product-specific conditions. The orientation of the geotextile is crucial for field installers. Designers must also consider if hydrated bentonite may extrude through the filaments, as this can significantly decrease the interface's shear strength.

Interfaces with non woven geotextiles:

The GRI-GCL3 specification requires a minimum mass per unit area of 200 g/m2 of nonwoven geotextiles for the nonwoven geotextile component of GCLs, with the weight of the geotextiles being sufficient to prevent extrusion of hydrated bentonite to the opposite interface(s).

5.4. Dynamic Shear behavior of needle-punched GCLs (Varathungarajan, 2006):

The study focuses on the dynamic and post-dynamic shear behavior of NP GCLs, specifically Bentomat ST manufactured by CETCO. Displacement-controlled cyclic shear tests were conducted using a dynamic direct shear machine, varying parameters such as cyclic shear displacement amplitude, shearing frequency, and number of shearing cycles. The results show that cyclic shear displacement amplitude significantly affects both the dynamic and post-cyclic shear strength of NP GCLs. Post-cyclic static strength decreases as cyclic displacement amplitude increases, largely dependent on the performance of needle-punched reinforcement. The effects of cyclic shearing frequency are less important, with post-cyclic static shear strength increasing with cyclic shearing frequency up to a certain point. The study also reveals that post-cyclic shear behavior is dependent on the number of shearing cycles, with shear strength decreasing non-linearly with continuing cycles until all needle-punched reinforcement fails.

5.5. Approach to obtain long term internal design strength of GCLs (Marr et al. (n.d.)):

The short-term peak strength of a GCL is measured at normal stresses and a displacement rate of 1.0 mm/min in accordance with ASTM D.6243. To obtain the long-term internal design strength of the GCL, reduction factors based on long-term tests are applied.

Creep and aging of polymeric materials placed in tension are handled in reinforced soil applications by applying reduction factors to the peak strength of the materials. In absence of long term direct shear test for the polymers, a creep factor of 3 has been recommended.(Marr et al. (n.d.))

For aging in polymers, oxidation is the main factor. In GCL for landfills etc, available oxyzen is low, hence low effect of aging on the strength of the polymers. Hence the recommended 1.1 to 2.0 aging factor will result a conservative design for 100 to 300 years respectively. (Marr et al. (n.d.))

Typical test results from laboratory shear box testing on materials used in liner systems are displayed in figure below. One test demonstrates the internal strength of a needle-punched GCL in which failure was pushed to occur within the bentonite and free swell of the GCL under low normal load was avoided. The GCL's interface strength with various materials, such as a clay soil, a geocomposite, and a textured geomembrane, is also displayed. In every test, hydrated materials were subjected to a normal stress of 69 kPa and sheared at a rate of 1 mm/min.

To stop the bentonite from leaking onto the interfaces, the materials' hydration and consolidation had to be controlled.

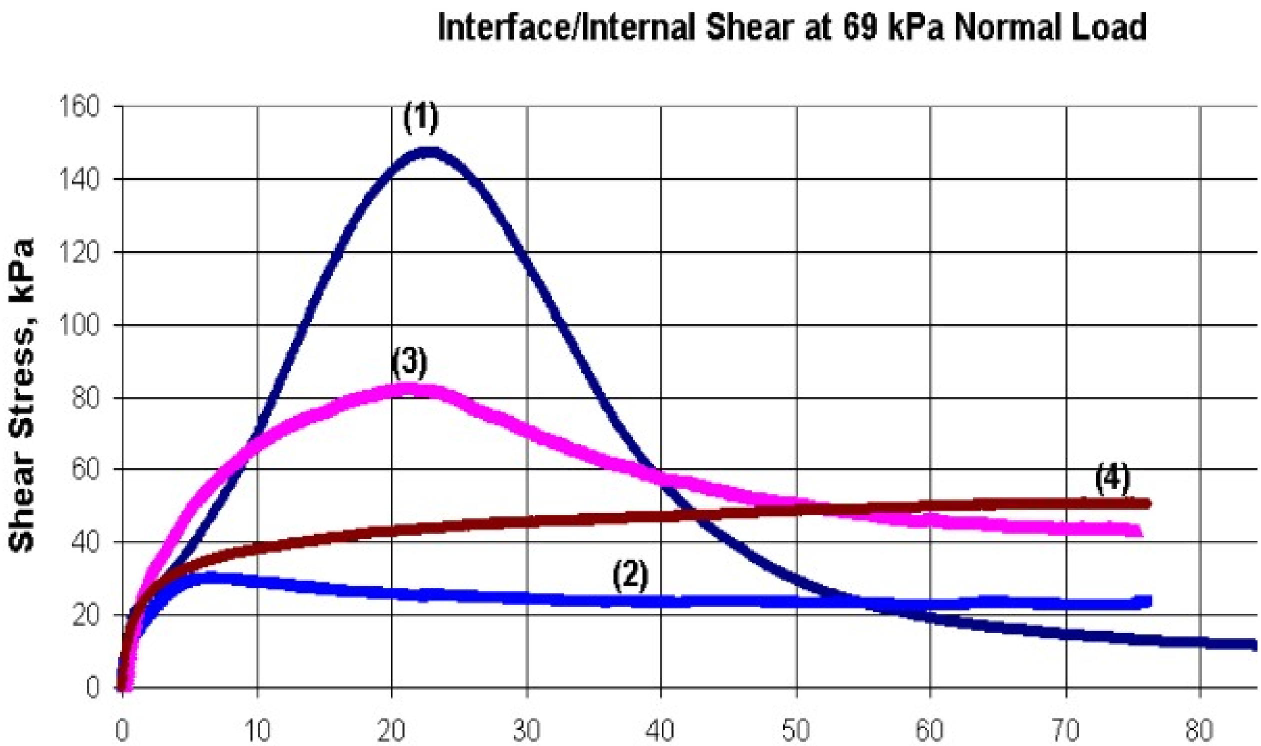


Figure-14 Typical Results for Internal and Interface Shear Tests (image source - SLOPE DESIGN USING GEOSYNTHETIC CLAY LINERS by Marr and Christopher)

Peak and residual shear of GCL:

The needle-punched GCL has the highest internal peak strength of any of the possible failure surfaces shown in figure, at roughly 150 kPa. Nevertheless, the GCL loses strength with continued displacement after achieving a high peak internal strength. At 10 kPa, the GCL's internal strength is the lowest of all at large displacements and keeps dropping. The material's high internal strength is provided by the needle-punching fibers that serve as reinforcement and hold the material together. The internal strength of the GCL is reduced when these fibers are stretched to the point where they pull out or shatter.

The reinforcing fibers' strength contribution may be nearly completely eliminated with further displacement. As a result, the bentonite's shear strength regulates the internal shear strength at large displacement. The lowest internal shear strength of the GCL and, consequently, the residual internal strength are represented by the low shear strength of the bentonite.

5.6. Design of slopes with GCLs:

Since, internal shear strength of GCLs is about five times higher than the interface, using the figure above, a material or an interface is selected, which does not experience large loss of strength with continued displacement. The system is design to fail in somewhere other than the GCL. Design using the lowest peak strength interface or material assumes that the peak strength of the interfaces and materials do not change with time.

In the absence of project-specific test data, a factor of 3 for creep times 1.1 for 100 years of aging or 2.0 for 300 years of aging is applied to the difference between peak and residual strength. The long-term internal design strength of the GCL is then calculated.

To prevent failure inside the GCL, another material or interface with a short-term peak strength less than the long-term internal design strength is provided. The strength of this material or interface is defined as the design peak strength and the residual strength as the design residual strength. A minimum factor of safety for global stability is used. For earthquake loads with a pseudo-static factor of safety less than 1, a deformation analysis using the design residual strength is performed.

Slope for application of GCLs that exceed the safe angle or respective interfaces within the system. Based on study on slopes 2H:1V and 3H:1V, 2H:1V is found too steep for normally considered factor of safety. Hence, 3H:1V is recommended with factor of safety of 1.5.(“SLOPE STABILITY OF GEOSYNTHETIC CLAY LINER TEST PLOTS,” 1998)

Chapter 6

Conclusion

In conclusion, Geosynthetic Clay Liners (GCLs) have proven to be an effective and reliable solution for a wide range of applications in geotechnical and environmental engineering. Their unique combination of natural bentonite clay and synthetic geotextiles provides excellent hydraulic properties, mechanical strength, and durability, making them ideal for applications such as landfills, containment systems, and environmental remediation projects.

While GCLs offer significant advantages in terms of ease of installation, cost-effectiveness, and performance, their long-term performance under varying environmental conditions requires careful consideration. Future research should focus on improving the resistance of GCLs to mechanical damage, biological degradation, and the effects of extreme weather conditions. Additionally, advancements in material technologies and manufacturing processes could further enhance the efficiency and sustainability of GCL applications.

Overall, GCLs represent a critical innovation in geotechnical engineering, offering a sustainable and efficient alternative to traditional liners. As further studies continue to evaluate and refine their performance, GCLs are likely to play an increasingly vital role in addressing modern environmental challenges.

References:

Herlin, B., & Von Maubeuge, K. (2002). Geosynthetic Clay Liners (GCLs). *4th International Pipeline Conference, Parts a and B*, 211–216. https://doi.org/10.1115/ipc2002-27012

Kong, D., Wu, H., Chai, J., & Arulrajah, A. (2017). State-Of-The-Art Review of Geosynthetic Clay Liners. *Sustainability*, *9*(11), 2110. https://doi.org/10.3390/su9112110

Lee, J.-M., & Shackelford, C. D. (2005). *Impact of bentonite quality on hydraulic conductivity of geosynthetic clay liners* (Vols. 131–131, pp. 64–77) [Journal-article]. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:1(64)

Marr, W. A., Christopher, B., GeoTesting Express, Inc., & Christopher Consultants. (n.d.). SLOPE DESIGN USING GEOSYNTHETIC CLAY LINERS. In *GeoTesting Express, Inc.* [Journal-article].

Petrov, R. J., & Rowe, R. K. (1997). Geosynthetic clay liner (GCL) - chemical compatibility by hydraulic conductivity testing and factors impacting its performance. *Canadian Geotechnical Journal*, *34*(6), 863–885. https://doi.org/10.1139/cgj-34-6-863

Sawada, Y., Nakazawa, H., Take, W. A., & Kawabata, T. (2019). Effect of installation geometry on dynamic stability of small earth dams retrofitted with a geosynthetic clay liner. *SOILS AND FOUNDATIONS*, *59*(6), 1830–1844. https://doi.org/10.1016/j.sandf.2019.08.007

SLOPE STABILITY OF GEOSYNTHETIC CLAY LINER TEST PLOTS. (1998). In *JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING* (Vol. 124, Issue 7, pp. 628–637).

Suzuki, M., Koyama, A., Kochi, Y., & Urabe, T. (2017). Interface shear strength between geosynthetic clay liner and covering soil on the embankment of an irrigation pond and stability evaluation of its widened sections. *SOILS AND FOUNDATIONS*, *57*(2), 301–314. https://doi.org/10.1016/j.sandf.2017.03.007

GRI-GCL5 - Design Considerations for Geosynthetic Clay Liners (GCLs) in Various Applications by Geosynthetic Research Institute (GRI),

J.G. Zornberg & J.S. McCartney book chapter – 8 - Internal and interface shear strength of geosynthetic clay liners

Lake (2000) – CONTAMINANT TRANSPORT THROUGH GEOSYNTHETIC CLAY LINERS AND A COMPOSITE LINER SYSTEM – by Craig B. Lake

Daniel, D. E., Koerner, R. M., Bonaparte, R., Landreth, R. E., Carson, D. A., & Scranton, H. B. (1998). Slope stability of geosynthetic clay liner test plots. *Journal of Geotechnical and Geoenvironmental Engineering*, *124*(7), 628–637. https://doi.org/10.1061/(asce)1090-0241(1998)124:7(628