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REPORT OF WORKSHOP ON GEOSYNTHETIC CLAY LINERS

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The United States Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the U.S. EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the U.S. EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report documents the available information concerning manufactured materials that might be utilized in liner and cover systems for landfills, impoundments, site remediation projects, and secondary containment structures. The information compiled in this report was obtained from literature, from information supplied by manufacturers, and from discussions at a 2-day workshop held on June 7 and 8, 1992 in Cincinnati. This report will be useful to scientists, engineers, and regulatory staff who are considering use of these types of materials.

E. Timohty Oppelt
Risk Reduction Engineering Laboratory

ABSTRACT

A workshop was held at the Risk Reduction Engineering Laboratory in Cincinnati, Ohio, on June 9-10, 1992 to discuss geosynthetic clay liners (GCLs). The purpose of the workshop was to present and discuss the most recent information available on the use of GCLs. This information will be of use to EPA program and regional officials, state regulatory officials, permit writers, and designers of waste disposal facilities.

Information about GCLs was first presented by manufacturers. Four commercial GCL producers manufacture distinctly different products from a variety of materials. One common feature, however, of all GCLs is a thin layer of bentonite clay. Two of the four manufacturers mix an adhesive with the clay while the other two use no adhesive but instead needle punch two geotextiles together with the bentonite sandwiched between the geotextiles. The manufacturers focused their discussions on technical developments, recent research results, quality control, and comparison of GCLs to compacted clay liners (CCLs).

Testing procedures were discussed next. A variety of conformance and performance tests can be performed, but standard test methods are lacking. In addition, no consensus has been reached on the types of tests that should be required or the appropriate frequency of testing. Interpretation of test data is not always free of ambiguity due in part to a lack of standard testing methods.

The performance of geomembrane/GCL composite liners was discussed at length. The hydraulic contact between the clay and geomembrane was the focus. If a geotextile separates the clay from the geomembrane (as is the case with most GCLs), and there is a defect in the geomembrane, some lateral spreading of liquid will take place in the geotextile. Although some equations are available to estimate the effect of the geotextile, more research is needed to quantify geomembrane/GCL composite behavior more fully.

Owner/operators of waste disposal facilities described their experiences with GCLs. Experience varies widely; some companies have used GCLs extensively while others have used them rarely. Experience seems to have been good to date but concern was expressed about the need for further refinement of construction quality assurance procedures and resolution of several technical issues.

Recent research findings at the University of Texas and Drexel University's Geosynthetic Research Institute were described. The response of GCLs to differential settlement, such as would be experienced in cover systems placed over compressible waste, has been studied. Most of the GCLs tested maintained low hydraulic conductivity even when subjected to large

differential settlement. The hydration, swelling, and strength of the bentonite in GCLs varies depending upon the fluid (water or leachate) being used. The need to test with the site-specific liquid was apparent.

The issue of equivalency of a GCL to a CCL was discussed. A number of criteria might be applied, but only a few seem truly rational. Steady-state water flux and solute flux are obvious and clear criteria that should usually be part of an equivalency analysis. Other criteria can be applied but most are much less meaningful in terms of addressing regulatory compliance.

Finally, regulatory acceptance of GCLs was discussed. Although numerous site-specific approvals of GCLs have been given by regulatory agencies, no blanket approvals or disapprovals were identified. The EPA's RCRA Subtitle D regulations prescribe a geomembrane/CCL for unapproved states but in approved states allow for equivalent designs to be accepted by state regulatory agencies.

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CHAPTER 1
INTRODUCTION

On June 7-8, 1990, the United States Environmental Protection Agency (EPA) held a workshop to discuss the use of alternative barriers in the design of cover and/or liner systems. The focus of the workshop was on the potential use of geosynthetic clay liners (GCLs) as an alternative barrier. Since that introductory conference, a significant amount of information has been gathered through research and field applications. For this reason, another workshop on the use of GCLs was held on July 9-10, 1992 at the EPA's Risk Reduction Engineering Laboratory in Cincinnati, Ohio.

The purpose of the second workshop was to present and discuss the most recent research available on the use of GCLs. As the use of GCLs has expanded dramatically over the last few years, it is important that EPA program and regional officials, state regulatory officials, permit writers, and designers keep up to date on the latest information available on the use of these products.

The information discussed at the workshop held on July 9-10, 1992 was as follows:

1) Manufacturer's Information. A compilation of information available on each of the major GCL products was presented by the manufacturing sector. (Presented by representatives for Bentofix®, Bentomat®, Claymax®, and Gundseal®)

2) Testing Procedures. The use of different testing methods and procedures to determine the physical properties of GCLs was discussed. (Presented by Richard Brown, John Boschuk, and Robert Bachus)

3) Intimate Contact. The mechanisms of intimate hydraulic contact between geomembranes and GCLs were discussed. (Presented by John Bove)

4) Owner/Operator Experiences. An overview of information on the field application of GCLs was presented by owner/operators of landfills. (Presented by representatives of Waste Management of North America, Browning-Ferris Industries, Chambers Development, and Laidlaw)

5) Recent Research. The most recent research carried out by Drexel University and the University of Texas at Austin was discussed. (Presented by Robert Koerner, David Daniel, Mark LaGatta, B. Tom Boardman, and Hsin-Yu Shan)

6) Equivalency. The equivalency of a GCL to a compacted clay liner was discussed. (Presented by David Daniel)

7) Technical and Regulatory Concerns. An open discussion was held on the technical concerns of the use of GCLs. (Presented by David Daniel and Robert Landreth)

The purpose of this report is to summarize the information presented at the GCL workshop held on July 9-10, 1992. This report does not represent the full extent of the information available on geosynthetic clay liners. Readers are directed to the summary of the GCL workshop held on June 7-8, 1990 for additional information (EPA 600/2-91/002). Rather, this report augments the proceedings from the first workshop.

Information on Bentofix®, Bentomat®, Claymax®, and Gundseal® is presented in Chapter 2. Testing Procedures are discussed in Chapter 3. Intimate contact is discussed in Chapter 4. Owner/operator experiences are listed in Chapter 5. Recent university research is discussed in Chapter 6. Equivalency concerns are addressed in Chapter 7. Technical concerns are voiced in Chapter 8. A list of references and published papers and reports on GCLs is included in Chapter 9. A list of attendees is presented in the Appendix.

CHAPTER 2
MANUFACTURER'S INFORMATION

At the present time, there are four major products available on the geosynthetic clay liner (GCL) market. These four products are Bentofix®, Bentomat®, Claymax®, and Gundseal®. Each product has its own unique properties.

The manufacturer of each product was asked to speak about technical discoveries that had been made since the previous meeting. The information presented in this chapter was provided by the manufacturer's speaker.

2.1 Bentofix® (By Georg Heerten, Naue-Fasertechniik GmbH & Co.)

Bentofix®, which was developed in 1987, is produced by the German company Naue-Fasertechnik and was introduced to the North American market in 1991 through the joint venture company Albarrie Naue Ltd. establishing an additional production facility in Canada. Bentofix® is designed as a layer of loose granular or powdered bentonite held between two non-woven geotextiles by a series of thin needle punched fibers (Fig. 2.1). Needle punching keeps the bentonite in place before and after hydration, and the needle punching is said to increase the internal shear strength of the GCL.

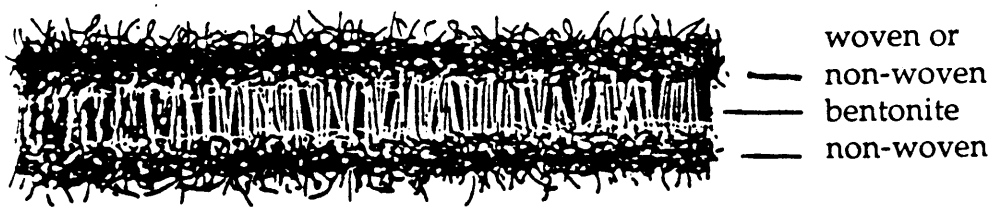


Figure 2.1 Needle Punched System of Bentofix®

2.1.1 Benefits of Needle Punching

Naue-Fasertechnik's purpose for needle punching a layer of loose bentonite between two non-woven geotextiles was to create a sturdy GCL that could withstand the rigors of installation. The needle punching helps to keep the bentonite in place even after hydration. For this reason, the manufacturer states that Bentofix® can be installed during rainy conditions or underwater.

A GCL bound by needle punched fibers is said to allow for the installation on steep slopes (up to 1.5 : 1), by preventing sliding between the components of the GCL, while also increasing the internal shear strength of the GCL as a whole.

2.1.2 Non-Woven Geotextiles

The manufacturer stresses the importance of the robustness of the geotextiles incorporated into the GCL. To allow the GCL to be needle punched together, at least one layer must be a non-woven geotextile. Both geotextile components must pass filter criteria in order to prevent the migration of bentonite out of the GCL. The upper layer non-woven geotextile must also be puncture resistant. For this reason, the top cover layer geotextile must have a minimum mass/area of .25 kg/m^2 and pass a German puncture test. However, a .12 kg/m^2 woven geotextile may also be used. The manufacturer has not had the opportunity to measure the hydraulic conductivity of a deformed section of Bentofix® after passing the puncture test. This is still being investigated.

To avoid lateral wicking in the upper non-woven geotextile, when a geomembrane is placed on the GCL to form a composite liner, the pore space of the upper geotextile is filled with powdered bentonite. The bentonite powder is said to be fixed by a patented system which fills the non-woven pores. This system is also said to improve the intimate contact between a GCL and an overlying geomembrane by reducing the amount of loose powdered bentonite dust where the two come in contact.

2.1.3 Bentonite

Bentofix® can be manufactured with powdered bentonite with 87% of the mixture having a grain size less than 0.002 mm, or as a granular bentonite in the size range of 0.5 to 4 mm. Due to its finer grain size, the powdered bentonite will hydrate much quicker than a granular bentonite. Granular bentonite used to be necessary when Bentofix® was used in conjunction with a geomembrane because the powdered bentonite would create welding difficulties for the overlying geomembrane. The manufacturer is said to have solved the problem of loose powdered bentonite influencing the welding process of geomembranes by fixing the bentonite to the geotextile, which addresses the intimate contact issue at the same time.

2.1.4 Laboratory Measurement of Hydraulic Conductivity

The manufacturer recommends that the procedures outlined in Table 2.1 be observed for the proper measurement of the hydraulic conductivity of a GCL. Differences in GCL sample preparations can lead to large variations in the measured value of hydraulic conductivity.

Table 2.1 Measurement of Hydraulic Conductivity for GCLs

Procedure	Important Steps	Possible Problems
Sampling	1) Exact Cutting (Stamping) 2) No bentonite loss on edges 3) Edge wetting	1) Flow around edge 2) Air encapsulation
Installation	1) Soaking filter plate 2) Applying flexible membrane carefully	1) Air slows down swelling 2) Loss of bentonite
Test Procedure	1) Proper saturation time (50 hours minimum) 2) Cell pressure (30 kPa minimum) 3) Hydraulic gradient	1) Inadequate water Adsorption
Calculation	1) Measurement of hydrated sample thickness	1) Incorrect calculation

2.1.5 Overlaps

In the past, the overlapping seams had to be filled with loose powdered bentonite or a hydrated bentonite paste. This will not be necessary in the future due to the upper layer non-woven geotextile being filled with bentonite powder. This system is said to provide a more intimate contact along the GCL overlap.

A prefabricated velcro system has also been designed to prevent displacement along the overlaps due to movements during or after the covering process.

2.1.6 Installation Procedures

Bentofix® will have the printing on the upper geotextile as well as an overlap mark. Naue-Fasertechnik has also developed an installation manual

which is delivered to each customer in advance. According to the manufacturer a correct overlap can be achieved, and wicking in the non-woven plane can be prevented, if the installation instructions are followed correctly.

2.1.7 Case Histories

1) Geomembrane Protection. In an effort to prevent the puncture of an underlying geomembrane by the placement of a granular drainage material with large particles (16 to 32 mm), Bentofix® has also been used as a cushion layer over the geomembrane. The GCL not only protects the geomembrane, but provides an additional seal, as well.

2) Vertical Gas Barrier. In an effort to prevent the seepage of landfill gas and leachate, Bentofix® was placed in a vertical cutoff trench surrounding a landfill. Apparently the soil moisture was sufficient to hydrate the bentonite resulting in a sufficient gas barrier.

3) Sealing a Canal. In an effort to seal a canal and cofferdam, Bentofix® was successfully installed in an underwater operation. The manufacturer states that the needle punching allowed the GCL to withstand the immediate swelling and the following installation procedure all while underwater.

4) Groundwater Protection System. In an effort to catch the run off from de-icing impurities at the Munich II Airport, over 700,000 m^2 of Bentofix® was installed. The project has proved successful to date.

2.1.8 Supplemental Information

After the conference, Mr. Klaus Stief submitted additional information. Because Bentofix® was developed in Germany, the manufacturer has followed German and European regulations for landfills particularly closely. The following is a summary of Mr. Stief's perspective on European policy on landfill linings.

The Commission of the European Communities published in May 1992 a proposed set of regulations for landfills. The proposal calls for liner systems, leachate collection systems, and engineered cover systems. The lining system may consist of natural, low-permeability soil, or lacking such soil, engineered

liners must be used. There are no specific requirements for engineered liners; the use of GCLs is in no way restricted.

Current German regulations are more stringent. The general liner requirement in Germany is for a single composite liner consisting of a geomembrane placed on 0.75 to 1.5 m of low-permeability compacted soil. Similar requirements exist for the cap, although the soil liner component has a smaller minimum thickness (0.5 m).

2.2 Bentomat® (By Robert Trauger, CETCO)

Bentomat® is manufactured by the Colloid Environmental Technology Company (CETCO), which is a subsidiary of the American Colloid Company. The representative from CETCO briefly discussed the results of recent laboratory testing on Bentomat®, but mainly concentrated on the highlights and advantages of the use of GCLs in the waste management industry.

2.2.1 A Brief History of Waste Management Practices

For several decades, the only practical means of waste containment was the construction of a hydraulic barrier consisting of a layer of compacted clay. Unfortunately, the possibility of complete containment to the extent that a 1977 US EPA report on landfill liners suggested a "different approach," whereby "pollution would be lessened by designing landfill liners for higher permeability and by selectively attenuating the most toxic pollutants from the leachate..."

This novel idea of emphasizing attenuation over containment was never implemented due to the emergence of geomembrane technology in the 1980's. The near zero hydraulic conductivity of geomembranes made the concept of true containment appear attainable. After a decade of technical progress, geomembranes are now accepted by most designers as a required component of landfill liners. The composite liner system, in which a geomembrane is placed over a clay layer, was another fundamental advance as designers abandoned attenuation considerations in favor of containment. Leakage rates through well constructed composite liners are far lower than through geomembranes or compacted clay liners (CCLs) alone. The only development missing in the shift to containment oriented landfills was a series of federal regulations for landfill liner design.

The US EPA has just recently released the long awaited federal rules on landfill design for municipal solid waste landfills. Unfortunately, GCLs were not well established when the rules were drafted, so there is not yet a federal policy on the role of GCLs in landfills.

2.2.2 The Potential Role of Geosynthetic Clay Liners in Landfills

Some have suggested that GCLs are not merely a convenient substitute for clay liners but instead represent the next step towards the goal of total waste containment. GCLs have an extremely low, uniform hydraulic conductivity and are not subject to the many materials and construction related problems that commonly plague CCLs. Potential landfill liner cross sections reflecting this design goal are shown in Fig. 2.2 and 2.3.

2.2.3 Future Directions for Research and Discussion

The GCL is an important innovation in lining technology, but its performance can be undermined by poor design and installation. As with any emerging technology, additional field and laboratory research is necessary to strengthen the feedback loop for better designs, installations, and products. Since the last GCL workshop held two years ago, a vast amount of useful data has been obtained for Bentomat®. Some of the data are shown in Tables 2.2 and 2.3. More work needs to be done, however, to realize the full performance capabilities of GCLs. Some of the most important remaining issues which the technical, regulatory, and manufacturing communities must address are discussed in succeeding subsections.

2.2.3.1 Intimate Contact

Concern has been expressed that the upper geotextile of a GCL could prevent intimate contact between the geomembrane and the bentonite clay and facilitate lateral movement along the interface. Overall leakage could consequently increase because liquid is distributed over a broader area. However, lateral movement may only occur at low confining stress, and the quantification of the phenomenon is incomplete. When considering this issue one must assess the theoretical advantages of geomembrane/CCL intimate contact with respect to the many performance and installation advantages of a geomembrane/GCL liner system.

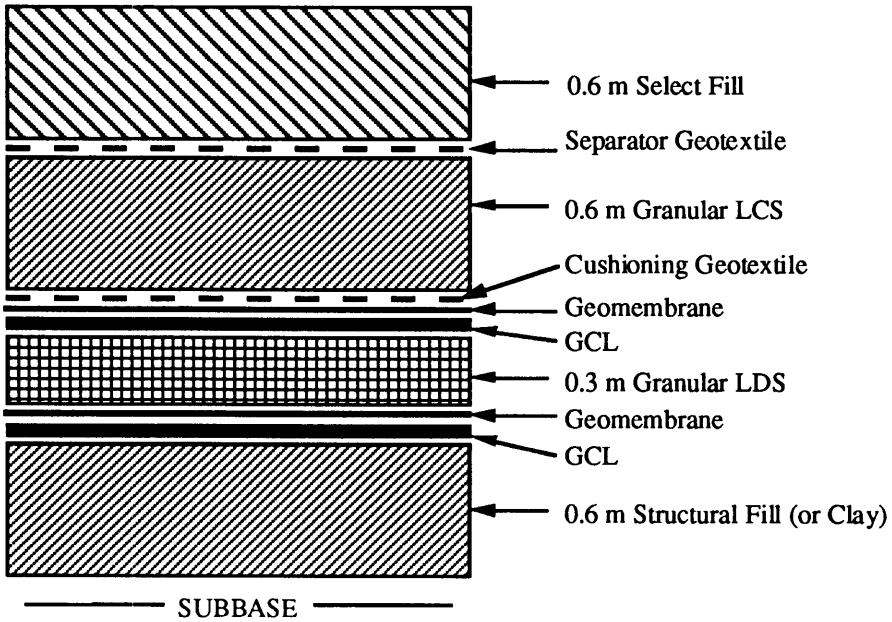


Figure 2.2 Potential Double Composite Liner System

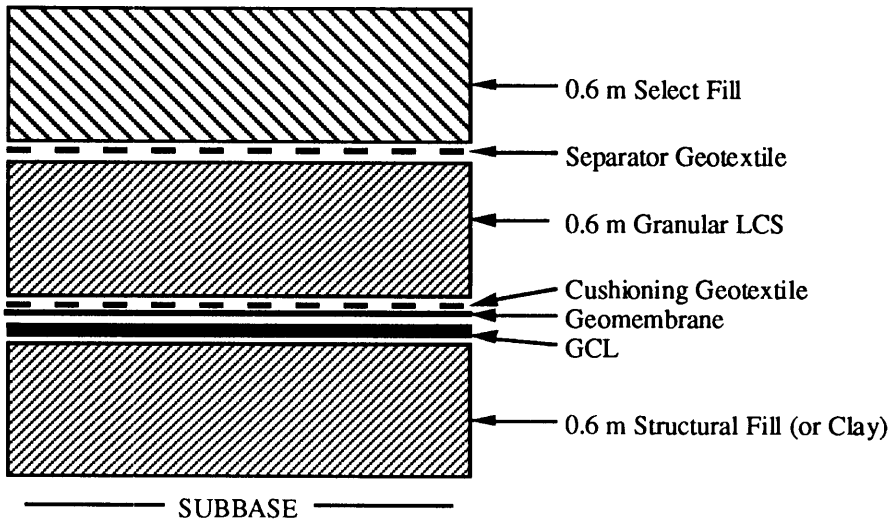


Figure 2.3 Potential Single Composite Liner System

Table 2.2 Summary of Triaxial Permeability Test Data on Bentomat®

TEST LAB*	DATE	PRODUCT	MAX. EFFECTIVE CONF. STRESS(KPA)	HEAD(M)	GRADIENT	TOTAL TIME(HRS)	PERMEABILITY (CM/SEC)
J & L	07-05-90	SS	56.5	.3	30	26	2.1×10^{-9}
			73	3.7	380	6	7.5×10^{-10}
			90.9	7.3	760	13	5.8×10^{-10}
			107	11	1100	4	6.6×10^{-10}
		CS	56.5	.3	35	62	5.6×10^{-9}
			73	3.7	450	19	1.1×10^{-9}
			90.9	7.3	900	46	9.8×10^{-10}
			107	11	1315	2	2.6×10^{-9}
J & L	09-21-90	SS	56.5	.3	30	36	7.3×10^{-10}**
			73	3.7	400	28	7.3×10^{-10}
			90.9	7.3	800	7	1.4×10^{-9}
J & L	12-17-90	CS	N/A	9.1	2250	25	1.4×10^{-9}
Geosyntec	12-20-90	CS	N/A	4.6	N/A	72	2.0×10^{-9}
J & L	01-08-91	CS	129	11	1800	25	1.6×10^{-9}
ACC	05-02-91	CS	207	2.1	200	216	3.6×10^{-9}†
J & L	07-05-91	SS	255	2.7	530	4	2.1×10^{-10}
D & M	07-15-91	PL	393	16	217	190	6.8×10^{-10}††
Geosyntec	07-31-91	PL	34	2	160	720	3.0×10^{-9}**
Nelson	09-04-91	SS	34	3.7	360	1440	3.5×10^{-9}‡
ACC	06-18-91	SS	34	7.0	840	3600	3.0×10^{-9}‡

Notes:

* J & L = J & L Testing Company, Inc., Canonsburg, PA
Geosyntec = Geosyntec Consultants, Norcross, GA
D & M = Dames & Moore, Salt Lake City, UT
ACC = American Colloid Company, Arlington Heights, IL
Nelson = Robert L. Nelson & Associates, Schaumburg, IL

** Permeant was landfill leachate

† Permeant was salt water

†† Permeant was 600 ppm NaCN

‡ Permeant was liquid fertilizer

Table 2.3 Summary of Direct Shear Test Data on Bentomat®

LAB*	DATE	INTERFACE**	NORMAL STRESSES(KPA)	MOISTURE CONDITION†	SHEAR RATE	FRICTION ANGLE(DEG)
J & L	05-30-90	NW/Sand	7 / 14 / 21	Hydrated	0.5 mm/min	35
		NW/Sand	"	Dry	"	28
		NW/Clay	"	Hydrated	"	41
		NW/Clay	"	Dry	"	31
STS	09-11-90	NW/1 mm Text. HDPE	240 / 360 / 480	Dry	5 mm/min	18
		NW/2 mm Text. HDPE	"	Dry	"	37
		W/2 mm Text. HDPE	"	Dry	"	24
J & L	11-06-90	NW/Sandy Soil	14 /24 / 34	Dry	0.5 mm/min	23
GRI	04-18-91	Internal	3 / 7 / 14 / 34 / 69 / 140 / 240	Dry	0.89 mm/min	42
		"	0.83 / 3 / 7 / 34 / 69	Hydrated	"	37
		"	0.83 / 3 / 7 / 34 / 69	Hydrated††	"	39
STS	05-28-91	NW/1 mm Text. HDPE	240 / 360 / 480	Hydrated	5 mm/min	20
		W/2 mm Text. HDPE	"	Hydrated	"	19
UTA	08-12-91	Internal	41 / 62 / 96 / 130	Hydrated	0.5 mm/min	26
J & L	09-09-91	W/Soil Cover	4 / 8.6 / 13.0	Hydrated	0.89 mm/min	22.5
		W/Geonet	"	Hydrated	"	17
		NW/2B Stone	"	Hydrated	"	53
TRI	05-06-92	W/1.5 mm Text. VLDPE	14 / 55 / 96	Hydrated	1 mm/min	22
		W/1.5 mmSm. VLDPE	14 / 55 / 96	Hydrated	"	14

Notes:

* J & L = J & L Testing Company, Inc., Canonsburg, PA (used a 75 mm Wykeham Farrance direct shear device)
STS = STS Consultants Ltd., Northbrook, IL (used a custom-made 300 mm shear box)
GRI = Geosynthetic Research Institute, Drexel University, Philadelphia, PA (used a Wykeham Farrance device)
UTA = University of Texas at Austin, Civil Engineering Laboratory (used a 60 mm direct shear box)
TRI = TRI Environmental Inc., Austin, TX (used a 300 mm direct shear box)

** NW = Non-woven geotextile of Bentomat
W = Woven geotextile of Bentomat

† "Dry" = sample tested in the as-received moisture state.
"Hydrated" = sample was hydrated prior to testing, although the actual hydration methods vary.
Samples were hydrated with distilled water unless otherwise noted.

†† Hydrated in leachate.

2.2.3.2 Puncture Concerns

There has been a great deal of concern over the potential for a GCL to be more susceptible to puncture damage. This concern is often cited by regulators as reason not to allow the use of GCLs. Liner systems in today's modern landfills are more controlled than ever before and great care is usually taken to prevent the possibility of puncture from above and below the liner. With GCLs, these practices must be even more strongly emphasized, especially in the post construction stage. The construction of a sound foundation and the placement of cover material over the liner system must be rigidly controlled. If deemed necessary, additional cover layers should be placed on the liner system to further preclude the possibility of puncture. In other words, puncture prevention should be emphasized during the construction process.

2.2.3.3 Construction Quality Assurance

GCLs can be easily and rapidly installed in comparison to geomembranes and CCLs, yet a stringent construction quality assurance (CQA) plan must be implemented. The best design and the most explicit project specifications mean nothing if the installation is faulty. Comprehensive and realistic CQA programs should be developed by GCL manufacturers and engineers. These programs should detail installation criteria as well as materials conformance criteria. The certification program under development by the National Institute for Certification of Engineering Technologists (NICET) will be extremely valuable for providing trained GCL installers, but more input is needed from installers regarding methods of installation which minimize the potential for GCL damage.

2.2.3.4 Research Directives

The long term compatibility of a hydrated bentonite layer with the variety of organic and inorganic chemicals it may encounter needs to be investigated. Due to time constraints, these tests are inconvenient to run in a controlled, repeatable fashion. New test methods may need to be developed to provide meaningful data in a reasonable period of time. Results of this research, however, could lead to improvements in contaminant resistant clays.

Direct shear testing is another area requiring additional research. There is a seemingly limitless variety of soil and geosynthetic materials which may be used in conjunction with a GCL. Each interface has its own unique frictional

characteristics, and the designer needs a reliable evaluation of the applicable friction angles to perform a slope stability analysis. A relatively sizable database is already available, but more information is needed.

A long term, full scale field study of GCLs would also be informative. The effects of freeze/thaw, desiccation, and settlement could all be observed on a large scale.

2.2.3.5 Test Standards

The engineering and performance characteristics of GCLs are typically evaluated using ASTM methods for soils and geosynthetics. For the geosynthetic components of GCLs, these test methods are already acceptable or only require minor modifications. Unfortunately there are no currently recognized standards for preparing GCL test samples, for determining the quality of the bentonite component, or for testing the entire product as a whole. At this time, all of the major GCL manufacturers are working with ASTM to develop the necessary standards.

2.2.4 Conclusion

The rapid increase in the use of GCLs over the past two years has made intrepid pioneers out of manufacturers, regulators, and installers. Still, a watchful eye must be maintained over the types of applications and designs in which GCLs are specified. A poorly conceived design, or a careless installation, can only serve to undermine the credibility that the industry has striven to attain. In the coming years, everyone is urged to share his information and experiences so that the state of the art can be advanced to the benefit of everyone involved with geosynthetic clay liners.

2.3 Claymax® (By Walter Grube, Jr., James Clem Corporation)

Claymax® is manufactured by the Clem Environmental Corporation, which is a branch of the James Clem Corporation. Claymax® was the first GCL product to be designed and introduced onto the market.

Claymax® produces two products. The Claymax® 200R is the original product which consists of a layer of granular sodium bentonite sandwiched between an upper primary woven geotextile and a lower secondary open weave

geotextile. Other materials can be specified for the lower backing depending on site specific needs. Claymax® 200R is normally installed with the primary geotextile on top, but this may be reversed depending on site-specific requirements. Claymax® 500SP has recently been introduced as a material with high shear and tensile strength properties. The increase in strength has been achieved by stitch-bonding the primary and secondary backing materials together and by increasing the tensile strength of the backing materials themselves.

2.3.1 Benefits of Using a GCL

The manufacturer discussed four reasons to use a GCL. These reasons are discussed in more detail below.

1) Stop Seepage. In an effort to reduce seepage, a GCL can be used to fulfill the low permeability requirement and as a design alternative to a compacted clay liner. In order to attain this low permeability, the in place overlapping GCLs must have seam integrity and the ability to successfully self heal.

2) Quality Control. The high degree of quality assurance/quality control (QA/QC) in the materials and manufacture of the GCL make it an attractive alternative to compacted clay liners. The manufacturer also states that they will provide field and technical support to ensure QA/QC. Also, the GCL customer may perform independent conformance testing.

3) Standards of the Industry. Both the bentonite and geosynthetic industries have a history of reliable standards and guidelines. The GCL manufacturers are working with various standard-writing organizations in an effort to ensure a high level of QA/QC.

4) Lack of Clay Reserves. Many regions do not have significant clay reserves. As an example, the landfill cover design recommended by the US EPA, shown in Fig. 2.4, is considered. As an alternative to a compacted clay liner, the manufacturer recommends the landfill cover design shown in Fig. 2.5, which has been modified to incorporate a GCL.

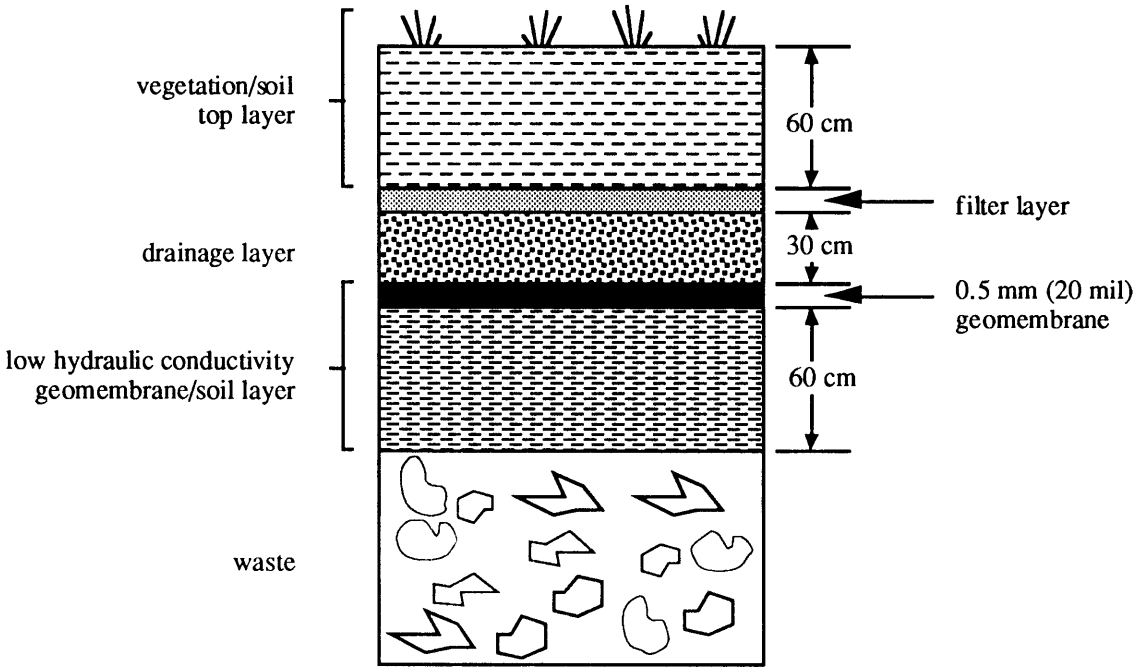


Figure 2.4 US EPA Recommended Landfill Cover Design (EPA/625/4-91/025)

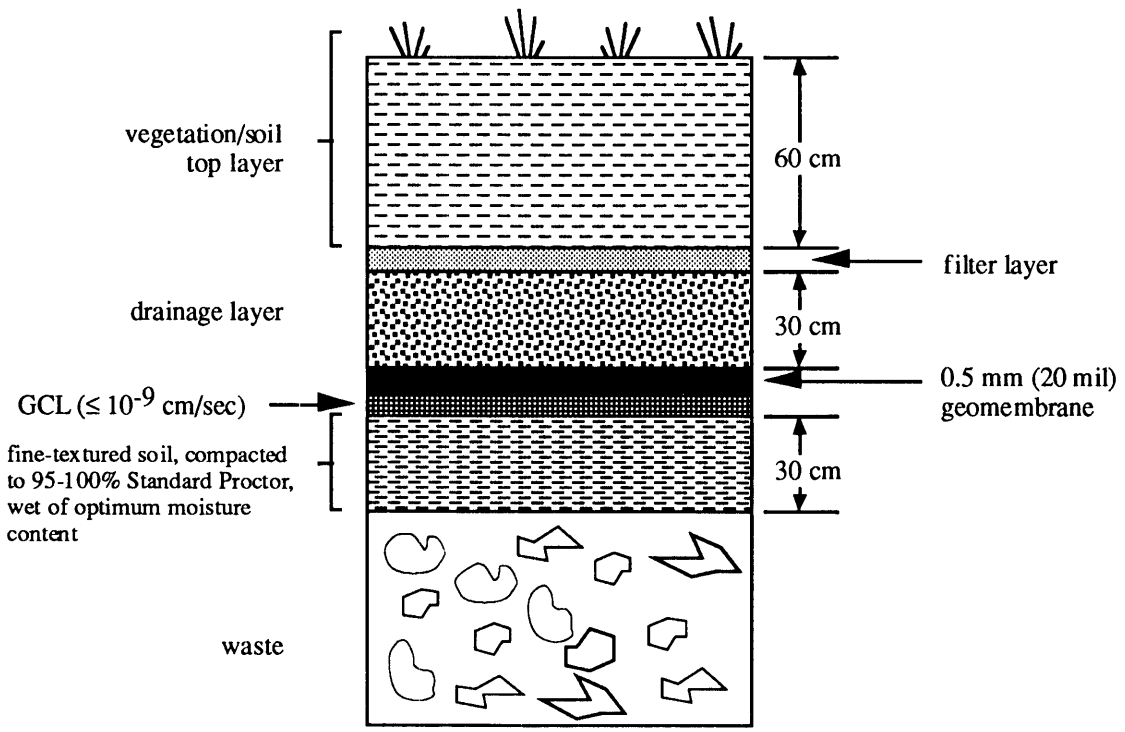


Figure 2.5 Potential Landfill Cover Design Incorporating a GCL

2.3.2 Quality Management

While data can be collected from small scale samples in the laboratory, how will the product perform as a whole in the field? This is where construction quality assurance for the GCL product becomes important.

The manufacturer states that the Clem quality management program is independent of manufacturing, and follows all applicable and relevant standard ASTM/API test methods. With each product sent to a client, a certification of compliance is included detailing the properties of that particular shipment.

A summary of the quality management program undertaken at the James Clem Corporation is shown in Fig. 2.6, and in Tables 2.4, 2.5, 2.6, and 2.7. Two partial lists of available testing data are shown in Tables 2.8 and 2.9.

2.3.3 Available Information on Claymax®

The manufacturer states that the following information is available on the Claymax® product:

1) Case histories
2) Laboratory data
    a) Compatibility studies
    b) Shear resistance
    c) Overlapped seam/damaged liner permeability tests
    d) Freeze/thaw tests
3) Customer assistance
    a) Engineers guide to GCL specifications
    b) Engineers guide to GCL CQA programs
4) Design models and comparison studies
    a) Slope stability analyses
    b) Comparative flows (clay vs. Claymax®)
    c) Composite liner system comparative flow rates
    d) Bentonite quantity calculations at seams

2.4 Gundseal® (By James Anderson, Gundle Lining Systems, Inc.)

Gundseal® is manufactured by Gundle Lining Systems, Inc. The Gundseal® GCL consists of a layer of bentonite (5 kg/m^2) adhered to a geomembrane. Depending on the types of fluids that may come in contact with

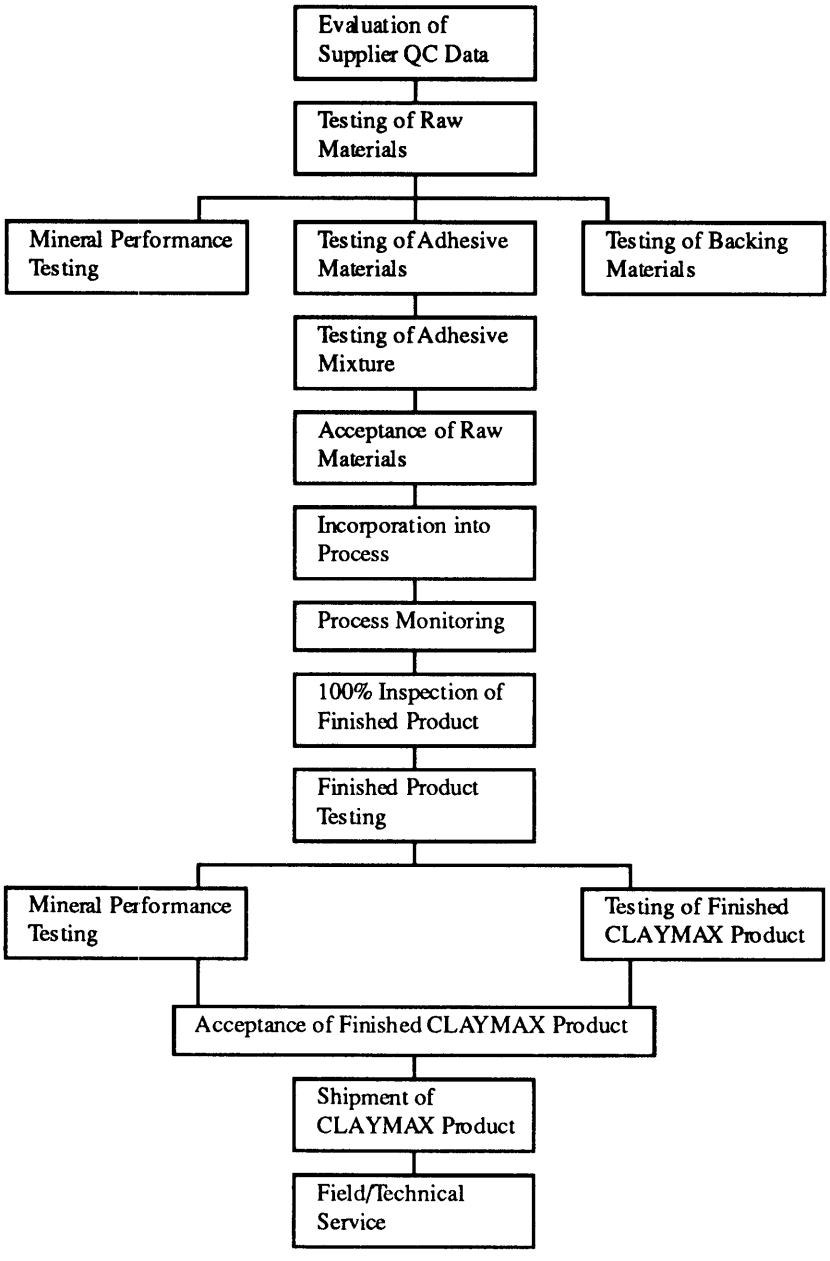


Fig. 2.6 Clem Quality Management Program Summary

Table 2.4 Claymax® Mineral Performance Testing

TEST	AS DELIVERED			AS REMOVED FROM FINISHED CLAYMAX		
	Performed?	Criteria	Frequency	Performed?	Criteria	Frequency
Gradation	X	per specs	8-10 per rail car	-	-	-
Moisture Content	X	< 10%	"	X	25% max.	2000 m^2 max.
pH	X	8-10.5	"	X	-	"
Plate Water Adsorption	X	860% min.	"	X	-	"
Free Swell	X	25 ml min.	"	X	27 ml min.	"
Fluid Loss	X	18 ml max.	"	X	12 ml max.	"

Table 2.5 Claymax® Backing Material Testing

TEST	SUPPLIER TESTED	CLEM TESTED	ACCEPTANCE CRITERIA (MARV)	CLEM TESTING FREQUENCY
Grab Tensile Strength	X	X	400 N	7-10 per delivered truckload
Grab Tensile Elongation	X	X	15%	"
Puncture Strength	X	X	220 N	"
Mullin Burst	X	-	1700 kPa	"
Unit Weight	X	-	0.12 kg/m^2	"
Wide Width Tensile	X	-	11 N/mm	"

Table 2.6 Claymax® Inspection andTesting

TEST	MINIMUM TESTING FREQUENCY	ACCEPTANCE CRITERIA
Bentonite Content	2000 m^2	4.6 kg/m^2 MARV
Composite Thickness	2000 m^2	5.0 mm MARV
Bentonite Thickness	2000 m^2	4.3 mm MARV
Permeability	70,000 m^2	< 5 x 10^{-9} cm/sec @ 14 kPa
Overlapped Seam Permeability (no granular bentonite)	70,000 m^2	< 5 x 10^{-9} cm/sec @ 14 kPa

Table 2.7 Claymax® GCL Material Specifications

	PROPERTY	TEST METHOD *	UNITS	CLAYMAX STYLE 200R	CLAYMAX STYLE 500SP
BENTONITE PROPERTIES **	Sodium Montmorillonite Content	X-Ray Diffraction	%	90 (typ)	90 (typ)
	Free Swell	USP-NF-XVII	ML	27 (MARV)	27 (MARV)
	Fluid Loss	API 13 B	ML	12 (Max. A.R.V.)	12 (Max. A.R.V.)
	Moisture Content †	ASTM D4643	%	20 (typ)	20 (typ)
ADHESIVE	Adhesion	Visual		Continuous Adhesion to Backing Material	Continuous Adhesion to Backing Material
PHYSICAL PROPERTIES	Thickness (excluding fabric)	ASTM D1777	MM	4.3 (MARV)	4.3 (MARV)
	Composite Thickness	ASTM D1777	MM	5 (MARV)	5 (MARV)
	Wide Width Tensile	ASTM D4595	N/MM	11 (typ) ††	18 (typ)
	Grab Tensile	ASTM D4632	N	400 (MARV) ††	400 (MARV) ††
	Bentonite Content † @ 20% moisture	Weigh 12" X Roll Width	KG/M^2	4.6 (MARV)	4.6 (MARV)
	Shear Resistance				
	Hydrated	ASTM D35.01.81.07 (draft)	DEG	>10	>40
	Dry		DEG	>35	>40
HYDRAULIC PROPERTIES	Permeability				
	A) 14 kPa Effective Stress	ASTM D5084	CM/S	5×10^{-9} (Max. A.R.V.)	5×10^{-9} (Max. A.R.V.)
	B) 200 kPa Effective Stress	ASTM D5084	CM/S	$< 5 \times 10^{-10}$ (typ)	$< 5 \times 10^{-10}$ (typ)
	Permeability (14 kPa effective stress)				
	C) 50 mm Overlapped Claymax (without the use of granular bentonite between the seams)	ASTM D5084	CM/S	$< 5 \times 10^{-9}$ (typ)	$< 5 \times 10^{-9}$ (typ)
	D) Damaged Claymax (3 each, 25 mm holes)	ASTM D5084	CM/S	$< 5 \times 10^{-9}$ (typ)	N/A ‡
	E) Claymax underneath damaged HDPE geo-membrane (25 mm hole)	ASTM D5084	CM/S	$< 5 \times 10^{-9}$ (typ)	N/A ‡
	F) after 3 Wet/Dry Cycles	ASTM D5084	CM/S	$< 5 \times 10^{-9}$ (typ)	N/A ‡
	G) after 5 Freeze/Thaw Cycles	ASTM D5084	CM/S	$< 5 \times 10^{-9}$ (typ)	N/A ‡

* Standard test methods modified where appropriate to facilitate testing a Geosynthetic Clay Liner (GCL).
** Properties of bentonite removed from finished GCL product.
† D4643 modified to included wet weight as the denominator.
†† Machine (warp) direction of primary backing.
‡ Testing in progress.

Table 2.8 Partial List of Claymax® Hydraulic Conductivity Testing Data

	RANGE OF RESULTS
Standard CLAYMAX 200R	2-4 x 10^{-9} cm//sec
CLAYMAX 500SP	2-4 x 10^{-9} cm/sec
25 mm hole prior to hydration*	3-5 x 10^{-9} cm/sec
50 mm overlapped seam*	3-5 x 10^{-9} cm/sec

* = self-healing tests on damaged liner and tests on overlapped seams were performed on both CLAYMAX 200R and CLAYMAX 500SP.

Testing Parameters (ASTM D5084)

- 100-150 mm permeameter cells
- 5 kPa during hydration
- 14 kPa effective stress during consolidation

Table 2.9 Partial List of Claymax® Frictional Resistance Data

INTERFACE	FRICTION ANGLE (°)	ADHESION (KPA)
PBM: smooth HDPE	12	1
PBM: textured HDPE	22	1.9
SBM: smooth HDPE*	11	3
SBM: textured HDPE*	24	1.4
SBM: textured VLDPE	30	2.4
PBM: sand	29	0
PBM: #57 stone	31	1.6
INTERNAL	**FRICTION ANGLE (°)**	**COHESION (KPA)**
CLAYMAX 200R	12	0.2
CLAYMAX 500SP	N/A	24

PBM = Primary Backing Material
SBM = Secondary Backing Material

* = test done on CLAYMAX 500SP

the GCL, the bentonite can either be a Wyoming sodium bentonite or a treated, contaminant-resistant bentonite. The geomembrane can be either a HDPE or VLDPE with a thickness ranging from 20 to 80 mils (0.5 to 2.0 mm). Textured geomembranes can be used, as well.

Gundseal® can be installed in two ways. The first configuration is with the geomembrane side facing downward against the subgrade, and with the bentonite side facing upward against an overlying geomembrane, forming a composite system. The second configuration is with the bentonite side facing downward against the subgrade. Certain design criteria must be applied depending on how the Gundseal® is to be installed.

2.4.1 Gundseal® Composite System

When Gundseal® is applied underneath a geomembrane with the bentonite side facing upward, a composite liner system is formed. The success of the composite system is a function of the hydraulic conductivity of the system, the effectiveness of overlapped seams, the degree of intimate contact with overlying geomembrane, the internal shear strength of the bentonite, and the interfacial friction resistance between the components of the system.

2.4.1.1 Hydraulic Conductivity

The hydraulic conductivity of an intact specimen of Gundseal® has been reported to be less than 4×10^{-12} cm/s. Researchers at the University of Texas (Daniel & Shan, 1992) and at GeoSyntec Consultants (1991) have reported that the bentonite element of Gundseal® alone has a hydraulic conductivity between 1×10^{-9} and 1×10^{-10} cm/s. Therefore, the 3 mm thick layer of bentonite, when considered by itself, is equivalent to at least 300 mm of 1×10^{-7} cm/s clay. The Gundseal® system, consisting of the geomembrane and the layer of bentonite, is equivalent to well over 900 mm of 1×10^{-7} cm/s clay.

2.4.1.2 Overlapped Seams

When Gundseal® panels are overlapped, close contact is developed between the bentonite portion of one panel and the geomembrane portion of the other. Researchers at the University of Texas (Estornell, 1991) investigated the effectiveness of this overlap by performing large scale tests on two separate overlapping specimens. One sample had an overlap of 40 mm, while the other

sample had an overlap of 75 mm. Two feet of gravel and one foot of water were placed over each of the specimens. During the five-month-long test, no outflow was noted through either of the overlapping specimens. Additional testing has been performed by GeoSyntec Consultants (1991) and no flow was noted through the overlapped seams after one hundred hours.

2.4.1.3 Composite Action

The effectiveness of the overlapped seams indicates that a good composite action is formed between a geomembrane and the hydrated bentonite. Additional research at the University of Texas (Estornell, 1991) has shown that the bentonite portion of Gundseal® is able to seal off defects in an overlying geomembrane. At the University of Texas, slits and holes were cut into a geomembrane. This geomembrane was placed on top of the bentonite portion of Gundseal®, and the system was covered with gravel and water. These tests were performed for five months, during which time no flow was observed through the system. After five months, the tests were dismantled and the condition of the GCL was observed. Around the largest hole (75 mm diameter) in the geomembrane, only a 130 mm diameter area was wetted on the bentonite, thus indicating excellent intimate contact and composite action (Fig. 2.7).

The effectiveness of intimate contact between Gundseal® and an overlying geomembrane was also investigated by the engineers at GeoSyntec Consultants (1991). Their results indicated that the hydrated bentonite can effectively seal a defect in an overlying geomembrane. Water contents were taken from the bentonite portion of Gundseal® directly beneath a 1 mm diameter hole. The water content tests indicated a significant reduction in the water content of the bentonite radially away from the hole (Fig. 2.8).

2.4.1.4 Internal Shear Strength

The internal shear strength of the bentonite portion of Gundseal® has been investigated by both the Geosynthetic Research Institute (1991) and the University of Texas (Daniel and Shan, 1992). The internal friction angle for the bentonite portion of Gundseal® in an unhydrated state (water content = 17%) was found to range from 22° to 26°. The manufacturer states that due to the effectiveness of composite action with an overlying geomembrane, the bentonite portion of Gundseal® will remain basically unhydrated. Thus the internal

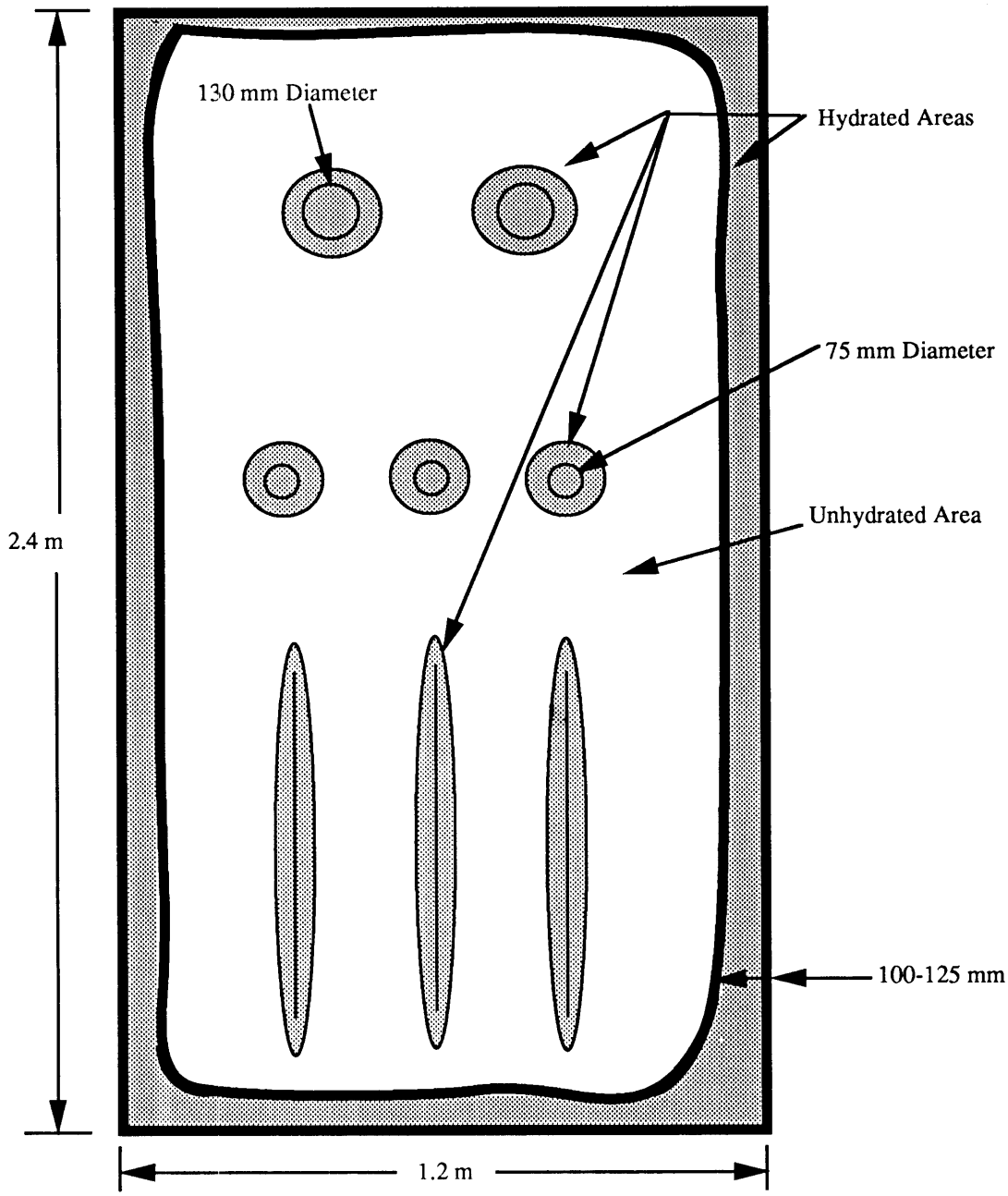
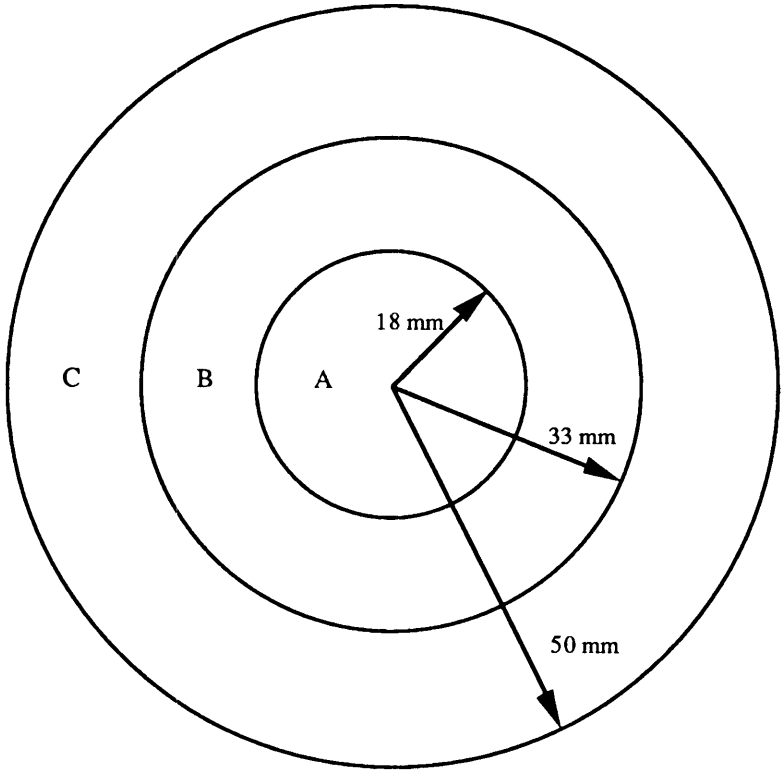


Figure 2.7 Composite Action Test with Overlying Defective Geomembrane (after Estornell, 1991)



Initial Specimen Conditions: Water Content - 7.3%

Final Specimen Conditions: Water Contents:
- Section A - 77.2%
- Section B - 30.2%
- Section C - 24.0%

Figure 2.8 Variations in Bentonite Water Content beneath a Defective Geomembrane (after Geosyntec Consultants, 1991)

friction angle of 22° to 26° can be used by designers if the bentonite remains "dry."

2.4.1.5 Interfacial Friction Resistance

The interfacial friction angle between the smooth sheet geomembrane portion of Gundseal® and the subgrade soil can be assumed to be approximately 16° (Koerner, 1990). If a higher interfacial friction resistance is necessary, the interfacial friction angle between a textured geomembrane portion of Gundseal® and the subgrade soil can be assumed to range from 25° to 32° (Koerner, 1990).

The interfacial friction angle between the dry bentonite portion of Gundseal® and the overlying geomembrane can be assumed to be 16° for smooth sheet (Koerner, 1990) and 32° for a textured sheet (Westinghouse Inc., 1991).

2.4.2 Gundseal® as a Single Liner System

In some cases, engineers and designers desire to use Gundseal® as a single liner system. This can occur in liner systems for reservoirs, disposal sites, and at hydrocarbon storage tank facilities. The major factors affecting the performance of Gundseal® in these areas are soil suction, hydraulic conductivity, internal shear strength, and subgrade contamination.

2.4.2.1 Soil Suction

The University of Texas (Daniel and Shan, 1992) recently completed a study on the effect of subgrade moisture content on the bentonite portion of Gundseal® when the GCL was installed beneath a layer of medium grained sand with the bentonite side of Gundseal® in contact with the sand. It was found that the dry bentonite has a very high suction value of 7500 kPa and will draw moisture from the sand. The amount of moisture "sucked up" by the bentonite depends upon the moisture in the sand. Equilibrium can be reached between the bentonite and the sand in a period varying from 2 to 14 days (Fig. 2.9).

2.4.2.2 Hydraulic Conductivity

If the bentonite side of Gundseal® is placed in contact with the subgrade soil, the bentonite will hydrate. Depending on the initial water content on the subgrade soil, the final water content of the bentonite can range from 50% to over 145%.

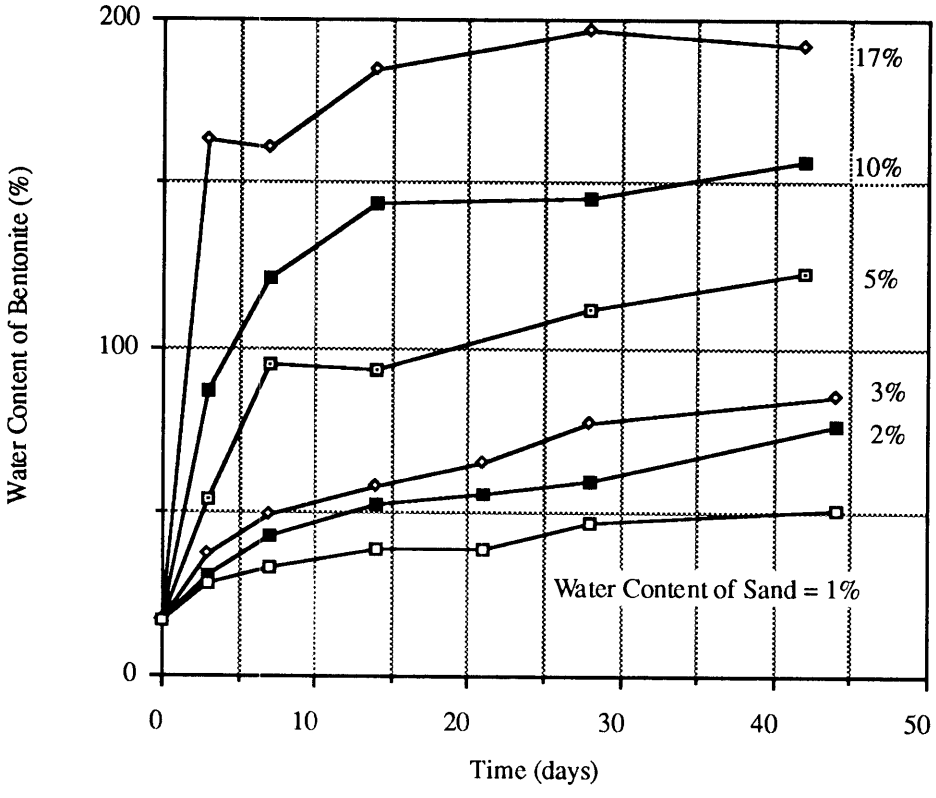


Figure 2.9 Water Content vs. Time for Samples of Gundseal® Placed Within Sands of Varying Water Content (Daniel & Shan, 1992)

The hydraulic conductivity of the bentonite portion of Gundseal® as a function of the initial water content of the bentonite was recently studied at the University of Texas (Daniel and Shan, 1992). Various hydrocarbons were used as the permeant liquid in the study. The results are shown in Table 2.10.

2.4.2.3 Internal Shear Strength

The internal shear strength of the bentonite portion of Gundseal® has been investigated by both the Geosynthetic Research Institute (1991) and the University of Texas (Daniel and Shan, 1992). The internal friction angle for the bentonite portion of Gundseal® in a hydrated (wet) state was found to 19° at a total normal stress less than 36 kPa, and 7° at higher normal stresses. Therefore, care must be taken to take into account the effect of normal stress when using a friction angle in a stability analysis.

Table 2.10 Permeability to Various Hydrocarbons as a Function of Initial Bentonite Water Content (Daniel & Shan, 1992)

PERMEANT LIQUID	PERMEABILITY (CM/S)				
	$w_0 = 17\%$	$w_0 = 50\%$	$w_0 = 100\%$	$w_0 = 125\%$	$w_0 = 145\%$
Benzene	3×10^{-5}	2×10^{-5}	5×10^{-9}	No Flow	No Flow
Gasoline	4×10^{-5}	4×10^{-5}	4×10^{-9}	No Flow	No Flow
Methanol	3×10^{-5}	3×10^{-5}	3×10^{-9}	No Flow	No Flow
MTBE	2×10^{-5}	3×10^{-6}	$<1 \times 10^{-9}$	No Flow	No Flow
TCE	4×10^{-5}	4×10^{-5}	3×10^{-8}	No Flow	No Flow
Water	2×10^{-9}	--	--	--	--

2.4.2.4 Seams

When Gundseal® is installed with the bentonite side facing down, the manufacturer recommends that tape be placed along the seam to prevent overlying cover soils from separating the seams.

Alternatively, the overlapping geomembrane of the Gundseal® can be heat seamed with fillet extrusion welding, or cap strip seams, to form a seamed membrane composite barrier.

2.4.2.5 Geotextile Separator

When placed in contact with the subsoil, the bentonite portion of Gundseal® will draw in moisture and become hydrated. While this reduces the permeability to hydrocarbons, it also reduces the internal friction angle of the bentonite. Therefore, in order to maintain the integrity of the bentonite and to prevent contamination from the lower soils, it may be necessary, in cases of nonuniform subgrades, to use a geotextile to maintain a separation between the bentonite and the lower subgrade soils.

2.4.3 Conclusion

Research has indicated that Gundseal® is an effective replacement for clay in landfill liner systems and covers. Concern has been expressed, upon occasion, by engineers, contractors, and regulators that the thin geosynthetic clay liners, such as Gundseal®, are susceptible to damage during installation. However, the installation of geosynthetic clay liners is much easier than the construction of compacted clay liners, and when the contractors utilize the same care that is needed to install a geomembrane, an effective liner or cover system is in place and protecting the environment.

CHAPTER 3
TESTING PROCEDURES

As GCLs are still relatively new to the market, the methods used to test and to interpret these tests are still in their initial stages. Each of the major GCL manufacturers is currently working to create standard methods of testing these products. Until these standards are completed, it will be up to testing companies and design engineers to decide how to set up and interpret the results of testing on GCLs. The major problem is variable results arising from different testing procedures.

Three speakers were given the opportunity to speak directly about testing procedures. The first spoke about the number of different ways one can assess the quality of the bentonite being used in the GCL product. The second spoke about the number of laboratory tests one can perform in order to determine the basic design parameters necessary to decide whether the product will perform as anticipated. The third spoke specifically about how to determine and interpret the shear strength of a GCL.

3.1 Quality Assessment for Bentonite Sealants (By Richard K. Brown, WYO-BEN, Inc.)

The use of bentonite as an environmental sealant in the development of low permeability horizontal barriers to fluid movement has become an accepted and standard practice in landfill and lagoon construction for waste containment. Despite this, and despite the fact that there are an abundance of methods available for assessing quality in bentonite, there is as yet no standard practice or accepted criteria for assessing the quality of the bentonite which is used in this capacity. This paper presents a summary of those methods which may be used for this purpose, along with a brief discussion of the suitability of each method for this task.

3.1.1 Bentonite

Any discussion of test methods used to define bentonite quality would be incomplete without a brief discussion of what bentonite is and how it works.

Bentonite is a clay composed primarily of the crystalline, hydrous alumino-silicate mineral montmorillonite. As a result, the unique physicochemical characteristics of montmorillonite define the performance capabilities of bentonite. Montmorillonite particles typically exist as minute, very broad, extremely thin, three-layered crystals which have negative electrical charges expressed on their surfaces. The presence of these charges causes inorganic cations and polar molecules, such as water, to be attracted by and absorbed to the montmorillonite crystal surfaces. There is strong evidence to indicate that water which is absorbed by montmorillonite crystals becomes bound in layers many molecules in thickness in a crystalline or quasi-crystalline arrangement similar to that found in ice. The thickness of the bound water layer is controlled by the negative electrical charge density on the montmorillonite crystal surfaces. This is modified, however, by the effect of the particular absorbed cations which are present, with sodium ions (Na^+) enhancing the effect while all other cations diminish it to varying degrees.

In dry bentonite, montmorillonite crystals tend to be arranged in a densely packed surface to surface facing structure similar to the arrangement of cards in a deck of cards. Water added to dry bentonite will be absorbed onto the crystal surfaces causing adjacent crystals to move further apart. This expansion will continue, as more water is added to the system up to the adsorption limits of the montmorillonite. This process is the cause of the swelling phenomenon observed when bentonites are wetted.

Studies have shown that the crystalline nature of the water absorbed by montmorillonite crystals appears to cause it to be immobile or to act as a highly viscous fluid, depending upon the hydraulic gradient under which it is placed. It is this resistance to flow found in the absorbed water layer on montmorillonite crystals which is the fundamental basis for the sealing capability exhibited by bentonite.

As a result, those test methods which can be used to define the water adsorption and swelling capability of bentonite should offer the best possibility of indicating sealing capability. This statement holds true only for natural, untreated bentonite or bentonite products, however. Many of the additives which are commonly used to treat bentonite sealants mask this mechanism making the definition of bentonite quality very difficult to accurately determine.

3.1.2 Primary Test Methods

The methods presented here are those which, directly or indirectly, define the sealing capability of bentonite and appear to offer the most promise, either singularly or in combination, for defining quality in bentonite sealants.

3.1.2.1. Permeameter Testing

By far the best, most accurate and most direct way of assessing the quality of a bentonite sealant would be to test its hydraulic conductivity under a standard set of test conditions. Several bentonite manufacturing companies have, in fact, established permeability performance tests specific for their own products. Unfortunately, these tests often vary in their methods and conditions making broad comparisons between products difficult. Although a standard test method now exists to facilitate this type of testing (ASTM D 5084-90) there has, to date, been no unified effort by any group to establish test conditions under which such quality testing might be accomplished. Nevertheless, standard test conditions for permeameter testing can be adopted by testing firms for project specific comparison testing in order to determine relative quality of competing bentonite sealant products.

The absence of any standardized hydraulic conductivity test data for bentonite sealant products, coupled with the high equipment cost for permeameters and slowness in obtaining test results, has led to the use of a number of other test methods which serve as indirect indicators of sealing capability.

3.1.2.2 Swell Tests

Swell tests measure the ability of a bentonite to adsorb water by measuring the increase in volume of a mass of bentonite which occurs during the adsorption process. Several methods are available which allow measurement of various aspects of the swelling characteristic.

3.1.2.2.1 Free Swell Test

This test method measures the swollen volume of a sample of powdered, dried bentonite which has been added in numerous small increments over a period of time to 100 ml of distilled water in a 100 ml graduated cylinder. Measurement of bentonite volume is made from the gradations on the cylinder.

Typically, this measurement is taken after the cylinder has set, undisturbed, for 2 to 24 hours following the final bentonite addition. In theory, this procedure gives the test bentonite the opportunity to adsorb water and swell in an uninhibited and unconfined fashion yielding a good representation of the swelling capacity of the clay. This method is easily used, requires little equipment, and typically has good reproducibility. Variations in the rate of bentonite addition, the amount of bentonite added at each addition, and the setting time allowed can all affect the result, however. Despite this, the results of this test method appear to correlate well with the results of hydraulic conductivity testing. Although no standard method currently exists for this test, one is now being developed by ASTM.

3.1.2.2.2 Modified Free Swell Index Test

This test method, developed by Sivapullaiah et al. (1987) for clays generally, measures the settled volume of clay sediment resulting from 3 additions of clay which have been mixed into a volume of water, typically 100 ml, in a graduated cylinder of suitable size, and then allowed to set, undisturbed, for 24 hours. The sediment volume is measured using the graduations on the cylinder. The resulting volume is then used to calculate the "Modified Free Swell Index" of the clay using a formula which takes into account both the weight and specific gravity of the solids used. This test is relatively simple to conduct and appears to have good reproducibility for most bentonite materials. The definition of sediment layer boundaries can be a problem when testing some high quality natural sodium bentonites as well as with some treated bentonite products, however. Reschke and Haug (1991) report that the results of this test method show good correlation with the results of hydraulic conductivity testing for compacted soil/bentonite mixtures (not pure bentonite).

3.1.2.2.3 Swelling Pressure Test

This test is included here because intuition suggests that swelling pressure should inversely correlate strongly with hydraulic conductivity. No published data have been found which establishes this correlation, however. Measurement of the pressure exerted by hydrating bentonite as it adsorbs water and swells in a confined space is typically done using consolidometers (Oscarson, et al., 1990).

As a result, this test requires both sophisticated equipment and personnel in order to properly conduct it. This may limit the wide spread use of this method.

3.1.2.3 Plate Water Absorption (PWA) Test

This test method measures the ability of a sample of powdered, dried bentonite to "absorb" water when placed on a piece of filter paper on a porous stone in a covered, water filled tray for 18 hours. The procedure for conducting this test has been standardized as ASTM E 946. When properly conducted this test is accurate to approximately $\pm$ 5%, with test values for bentonites ranging from 200 to 1100. The test is very sensitive to a number of conditions, such as variations in the thickness of the bentonite sample on the filter paper, the number of samples placed on each porous stone, the water level within the test tray, and to even minor fluctuations in temperature during the period of the test. Failure to adequately control these can result in swings in test results and very poor reproducibility. As a result experienced personnel are required for this test in order to obtain consistent results. Results from this test method appear to correlate well with the results from hydraulic conductivity testing and with the results of free swell testing. There appears to be very poor correlation between PWA test results and modified free swell test results, however.

3.1.2.4 Liquid Limit Test

This test, as standardized in ASTM D 4318, sets forth a method for determining the water content of a soil at the boundary between the soil's plastic and liquid states. This method provides us another way to measure the water adsorption capability of bentonite. Sivapullaiah et al. (1987) state that the liquid limit, when expressed on a volume basis (volume of water to volume of soil), shows a strong correlation with the modified free swell index test results. Limited data presented by Reschke and Haug (1991) suggests a strong correlation between liquid limit (as normally calculated) and both the modified free swell index and hydraulic conductivity test results for high quality sodium bentonites. These same data suggest little correlation for low quality sodium bentonites. The simplicity of this test makes it a desirable one for use in assessing sealing bentonite quality. However, additional testing is necessary to establish the relationship between liquid limit and hydraulic conductivity.

3.1.3 Secondary Test Methods

The methods described here are those which may be used in addition to the primary test methods to further assist in defining quality in bentonite sealants. These methods do not, by themselves, yield enough information to be used as independent tests. As a result these tests should never be used as the sole criterion in determining bentonite quality.

3.1.3.1 Apparent Colloid Content Test

This test method measures the fraction of a 2% water-dispersed sample of bentonite that remains in suspension after an 18 to 24 hour settling period. In theory, this test should be capable of measuring the montmorillonite content of a bentonite sample because montmorillonite crystals should all be smaller than the 0.5 micron size threshold delimiting colloidal size particles which, by definition, are small enough to stay permanently in aqueous suspension. Unfortunately, factors such as incomplete sample dispersion, flocculation due to chemical contaminants, and the effects of various additives all act to bias the test results. In effect this test is simply a larger version of the Modified Free Swell Index Test which was previously described, although different methods of analysis are used in this method. When analyzed using the criteria of the Modified Free Swell Index Test the results produced by the apparent Colloid Content Test do not duplicate the results of the other test. Further, the Apparent Colloid Content Test does not correlate strongly with the any of the primary tests, exhibiting only moderate correlation with the Free Swell Test and the PWA Test.

3.1.3.2 X-Ray Diffraction (XRD) Mineralogical Analysis

X-Ray Diffraction analysis of a bentonite sample can be used to determine its approximate mineralogical composition. However, because XRD is a semi-quantitative method absolute percent compositions are not possible. Further, while some inferences can be drawn from the results of this test as to the quality of the montmorillonite crystals in a sample it is not possible to make any accurate statements about sealing capabilities of the bentonite sample being tested based solely on XRD results. At best, this method can be expected to provide only a close approximation of the amount of montmorillonite present in a sample.

3.1.3.3 Cation Exchange Capacity (CEC)

The methods used to determine CEC measure the negative charge present on the montmorillonite crystals in a bentonite. Although other, more accurate methods are available, the CEC of bentonite is most often measured by determining the ability of a sample to adsorb the positively charged dye, methylene blue. The Methylene Blue Dye Test has been standardized by the American Petroleum Institute. The Methylene Blue Dye Test is capable of yielding consistent, reproducible results when properly performed, although these results are generally slightly lower than those produced by other CEC determination methods.

3.1.3.4 Specific Surface Area

This test provides a measure of the montmorillonite crystal surface area upon which water can potentially be adsorbed. Generally, higher surface area values should be indicative of high quality bentonites having low hydraulic conductivity. Limited data presented by Reschke and Haug (1991) show only moderate correlation between surface area and hydraulic conductivity.

3.1.3.5 Chemistry

Definition of the gross chemical composition of bentonite, using X-Ray Fluorescence or wet chemistry techniques, as well as definition of the exchangeable cations present, using both wet chemistry and flame photometry, can offer insights into bentonite quality. For example, Reschke and Haug (1991) found that a strong correlation existed in the bentonites they tested between the $SiO_2Al_2O_3$ ratio and the quality of the material, while Alther (1986) found the ratio of exchangeable sodium, calcium and magnesium had a significant effect on the rheological and contamination resistance properties of bentonite. It must be remembered, however, that the results of bentonite chemical analysis are only useful when they are evaluated in the context of the results from other testing. A wide variety of relationships between gross chemical and exchangeable cation chemistries which would yield similar quality bentonites are no doubt possible.

3.1.4 Conclusion

Quality in bentonite sealants is specifically defined by the level of impermeability or hydraulic conductivity achievable by a particular bentonite.

Permeameter testing under a set of standard test conditions, therefore, offers the most direct method of determining the quality of a bentonite sealant product. Where this cannot be done, the water adsorption and swelling capabilities of a bentonite, which are both fundamental characteristics of the sealing process, may also be tested as indirect indicators of sealing effectiveness. A variety of test methods may also be employed to define other bentonite characteristics such as mineralogical composition, specific surface area, cation exchange capacity, and others which, in combination with the results of water adsorption and/or swelling tests, can serve to give a more complete picture of the quality of bentonite sealants. However, additional test methods do not provide sufficient information about the mechanism of the sealing process to enable them to be used independently or as the principal method for determining bentonite sealant quality.

3.2 Conformance Testing of Geosynthetic Clay Liners (By John Boschuk, Jr., J & L Engineering, Inc.)

As part of important construction activities using man-made or natural materials, the engineer needs verification that specific materials for the project conform to the design requirements and will perform as anticipated. Over the past several years, a number of basic tests for each of the major geosynthetic types have evolved and are included in specifications as conformance tests. These tests are typically performed on material samples taken from the rolls as they are manufactured or from the rolls on-site before the material is deployed.

Geosynthetic clay liners are increasingly being used in many projects and may be considered relatively new to many engineers and regulators. Conformance testing for these products is not yet well defined. The purpose of this discussion is to suggest guidelines for testing methods and test frequencies necessary to verify conformance of the materials with the design engineer's requirements.

Unlike most other single-material-component geosynthetics, GCLs are a combination of two or three different elements fused together to create a single composite material. Two of the three elements consist of man-made geosynthetics and the third is a processed natural material containing additives

to bond the particles, assist in fusing the material to the geosynthetic or to improve performance of the bentonite.

Considering the differences in the products, two basic choices exist for conformance tests:

1) Test the individual elements of the composite.
2) Test the composite as a single material.

The first option is generally very difficult to exercise since the components are bonded together. Separating the layers to perform tests on each material component would probably damage the components and yield misleading test results. Consequently, it is more logical to test the products as a composite. Furthermore, the designer selected the material to function as a composite and the design is based on the geosynthetic working as a composite.

3.2.1 Testing Options

As part of the research for this paper, the author queried the major users of the material to determine what conformance tests they typically perform on GCLs. Not surprising, testing has generally been limited to hydraulic conductivity of the GCL, coupled with manufacturer's certifications. Often no conformance testing is performed and verification is limited only to manufacturer's certifications.

Further research indicates that no specific conformance, or even quality control, testing of these products is typically specified other than hydraulic conductivity. Verification is usually limited to visual inspections and visual field checks to insure the material is not saturated until it is sealed and covered with a confining load.

Before suggesting test protocols, an evaluation of the engineering properties is warranted. First and foremost, the GCL products are being marketed as a low permeability barrier. Consequently, hydraulic conductivity and compatibility with the liquid to be retained should be emphasized. However, there are several other important considerations, e.g., shear strength.

3.2.1.1 Shear Strength

As part of the design, the engineer may need to evaluate shear strength of the composite and develop design properties for the material. Once production of the material commences, verification of conformance to performance characteristics would then be warranted.

3.2.1.2 Tensile Properties

For some designs the product may be subject to short term tensile stresses such as during deployment. In this case the engineer would determine what allowable tensile loads can be applied to the product without adversely affecting other properties. Once these maximum allowable stresses are determined, conformance testing would be specified to insure that the production materials meet these standards.

In other instances, a design may require the product to be subjected to unavoidable long term or residual stresses. If this is the case, long term creep strains may occur and reduce its performance characteristics. Once the engineer determines the maximum allowable sustained stress, criteria can be established for design testing to verify material capabilities. Due to the duration of creep testing, conformance testing is probably not warranted if the design carefully considers these conditions.

3.2.1.3 Puncture Resistance

These products all have some puncture resistance capability. The engineer's design testing program would evaluate how the material will perform under the design conditions. Conformance testing is most likely not warranted to verify this property. Competent field visual observations to insure that the GCL is installed properly should suffice to insure performance.

3.2.1.4 Biaxial Stresses

Under certain conditions GCLs may be subject to differential settlements such as in landfill cover systems. As part of the design, the engineer may perform tests to assess performance and to establish design parameters. These assessments may include biaxial stress tests followed by other engineering tests on the stressed material. With these properties established, conformance testing

under biaxial conditions may be warranted to verify material compliance with critical design criteria.

3.2.1.5 Freeze-Thaw and Desiccation

GCLs contain bentonite which can be subjected to freeze-thaw and desiccation that may affect performance. As part of the design process, these conditions are evaluated and the design adjusted to accommodate these concerns. Although conformance testing may be warranted under certain unique conditions, bentonite supplied for these products is generally very uniform and accompanied by supplier certifications and supplier QC testing. Research to date also indicates that bentonite has unique healing properties after freeze-thaw and desiccation. Proper design to accommodate freeze-thaw and desiccation, coupled with supplier testing and certification documents, will most likely be sufficient to insure satisfactory performance.

3.2.2 Suggested List of Conformance Tests for GCLs

Considering these design and performance elements a suggested list of conformance tests is presented as a recommendation to design engineers:

3.2.2.1 Hydraulic Conductivity Testing

Two types of hydraulic conductivity tests are available: flexible-wall permeameters (ASTM D5084) and rigid-wall permeameters. A schematic of each is presented in Fig. 3.1 and 3.2. A modified large-scale rigid wall apparatus, which is large enough to test seams in these products, is shown in Fig. 3.3. When specifying these tests, it is recommended that the permeant be similar to the liquids which will be exposed to the in-place material. Hydraulic gradients and pressures should be specified by the engineer. Extreme care should be exercised to insure the material is saturated and sealed at the sample edges.

3.2.2.2 Shear Strength Testing

Direct shear tests through the plane of bentonite can be performed on either the standard 100 mm shear box or 305 mm shear box. J&L Engineering has performed comparative tests with these products using both types of apparatus and found the 100 mm shear box to be satisfactory for GCL materials. The engineer should specify normal loads, rates of strain, liquid of saturation, fixity

conditions, and preferred size of sample. Figures 3.4 and 3.5 present schematics of the test configurations and fixity conditions.

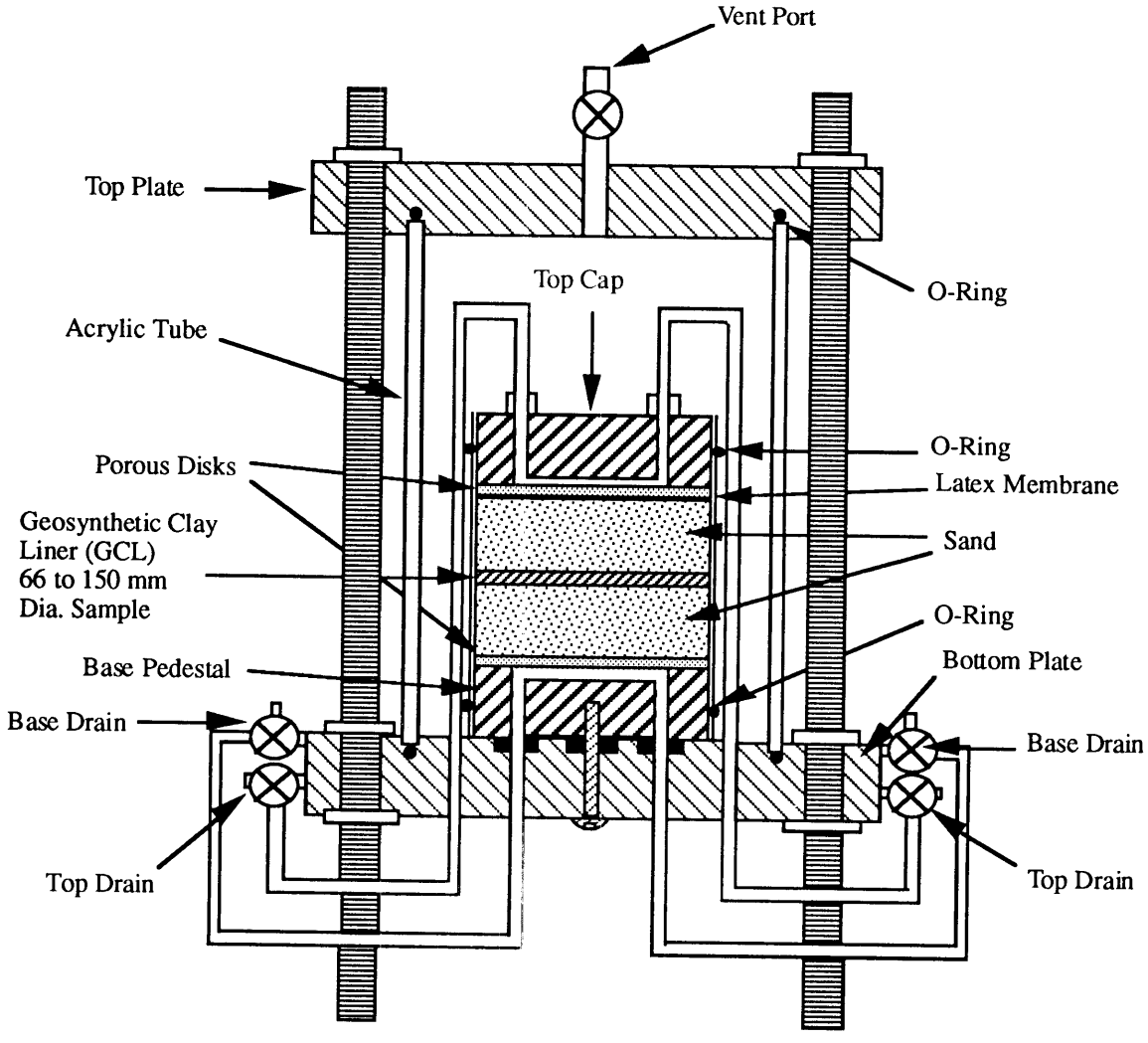


Figure 3.1 Flexible-Wall Apparatus

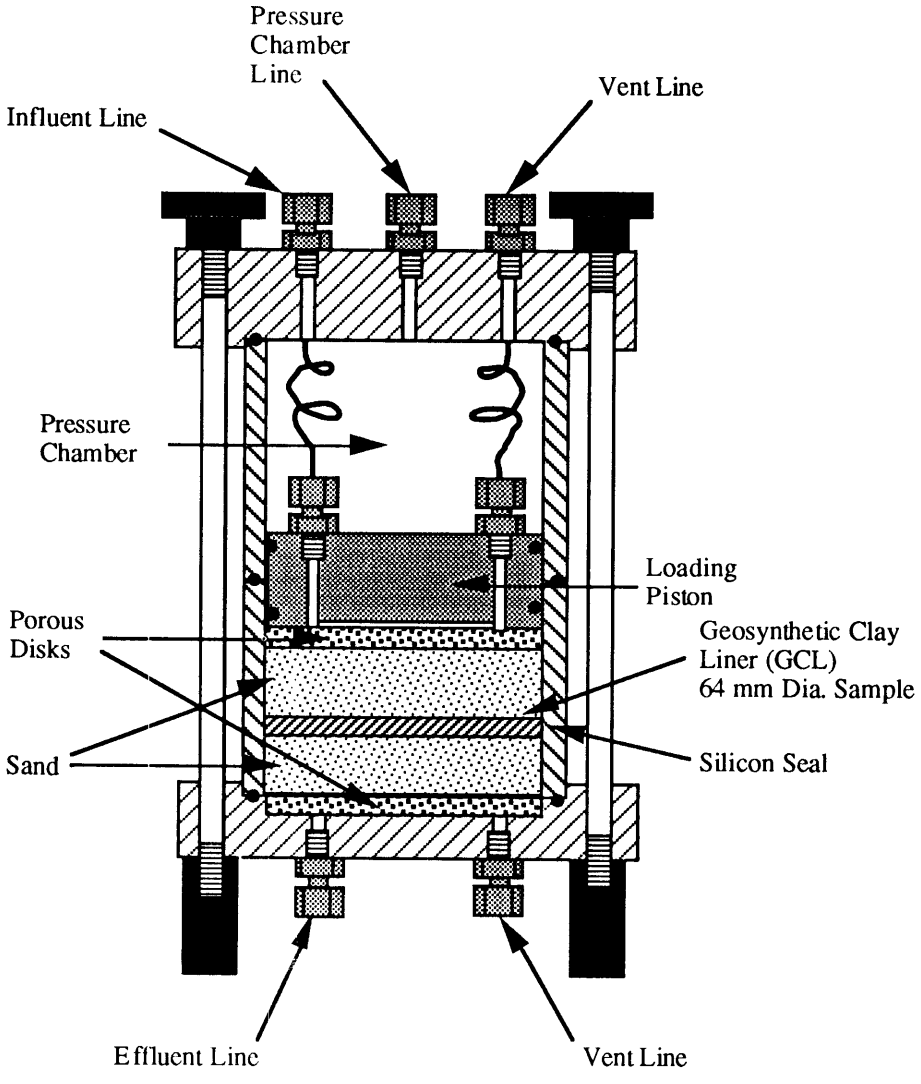


Figure 3.2 Rigid-Wall Apparatus

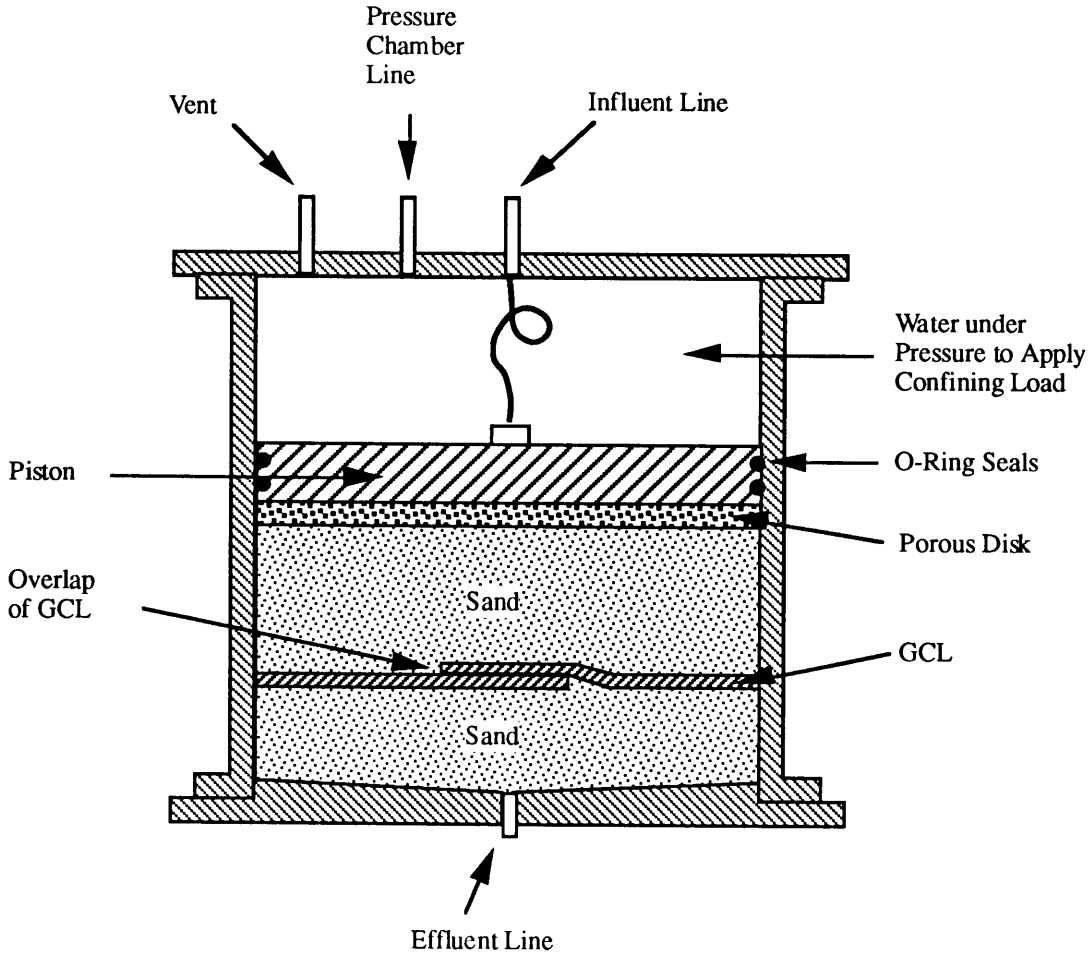


Figure 3.3 Large Diameter Rigid-Wall Apparatus

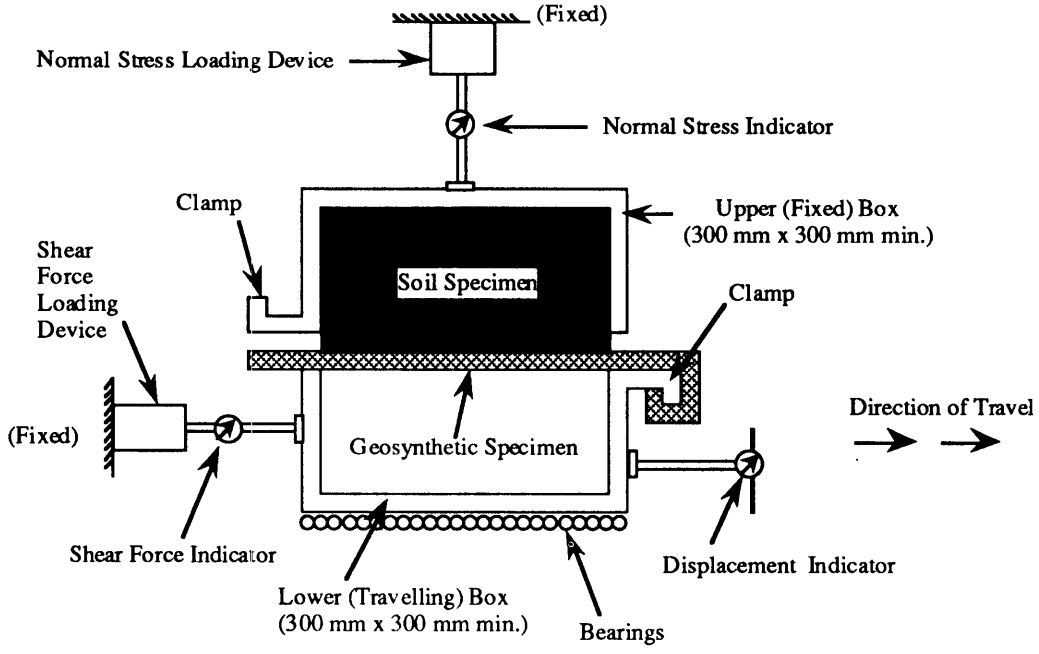


Figure 3.4 Typical Direct Shear Friction Apparatus Schematic

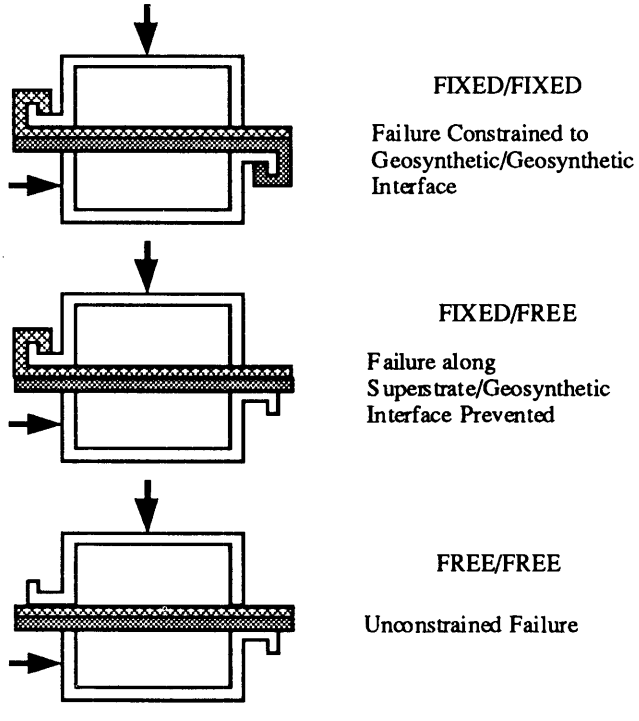


Figure 3.5 Geosynthetic/Geosynthetic Direct Shear Testing

3.2.2.3 Tensile Property Testing

For short term peak stress considerations, wide-width tensile testing per ASTM D4595 is the most appropriate nationally recognized test procedure available (Fig. 3.6). Care must be exercised to insure that the multiple composite is properly clamped. The engineer may have to specify the grip type to insure comparable results between the design and conformance tests, which may be performed by different laboratories. As previously discussed, peak stresses may develop during deployment of the GCL. Therefore, this testing would be performed on the dry products.

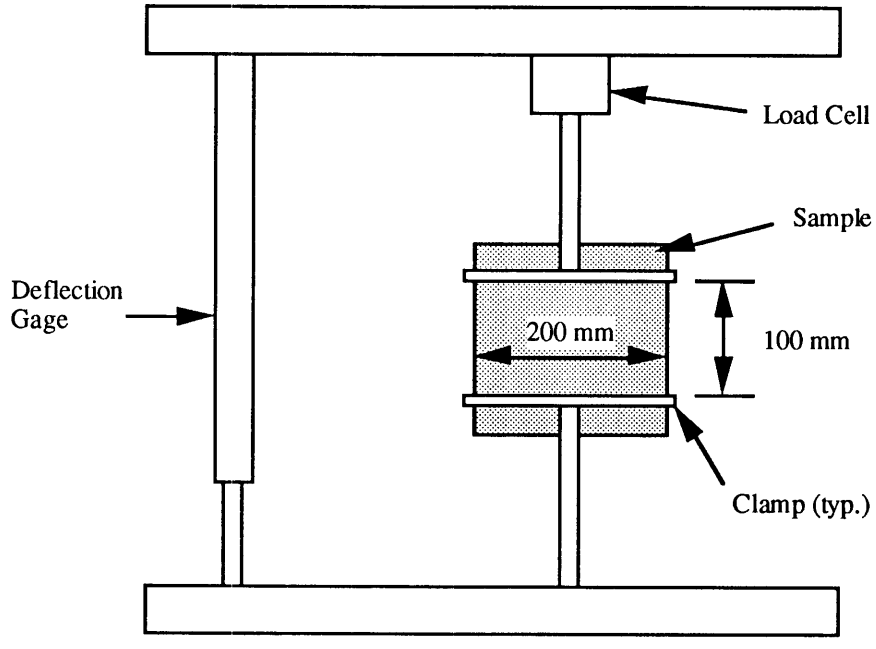


Figure 3.6 Wide Width Tensile Test Schematic (Source: John Boschuk)

Creep testing is probably not warranted in that the design addresses this issue and creep testing requires a long period of time to perform. If required to insure compliance, the material should be saturated with the same type of liquid the product will be exposed to in the field (Fig. 3.7).

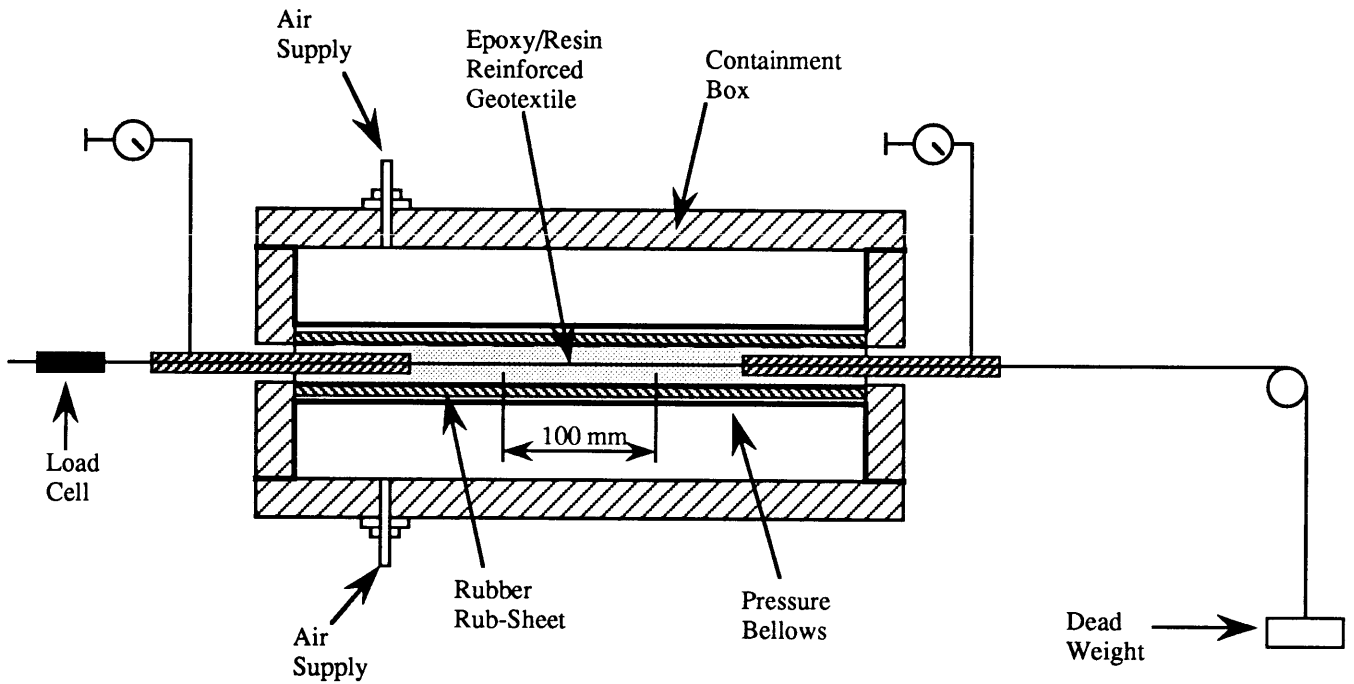


Figure 3.7 Cross Section of a Horizontal Containment Box in a Confined Creep Test Mode (Source: John Boschuk)

3.2.2.4 Biaxial Stress Testing

Biaxial testing per GRI Test Method GM4 can be specified as a conformance test to assess material bonding performance under conditions similar to those in the field. The fluid used in the test should be similar to the fluid the material will be exposed to in the field. The engineer should specify the fluid, pressures, rate of pressure increase and allowable deflections (Fig. 3.8).

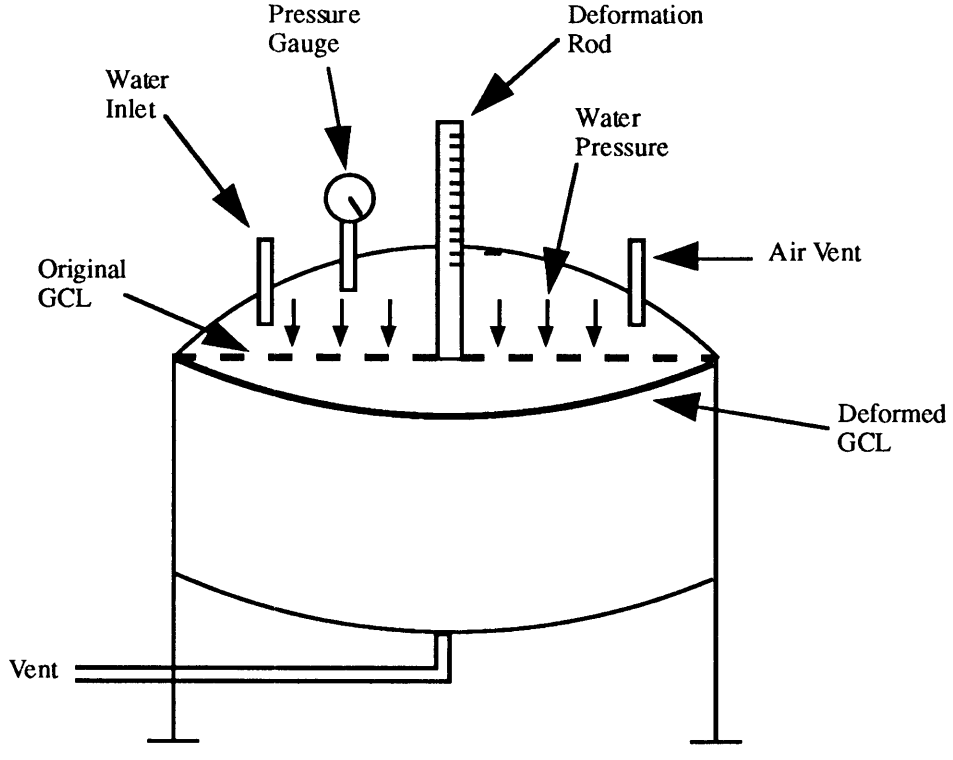


Figure 3.8 Biaxial Test Apparatus Schematic (Source: John Boschuk)

3.2.3 Testing Frequency

Typically, conformance tests are performed at a rate of one test series per 9000 m^2 of product manufactured during a single run. If products are obtained from a stockpile consisting of materials from different runs, testing frequencies should be increased to insure that all runs are adequately tested. Recently, at several projects of which Mr. Boschuk is aware, the testing frequency has been increased to one test series per 4600 m^2 of product. The engineer may have to negotiate this frequency with regulatory authorities.

3.2.4 Conclusion

GCLs are relatively new to the industry and conformance tests are still evolving. This presentation attempts to present technical considerations to establish a conformance test program for GCLs which focuses on verification of the designed performance properties of the product for its specific application. Testing frequencies have also been suggested based on the testing frequencies used for other geosynthetic materials.

It is important to note that these products are still evolving. Manufacturers may be adjusting and changing the geosynthetics used in their products, adjusting the methods of bonding the materials and even the types and distribution of the bentonite used in the products. It is important that whatever product is evaluated in the design be the same product used in the field. Specifications need to address this issue and the manufacturer should be consulted to insure the product tested in the design is the same product used during construction.

3.3 The Determination and Interpretation of Shear Strength (By Robert Bachus, GeoSyntec Consultants)

The topic of shear strength is familiar to anyone associated with geoenvironmental engineering. With the development of geosynthetic clay liners (GCLs), engineers are now faced with the task of evaluating the ability of GCLs to transmit shear at an interface, or through the liner system. The solution to this is to simulate expected field conditions in the laboratory in an attempt to model and test the expected mode of shearing failure. The problem is that the "shear strength" of the GCL is actually composed of three distinct components (internal

shear strength, interfacial frictional resistance, and tensile strength). This breakdown into the different components of shear strength coupled with the fact that lab and/or field conditions greatly influence their value, makes the fundamentals of shear strength much more complex than most people realize.

3.3.1 Test Conditions

The shear strength of a GCL must be determined under conditions matching those anticipated in the field. When incorporating a friction angle into a slope stability analysis one cannot expect any degree of accuracy if that friction angle was determined under conditions varying widely from those in the field analysis. The variation in normal stresses, degree and type of fluid hydration, rate of shear, and method of failure are all important variables that a designing engineer must consider.

3.3.1.1 Normal Stress

Over a small range of normal stresses there may appear to be a linear relationship between normal stress and shear stress at failure (Mohr-Coulomb failure envelope), but if taken over a broader range of normal stresses, this relationship may not be linear. Therefore, the shear strength parameters of angle of internal friction (Φ') and cohesion (c') are not constant and depend upon the range of normal stresses over which they are determined. Unfortunately, friction angles and cohesion values are often published without any reference to the normal stress at which they were determined. One must remember that Φ' and c' are not inherent properties of a GCL, but rather a convenient way of representing the shear and normal stresses acting along a plane at the time of failure.

3.3.1.2 Hydration Conditions

In addition to the type of fluid and the length of time for hydration, the method used to hydrate the GCL can affect the measured internal shear strength. For example, prior to direct shear testing, a GCL sample can be hydrated under a normal load in or out of the shear box. Due to sample disturbance caused by unloading and reloading, the sample hydrated outside the shear box will have a different shear strength than the undisturbed sample hydrated within the shear box.

Another concept to consider is when should a hydrated GCL be considered saturated? The bentonite within a GCL is generally a non-homogeneous mixture of individual nodules. These nodules will tend to adsorb any free water. Thus, at what water content will adsorption cease, and the sample be considered saturated?

3.3.1.3 Rate of Shear

One of the testing variables most often overlooked is the rate at which the sample is sheared. The slower a hydrated sample is sheared, the more time excess pore water pressures have to dissipate. Thus the shear strength of a saturated GCL is directly related to how quickly the sample is sheared.

This is why geoenvironmental engineers specify whether the shear strength parameters Φ' and c' are for drained or undrained conditions. If a hydrated sample is loaded slowly enough that excess pore water pressures have time to dissipate, then the test is considered drained. If an engineer performs a long term slope stability analysis (i.e. drained conditions), he must test a representative sample under drained conditions as well. Due to the low hydraulic conductivity of sodium bentonite, a direct shear test cannot be carried out in a day on a GCL. Using the methods proposed by Gibson and Henkel (1954), the time to failure can be estimated for very soft clays as $t_{failure} = 50t_{50}$, where t_{50} is the time required to achieve 50% consolidation under the normal stress being used. Using a constant shear rate of 0.02 mm/hr (1.31×10^{-5} in/min), researchers at the University of Texas (Daniel & Shan, 1991) found that the peak shear stress was typically reached after 5 to 20 days of shearing for GCLs incorporating sodium bentonite. Only two samples failed in less than five days. Based on previous consolidation tests, the calculated minimum time to failure was approximately 3 days. Thus, for these tests, the rate of shearing was slow enough to ensure full dissipation of excess pore water pressure at the time of failure.

Hydrated sodium bentonite clays have also been known to be susceptible to creep. What effect does the long term sustained transmission of shear loads have on the shear strength of a hydrated GCL? This question requires further study.

3.3.1.4 Method of Failure

The type of testing equipment can predetermine the mode of failure of a GCL. A direct shear test would be used to determine the internal shear strength of a GCL, while an inclined tilt table would be used to measure interfacial friction resistance. Finding the tensile or internal shear strength of a stitch bonded or needle punched GCL can be more difficult due to localized stress concentrations caused by the stitching. Direct shear tests have been modified in order to force the failure plane through the stitch or needle punch bonding.

3.3.2 Conclusion

While a lot of time and money can be put into measuring the shear strength of GCLs, this information will not be very effective if it is not interpreted correctly. One must remember that there is a non-linear relationship between normal stress and shear stress at failure (curved failure envelope). Not only are Φ' and c' affected by normal stress, but also by the degree and fluid of hydration. The testing conditions must always be specified when determining the shear strength of a GCL. These testing conditions not only should match anticipated field conditions, but should also be listed with the final results in order that others may understand how to interpret the results.

CHAPTER 4
INTIMATE HYDRAULIC CONTACT WITH GEOMEMBRANE

4.1 Intimate Contact for GCL/Geomembrane Composite Liner Systems (By John Bove, Hazen and Sawyer, P.C.)

The concept of "intimate contact" within composite liner systems for waste disposal and storage facilities is not a new one. The intimate contact approach is intended to minimize the lateral migration of fluid that may pass through defects in the geomembrane, which is typically the upper component of the composite liner. This concept enhances the contribution of the soil liner component of the composite system in minimizing leakage through the liner and discourages the use of a geotextile directly beneath the geomembrane.

Empirical and theoretical analyses of composite liner performance persuasively highlight the advantages of intimate contact. Analyses indicate that the presence of a high transmissivity drainage medium directly below the geomembrane may increase the leakage rate through the liner by several orders of magnitude compared with a composite system with good contact between the components.

4.1.1 In-Situ Behavior of a GCL

Depending on the in situ conditions, the GCL may exhibit behavior similar to anything ranging from a thin geotextile to a compacted soil liner in good contact with the geomembrane. When considering the use of a GCL as a substitute for the compacted soil component, it is important to understand the mechanisms that may interrupt the ability to attain "intimate contact." Possible mechanisms include:

- Excessive transmissivity within the upper GCL geotextile (e. g., an excessively thick upper geotextile)
- Gaps, cracks, or breaks in GCL or at GCL panel ends
- Imperfections in overlapped GCL seams
- Localized wrinkles in GCL and/or geomembrane

- Uneven GCL subgrade surface

If a designer, owner/operator, or regulator believes that the presence of the mechanisms listed above, or any others not listed, will prevent "intimate contact," the use of GCLs in place of soil may be restricted. This provides a challenge to the producers and users of GCLs.

4.1.2 The Case For Geotextile Placement Within a Composite Liner

The use of a thin geotextile between the soil and geomembrane components of the soil liner system, while providing a drainage pathway, can only transmit a finite quantity of fluid that has passed through a geomembrane defect. This quantity is one or two orders of magnitude less than the upper bound theoretical volume predicted by research conducted by the EPA (assuming that the quantity of leachate at a given hydraulic head is always available at the defect location). For thinner geotextiles with relatively low hydraulic transmissivity, the volume of fluid that can be laterally transmitted may be smaller than the quantity of fluid potentially generated by consolidating soils or the dehydration of a GCL.

Even though a quantity of fluid can be transmitted laterally, it must still pass through the bentonite component of a GCL before it can be considered as leakage through the composite liner. For an intact GCL having a hydraulic conductivity in the range of $1x10^{-9}$ to $1x10^{-10}$ cm/s, this is a difficult task. In reality though, the flow through the system is most likely to be controlled by the apparent hydraulic conductivity and transmissivity of GCL seams and defects, rather than the upper layer geotextile alone.

In an effort to increase slope stability, a separate geotextile placed between the geomembrane and the underlying soil liner may actually allow for the dissipation of excess pore water pressures. Thus, an increase in the internal shear strength is realized at the expense of an increase in lateral flow.

4.1.3 Evaluation of Potential Leakage Rates

A significant step in understanding the future role of GCLs in composite liner systems would be to define "intimate contact" in terms that may be measured in the laboratory or the field. Clearly a composite system can allow "some" volume of lateral drainage and still function as intended. The Action Leakage Rate (ALR) quantity of 187 L/hectare/day often used for double lined

systems with leak detection layers can provide some perspective on allowable leakage rates per defect.

For the evaluation of localized fluid transmission at the geomembrane/GCL interface (i.e. where "intimate contact" has not been attained), the quantity of leakage through a defect is a function of the hydraulic head, size of the defect, and the properties of the GCL. If a defect having an area of 1 cm^2 is considered with a constant head of 30 cm (1 ft), then the leakage quantity through a GCL specimen is mainly a function of the following GCL properties:

- Initial transmissivity of the upper GCL geotextile
- Rate of hydration of the bentonite
- Extrusion of bentonite into the upper GCL geotextile (i.e. long term transmissivity of the upper GCL geotextile)
- Continuity of the leakage source (i.e. steady state)
- Vertical percolation rate through the GCL (initial and long term)

If it is assumed that bentonite can intrude into the pores of the upper geotextile, the hydraulic transmissivity of that interface will decrease. While the rate of leakage may be initially high, it could decrease with time to a level that is insignificant in terms of the leakage quantities through the composite liner.

4.1.4 Ongoing Research

The issue of whether migrating bentonite can reduce the transmissivity of the upper geotextile has been evaluated in laboratory research funded by the GCL manufacturers. There has been a lot of attention paid to the initial leakage rates as opposed to the longer term rate. With relatively small scale laboratory GCL specimens (150 to 300 mm diameter), the fluid initially introduced to the GCL through the geomembrane defect often flows out of a radial flow device before the GCL can hydrate. If the test specimens were larger in diameter (600 to 1500 mm), it is conceivable that lateral flow from the edge of the specimens would not be observed even from the GCL specimens with the highest initial leakage rate. From a design standpoint, this is the critical behavior to quantify.

To begin to define the role of a GCL in an "intimate contact" composite liner, the investigation of the rates of hydration of larger GCL specimens at the geomembrane interface should be coupled with ongoing research on GCL seams and shrink/swell behavior to estimate the effective radius of saturation of a GCL. This radius will determine the area that has been essentially saturated such that vertical percolation through the bentonite component of the GCL will begin to occur. This area can be used to estimate long term leakage through the composite liner. This is the quantity that is of the greatest concern to the waste industry and will provide the information necessary to evaluate the use of GCLs. If the maximum computed leakage is acceptable, then GCLs can be considered as a replacement for portions of or all of the compacted soil component.

4.2 Questions from the Audience

Upon the conclusion of his lecture, Mr. Bove held a question/answer session where several important topics were discussed.

1) From the point of view of intimate contact, what is the difference between a compacted clay liner and a GCL?

Ans) The use of a GCL potentially introduces an interface that allows flow. The important point though, is how much flow occurs, and can we get sufficiently low flow with either the compacted clay or the GCL?

2) As the upper geotextile of a hydrated GCL is said to be "plugged up" with migrating bentonite, why is there such a concern for the transmissivity of the upper geotextile?

Ans) From a regulatory standpoint, a geotextile is a geotextile whether it is incorporated into a GCL or not. And if the placement of a geotextile beneath a geomembrane is unacceptable, then the same goes for a GCL incorporating an upper layer geotextile. One could make the geotextile thin enough that lateral flow does not become a big issue over time, or one could have the mentality that there is no geotextile that is satisfactory.

While manufacturers and testing companies may claim that once hydrated, a GCL makes good contact with an overlying geomembrane, until this is demonstrated on a full scale sample, some skepticism will remain.

3) Could a layer of condensed water between a geomembrane and a compacted clay liner be a potential pathway for lateral transmission?

Ans) Depending on the overburden stress, it would most likely provide a localized pathway as opposed to a continuous one.

4) Which provides better intimate contact, a smooth or textured geomembrane?

Ans) This is a difficult question that depends on a lot of factors. For example, if one has a very hard compacted clay liner and a textured geomembrane under low normal loading, one could easily imagine high levels of lateral flow if the geomembrane does not penetrate the liner.

5) If the concern revolves around a damaged geomembrane, why not place a thick geotextile or a GCL protection layer on top of the geomembrane in order to prevent damage as it is done in Germany?

Ans) This is a good point in that designers need to get out of the mode that a GCL will just replace the layer of compacted clay. A new design philosophy is necessary to realize the full potential use of a GCL.

4.3 Final Comments

Part of the purpose of displaying ranges of geotextile transmissivity data was to show that the amount of water that can potentially move laterally the geotextile component of a GCL is very small. Furthermore, the distance traveled by this liquid is limited by GCL hydration. Mr. Bove stated that the risk of significant leakage through a GCL in this mode is very small, especially in double composite liner systems.

The question of intimate contact between a geomembrane and a compacted clay liner was raised by several people. It was pointed out that wrinkles in the geomembrane make intimate contact with a compacted clay liner questionable.

CHAPTER 5
OWNER/OPERATOR EXPERIENCES AND CONCERNS

Representatives from four waste disposal companies were given the opportunity to voice their opinions on the use and performance of GCLs. While one company representative was very confident of the ability of GCLs to perform, the others expressed concerns over several technical issues.

5.1 Clarke Lundell, Representing Waste Management of North America, Inc.

Up to now, the use of GCLs has been limited to a backup role. Typically, GCLs are placed as a redundant seepage barrier in secondary liner systems for which only a single geomembrane liner is required. The company is reluctant to make a general statement about whether a GCL can be used alone in the primary liner when no secondary liner is present. This decision would be dependent on the geologic conditions at the site.

There needs to be more information gathered about GCLs. While it appears that the products do work, more work is needed to determine why they work.

Some of the issues that need to be investigated are:

- Intimate contact with a geomembrane
- Frictional properties
- Hydration and swelling
- Quality assurance
- Storage
- Deployment
  - --What equipment should be used?
  - --What about soft subgrade?
  - --Weather factors

5.2 Charles Rivette, Representing Browning-Ferris Industries (BFI)

While GCLs have been used within the company, there is not a general consensus on them yet. If one polled a representative from each of their 100 landfill sites, one would most likely get 100 different answers. Within their sites

in the United States, the use of GCLs has mostly been limited to sumps, header pipes, and as secondary containment for leachate and fuel storage. However, in Italy, BFI has some sites in use, or permitted for later use, where a GCL is the primary seepage barrier. The most likely future use of GCLs will be in cover systems used to cap older landfills that were closed in the 1960s.

The company still has some concerns about the products. Some of these concerns are:

- Construction

  --There is still some concern about how to successfully install a GCL. An example was given describing a site in Louisiana where a GCL was installed below an HDPE geomembrane. Before installers could completely seal off the upper geomembrane, a sudden rain storm hydrated the yet unfinished liner. The effort involved in the ensuing clean up and reinstallation was enormous.

- Quality assurance/quality control (QA/QC)

  --QA/QC is not only important for construction, but for the manufacturing of the products, as well.

- Cost

  --Due to the high costs of clay in the Northeast, and along the West coast, GCLs are more likely to be used. In the South and Midwest, where suitable clay is readily available, compacted clay liners are going to continue to be used extensively.

- Interface friction

  --The use of canyons and valleys for landfill sites has become more common. Unfortunately, during interim fill conditions there exists the possibility of a massive wedge failure for bottom slopes of only 2 to 4 %. While they would like to attain a factor of safety of 2 for their designs, they often cannot even achieve a factor of 1.5 when using current interface friction values in their analysis.

  --The values of interfacial friction angles measured so far have been highly variable. They would like to see more repeatability of results.

At the present time, BFI has one site in use and at least three liners in the process of design and/or obtaining a permit where a composite HDPE/GCL

system is serving as the primary liner. In each case, the design is necessary due to the lack of local clay soils at the site.

5.3 Kurt Shaner, Representing Chambers Development Company, Inc.

At the present time, Chambers operates or is in the process of permitting 20 municipal solid waste landfills. GCLs are incorporated into the liner system at 10 of these sites. Of these 10, 5 sites are in operation, 3 are permitted with construction ongoing, and 2 are in the permitting process. The most common application of the GCLs has been in the formation of primary composite liners at double lined sites.

While the company views GCLs as a positive development in the area of liner technology, is still has some concerns. Some of these concerns include:

- Quality Assurance Standards

  -Uniform procedures for the QA/QC of the manufacturing and installation of GCLs are needed.

- Shear Strength Determination

  -Repeatable results for the testing of internal and interface friction need to be determined. This testing should account for variables such as normal stress, shear rate, amount of hydration, hydration liquid, etc. Potentially, a data base could be created to correlate between each of the variable parameters and frictional resistance.

- Construction Considerations

  -Some problems with premature hydration have been encountered due to leaking trailers and precipitation events. While not a problem with the performance of the material, it does illustrate a difficulty with the installation of the product.

Perhaps the greatest benefit of the use of GCLs is the ease of their installation compared to CCLs. The installation of GCLs does not require compaction nor the control of moisture content and can be completed in cold weather. The non-applicability of these factors improves the probable quality of an installation, especially when placed to form a primary composite liner.

5.4 John Workman, Representing Laidlaw Waste Systems

Due to the abundance of clay at each of their sites, Laidlaw has never incorporated GCLs into any of their designs. For GCLs to be used at a future date, the reliability of the product will have to be well established. Some of the criteria used to ensure this reliability are discussed below:

- Efficiency
  --The efficiency of a liner system refers to its ability to shed water. Efficiency is a measure of the amount of leachate diverted to a drainage sump versus the amount that percolates through the liner.
- Damage resistance
  --There is the human element of big, bulky equipment being operated at sites. This equipment, if improperly handled, can damage a liner.
- Long term performance
  --Chemical resistance
  --Leakage potential
  --Break through potential
- Constructability
- Availability
  --The company is not opposed to the use of GCLs. It has just always had a readily available source of clay at its sites. There are some sites that do not have clay, and the use of a GCL may be warranted at these sites.

CHAPTER 6
RECENT RESEARCH

Representatives from the University of Texas and Drexel University were given the opportunity to discuss the results of the most recent research undertaken at their respective universities. Research at the University of Texas has tended to focus on large-scale hydraulic conductivity testing and on the stability of final covers. Research at Drexel University has concentrated on the hydration behavior, swelling characteristics, and internal shear strength of GCLs.

6.1 The Hydraulic Conductivity of Large Scale Intact, Overlapped, and Composite Geosynthetic Clay Liners (By David Daniel University of Texas)

The hydraulic conductivity of three 2.8 m^2 geosynthetic clay liners (GCLs) was measured. The apparatus is shown in Fig. 6.1. Tests were performed on Bentomat®, Claymax® 200R, and Gundseal. The GCLs were placed above a drainage medium and covered with 0.3 or 0.6 m of gravel. A constant hydraulic head of 0.3 or 0.6 m was established. Tests were conducted on either a single piece of material (control sample) or on two pieces of material that were overlapped 37 or 75 mm. (Gundseal) or 75 or 150 mm. (Bentomat® and Claymax® 200R). Tests showed that overlapped panels self sealed; flow rates through the overlapped GCLs were about the same as those through the control samples.

A defective high density polyethylene (HDPE) geomembrane was placed on top of samples of GCL material, covered with gravel, and then flooded with water. Effective composite behavior did not occur with those GCLs that contained a geotextile between the defective geomembrane and bentonite but did occur for the GCL in which the defective geomembrane was in direct contact with the bentonite in the GCL.

Further details on this research is provided by Estornell (1991) and Estornell and Daniel (1992).

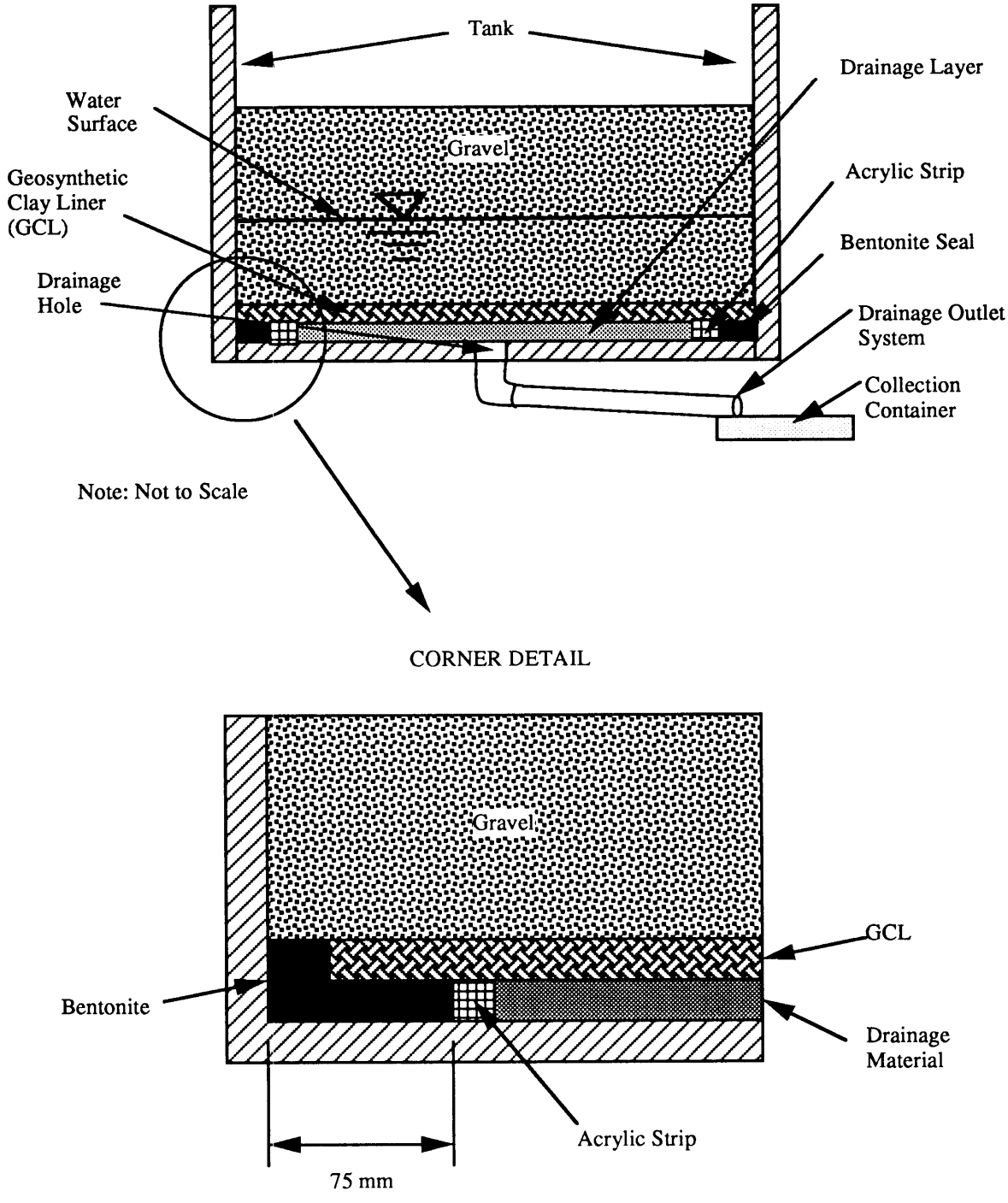


Figure 6.1 Cross Sectional View of Test Set Up

6.2 The Effect of Differential Settlement on the Hydraulic Conductivity of Geosynthetic Clay Liners (By Mark LaGatta and B. Tom Boardman, University of Texas)

One of the more likely future uses of a GCL is as a component in the final cover of a municipal solid waste landfill. Subsidence generally occurs beneath the final cover due to biochemical decay of waste, collapse of underlying materials, or consolidation of saturated waste material. Unlike a wide embankment fill, the landfill will most likely not settle as a uniform mass. There will be localized settlements randomly distributed across the cover. Unfortunately, these localized settlements tend to cause the most damage to a flexible cover due to tensile strains caused by large differential settlement.

In an attempt to determine the effects of settlement on the hydraulic conductivity of a GCL, Mr. LaGatta modified the steel tanks developed originally by Estornell. A wood frame and a large, deflatable, water-filled bladder were placed in the bottom of each tank to allow settlement to occur. By opening a valve beneath each tank, the rate and amount of settlement could be controlled after the installation of the GCL (Fig. 6.2 and 6.3).

Both intact and overlapping samples were tested. A conservative overlap of 225 mm was used. The overlapping samples were aligned with the overlap running parallel to the length of the tank and the deflatable bladder. A non symmetrical bladder was used to ensure one dimensional distortion and tensile strains.

Mr. LaGatta has studied the effects of differential settlement on a hydrated GCL. The full size GCL samples were hydrated within the tank after the GCLs had been covered with 0.6 m of gravel. The valve to the bladder was then opened, and a series of incremental settlements were induced beneath the GCL. The effect of each incremental settlement on the hydraulic conductivity of the deformed GCL was then closely monitored.

Intact and overlapping samples of Bentomat®, Claymax® 200R, and Gundseal were tested. The effective normal stress was approximately 7.6 kPa for each test. The results are shown in Fig. 6.4 through 6.11. There was no measured outflow for either the intact or overlapping samples of Gundseal at any deformation.

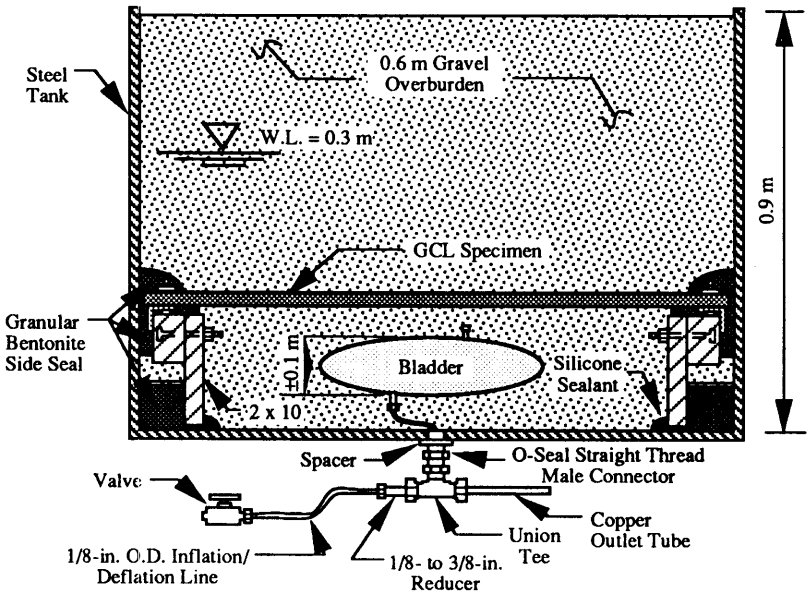


Figure 6.2 Cross Sectional View of Modified Test Set Up

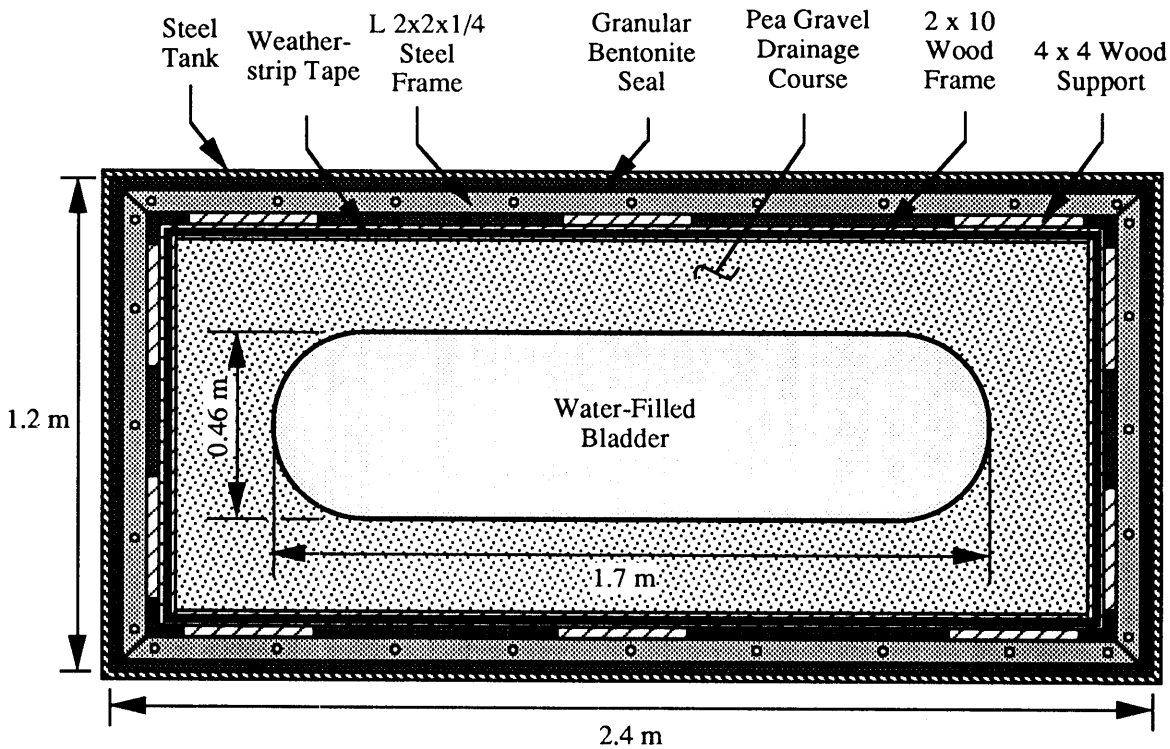


Figure 6.3 Plan View of Tank and Deflatable Bladder

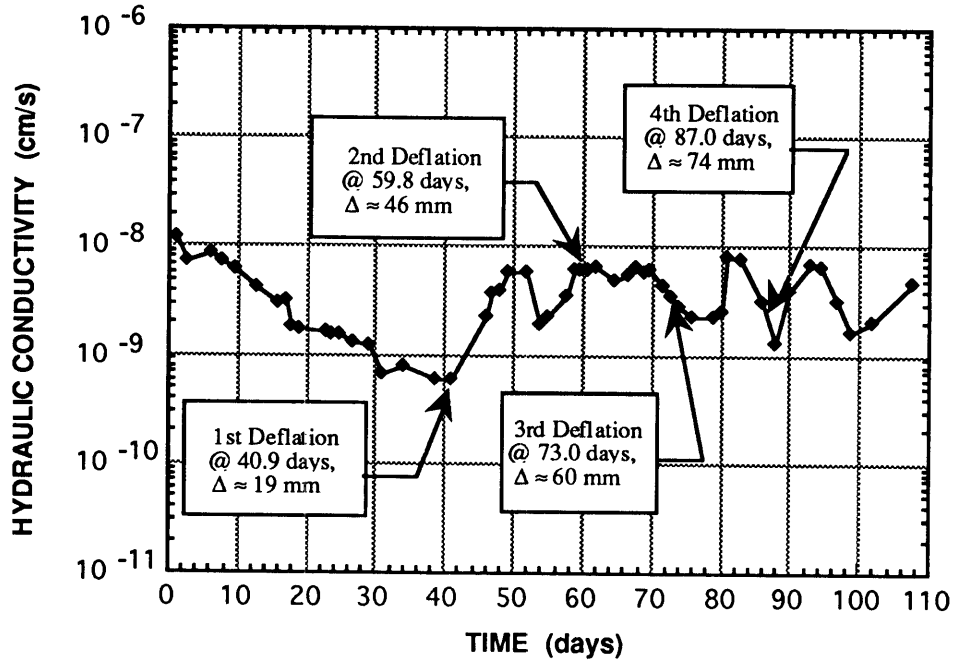


Figure 6.4 Hydraulic Conductivity vs. Time for Intact Bentomat® Sample IHS-2-D

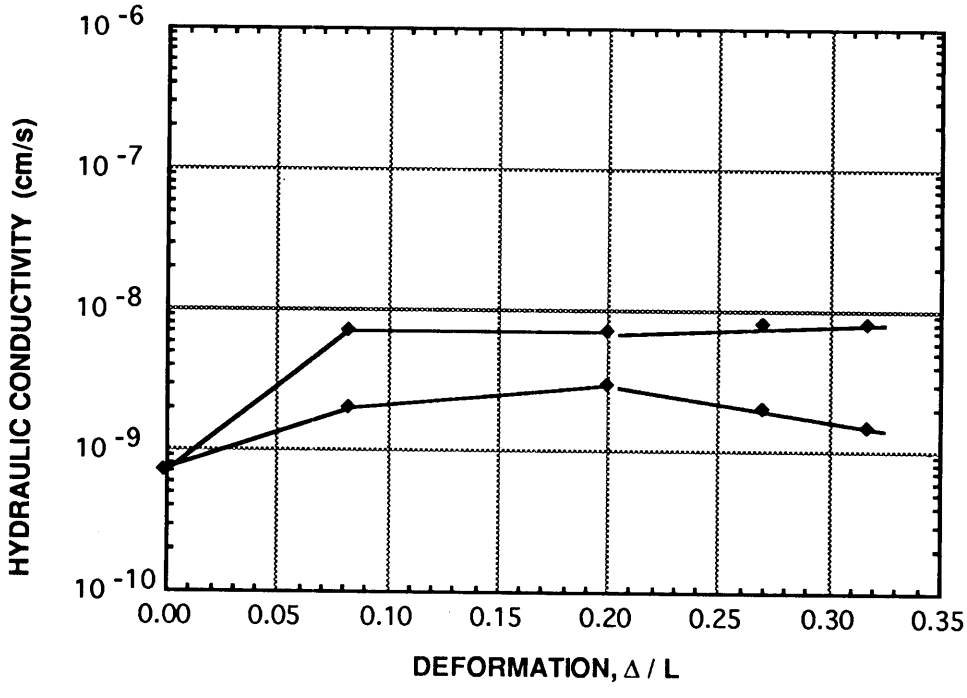


Figure 6.5 Hydraulic Conductivity vs. Deformation for Intact Bentomat® Sample IHS-2-D

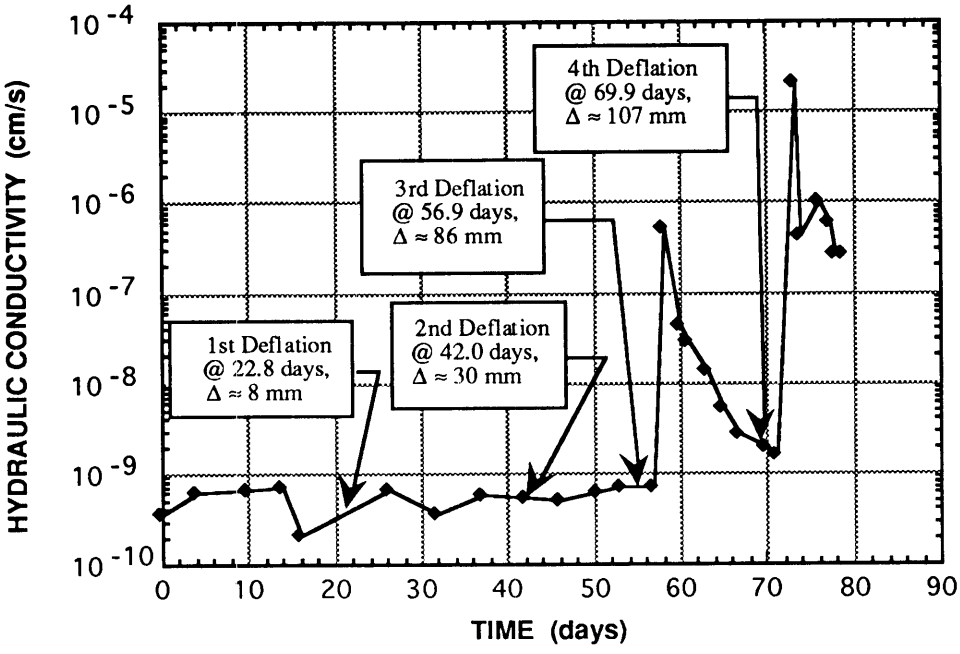


Figure 6.6 Hydraulic Conductivity vs. Time for Overlapped Bentomat® Sample OHS-2-C

Note: Loose 0.25 lb/ft bentonite placed along outer edge of overlap as opposed to centerline of overlap

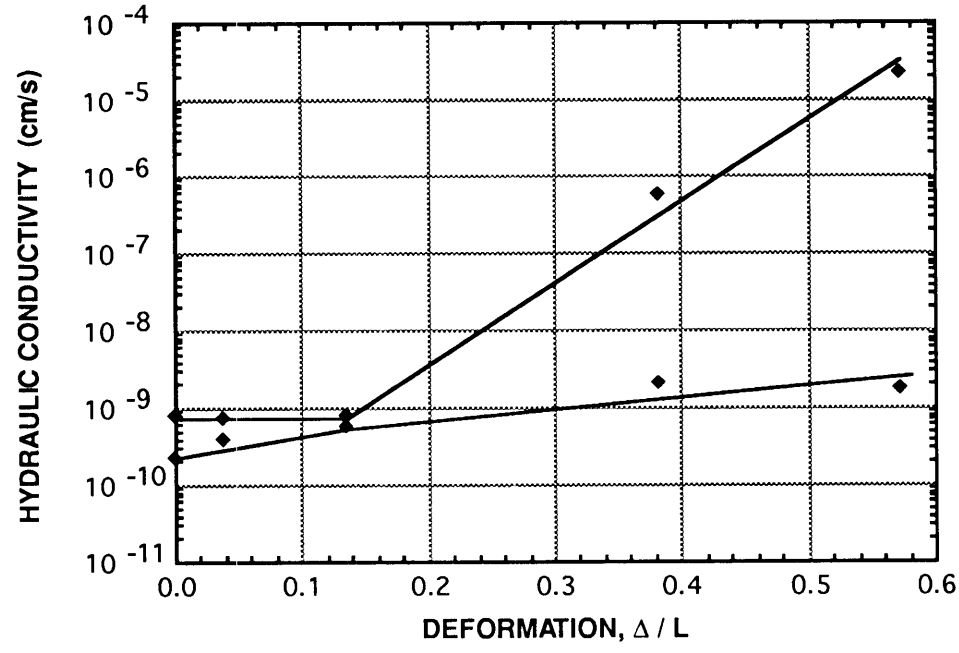


Figure 6.7 Hydraulic Conductivity vs. Deformation for Overlapped Sample OHS-2-C

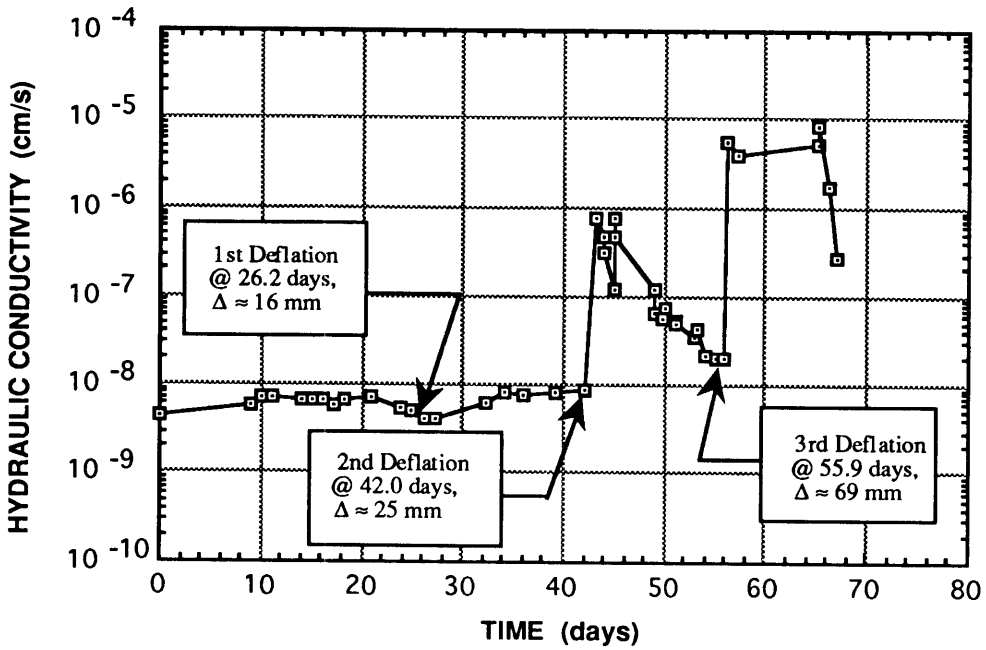


Figure 6.8 Hydraulic Conductivity vs. Time for Intact Claymax® Sample IHS-1-A

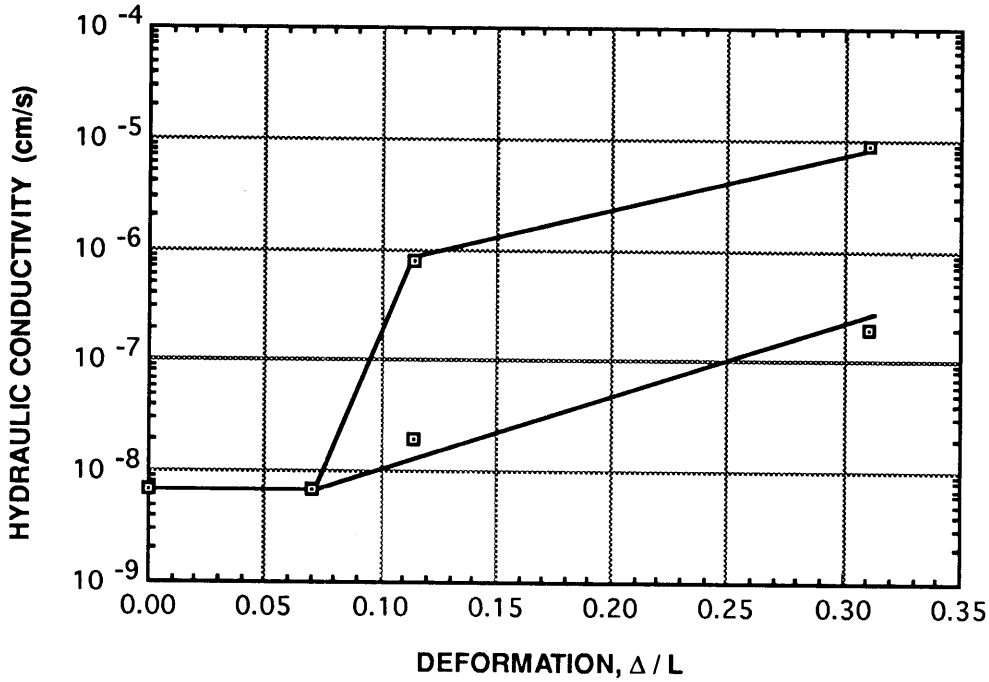


Figure 6.9 Hydraulic Conductivity vs. Deformation for Intact Claymax® Sample IHS-1-A

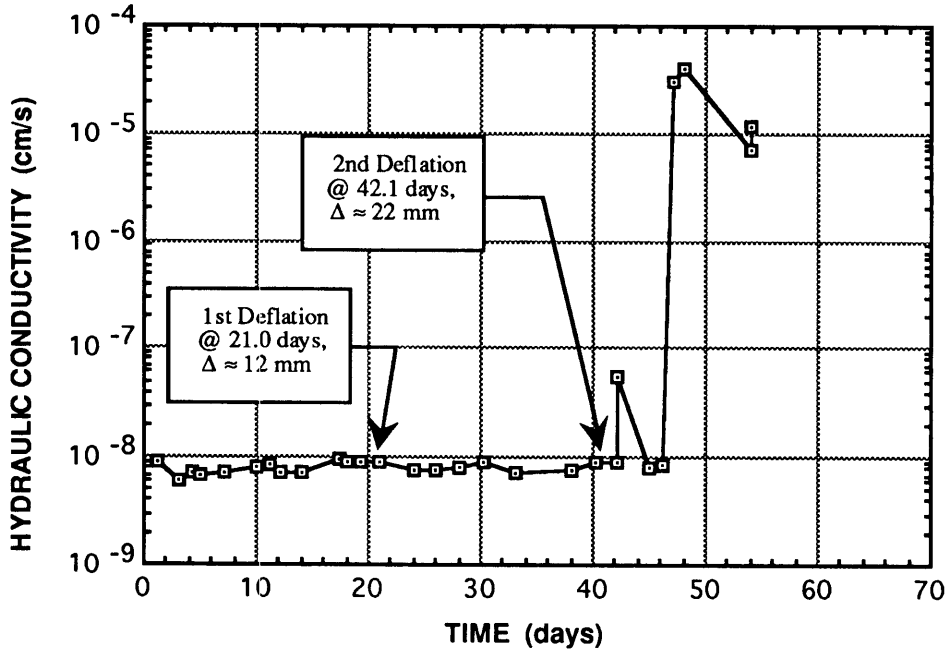


Figure 6.10 Hydraulic Conductivity vs. Time for Overlapped Claymax® Sample OHS-1-F

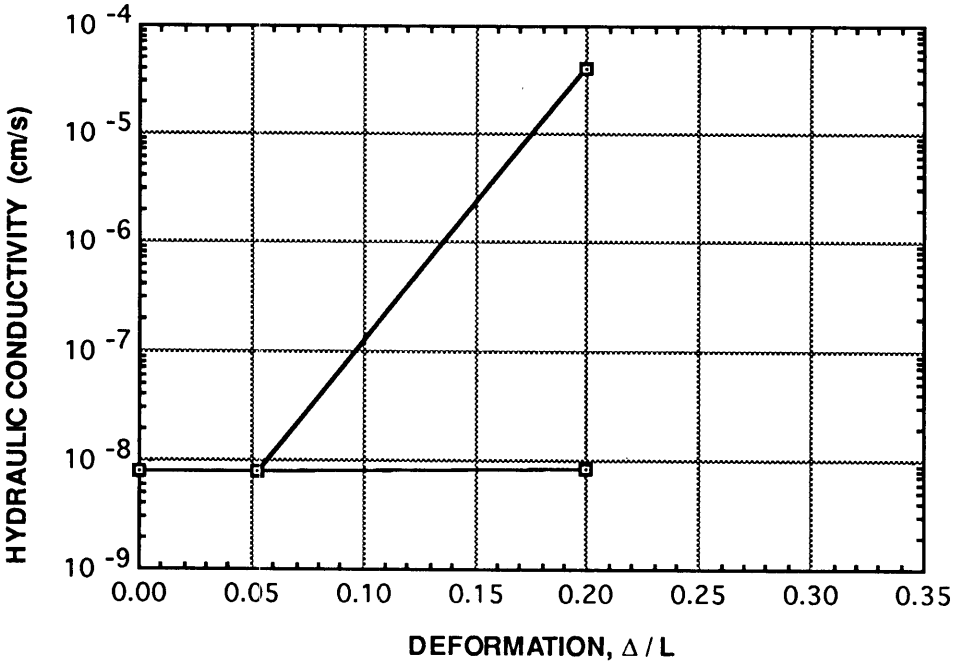


Figure 6.11 Hydraulic Conductivity vs. Deformation for Overlapped Sample OHS-1-F

Mr. Boardman is studying the effects of differential settlement on unhydrated, overlapping GCLs. After the installation of the dry GCL, a large settlement is induced beneath the sample. The deformed GCL is then slowly hydrated over a span of several days. The ability of the deformed sample to self heal at the overlap is then closely monitored. The results of two tests are shown in Fig. 6.12 and 6.13. Both intact and overlapping samples of Bentomat®, Claymax®, and Gundseal will be tested to determine the effect of the overlap. A conservative overlap of 225 mm is being used. More details may be found in LaGatta (1992).

6.3 Stability of Final Covers Placed on Slopes with Geosynthetic Clay Liners (By Hsin-Yu Shan, University of Texas)

There has been some concern about the use of GCLs in sloping final cover systems. Even with geogrid reinforcement, a GCL will lose strength and potentially deform once hydrated. This concern needs to be addressed as GCLs are expected to be more common in final cover systems.

A typical profile of a final cover incorporating a GCL is shown in Fig. 6.14. The current slope design method is the limit equilibrium method. Unfortunately, there is no way to predict the amount of deformation with this method. In an effort to predict this deformation, Mr. Shan developed a numerical model incorporating the properties of the top soil, geogrid, GCL, and cover soil. The profile of the slope used in the model is shown in Fig. 6.15.

The model has been simplified by reducing the number of possible interfacial friction values to the most critical one and by representing the tensile resistance of all of the geosynthetics by one material (a geogrid). The top soil is assumed to be 0.9 m thick and to have a unit weight of 15.7 kN/m^3. For the range of expected normal stresses, Φ' and c' are assumed to be 30° and 4.8 kPa, respectively, for the top soil. The degree of hydration of the GCL can be varied.

The numerical model was developed as a finite element program. Some results of the model are shown in Fig. 6.16 and 6.17. As expected, for a given slope, the lower the minimum interfacial friction angle, the higher the relative displacement, and the higher the tension within the geogrid.

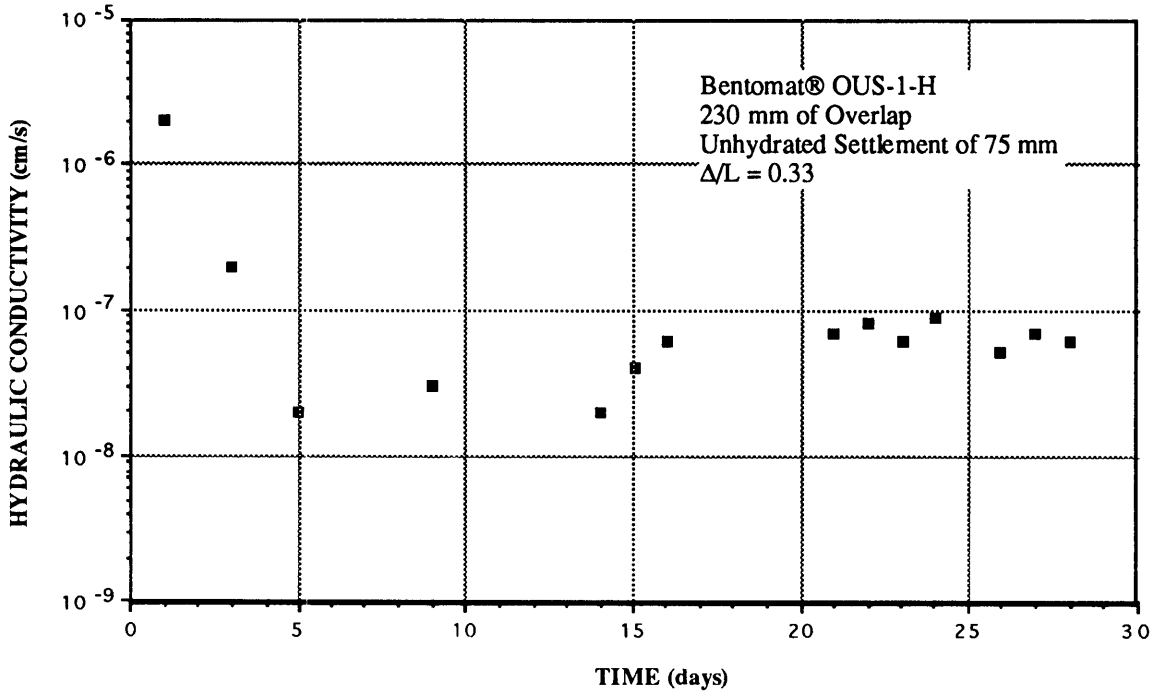


Figure 6.12 Hydraulic Conductivity of Bentomat® after a Large Settlement Prior to Hydration

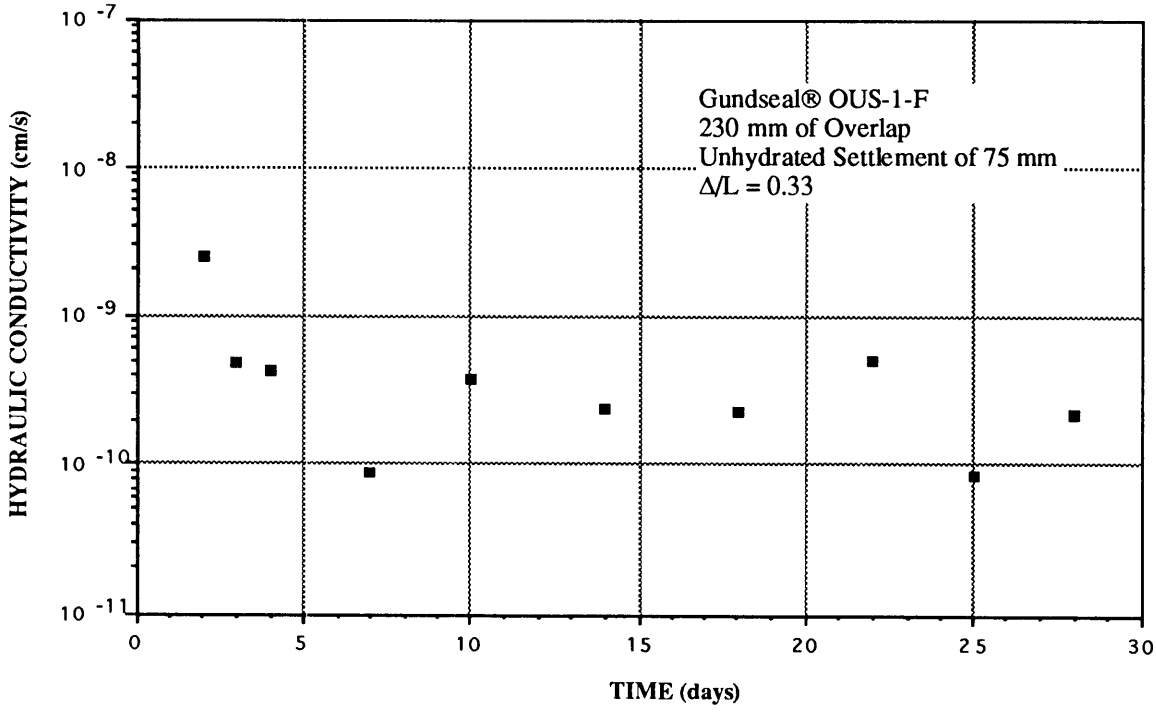


Figure 6.13 Hydraulic Conductivity of Gundseal® after a Large Settlement Prior to Hydration

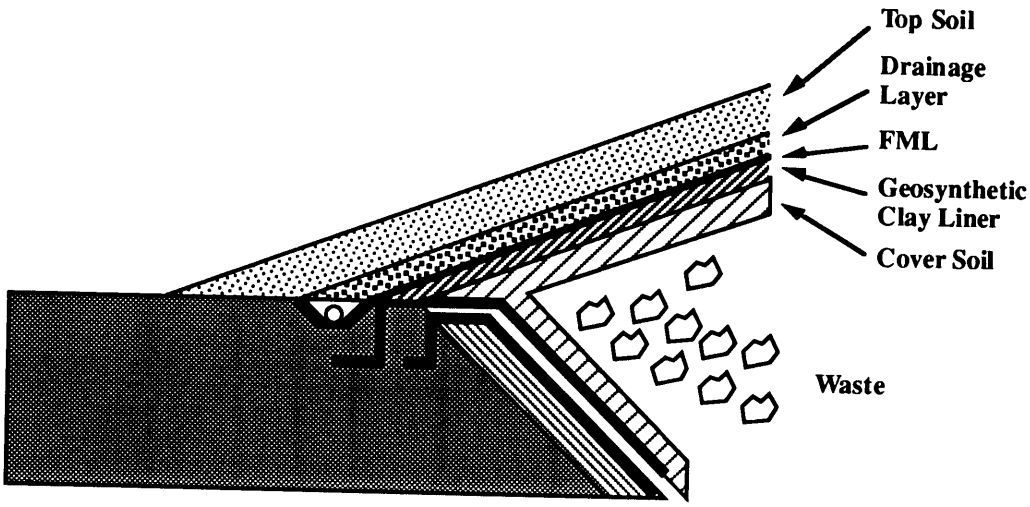


Figure 6.14 Typical Profile of Final Cover with Geosynthetic Clay Liners

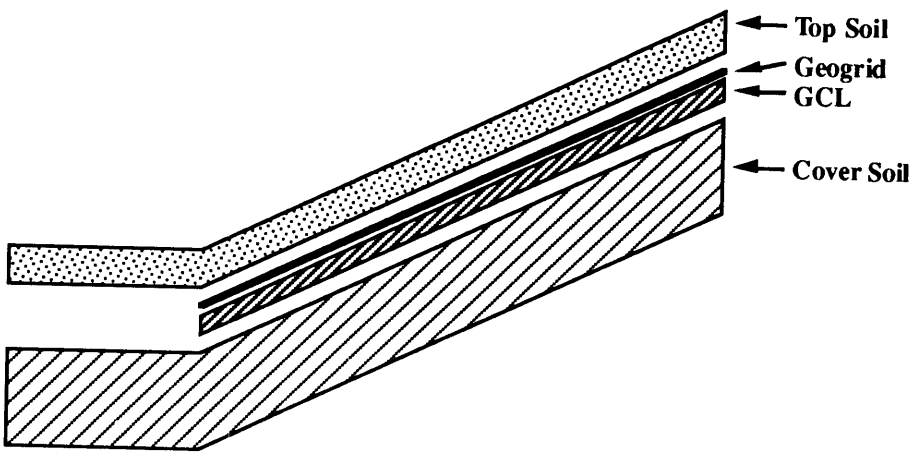


Figure 6.15 Profile of the Slope Used for Computations

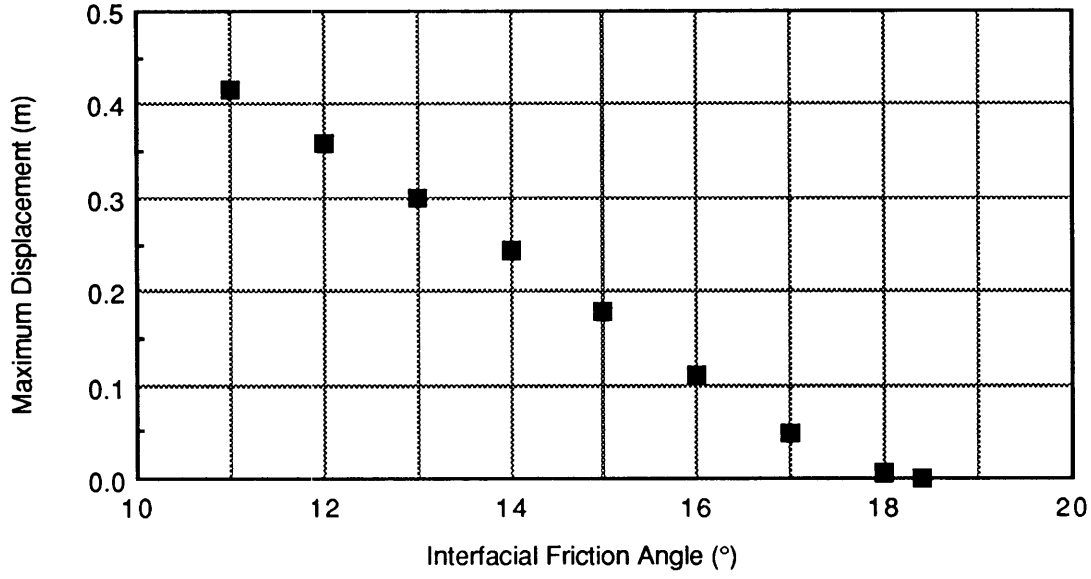


Figure 6.16 Relationship between Maximum Interfacial Displacement and Minimum Interfacial Friction Angle for a 3:1 Slope

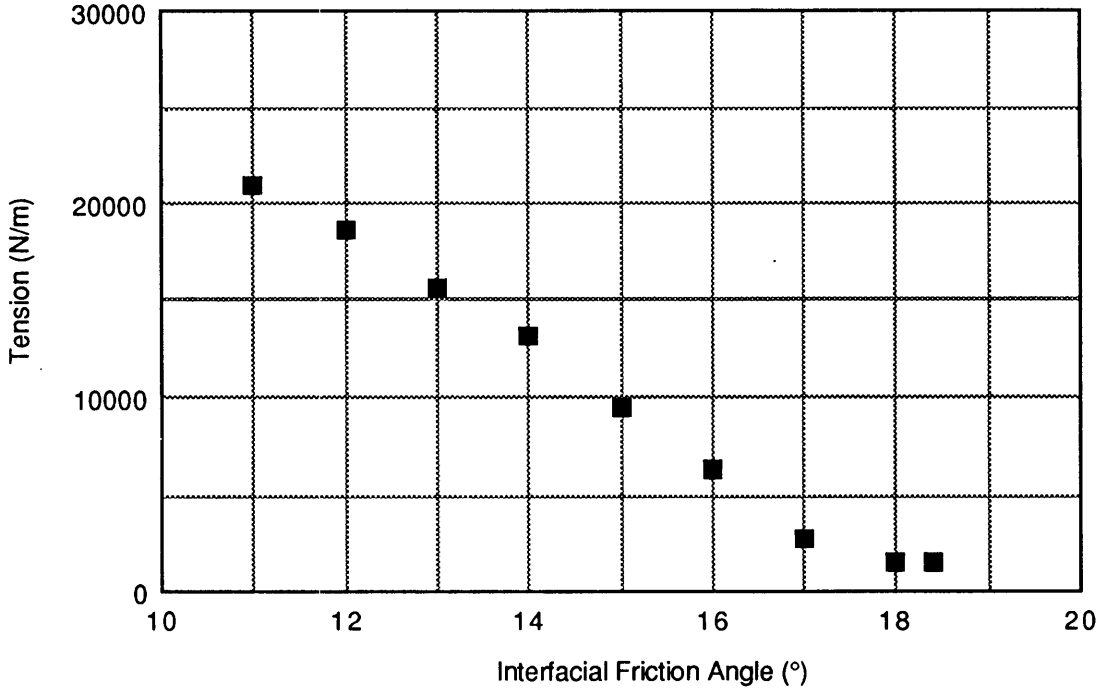


Figure 6.17 Relationship between Tension in the Geogrid and the Minimum Interfacial Friction Angle for a 3:1 Slope

While this analysis is still in its initial stages, it is hoped that by running the model over a range of conditions one can draw conclusions about:

- The probable short and long term shear strength parameters of GCLs
- The possibility of using GCLs on slopes without excessive deformation occurring
- The usefulness of design schemes to reinforce the slope

6.4 The Hydration Behavior and Mid-Plane Shear Strength of Four Geosynthetic Clay Liners (By Robert Koerner, Drexel University)

The focus of GCL research and development at Drexel University's Geosynthetic Research Institute (GRI) is on the hydration behavior of the various products and on their mid-plane shear strength. Work is ongoing with four different commercially available products: Bentofix®, Bentomat®, Claymax®, and Gundseal®. Each of these products have been evaluated in five different liquids: distilled water, tap water, mild leachate, harsh leachate, and diesel fuel.

The first series of tests focused on the hydration behavior under varying normal stresses. These hydration tests were conducted on 150 by 150 mm samples contained in steel boxes with perforated loading plates so that the hydrating liquid was available to hydrate the entire surface area of the test samples. The deformation curves shown in Fig. 6.18 display the following information:

- The products swelled from highest to lowest amounts in the following order: distilled water or tap water, mild leachate, harsh leachate, and diesel fuel
- For a given hydration liquid, Claymax® swells the most, followed by Gundseal®, Bentomat®, and Bentofix® in descending order. Clearly, the needle punching of Bentomat ® and Bentofix® restrained the swelling in these latter two products

Upon completion of the hydration tests, the samples were carefully removed from their respective test devices and trimmed to fit in a 100 by 100 mm direct shear test device. The location of the shear plane was set at the mid-plane of each of the test specimens. The test specimens were sheared at a strain rate of

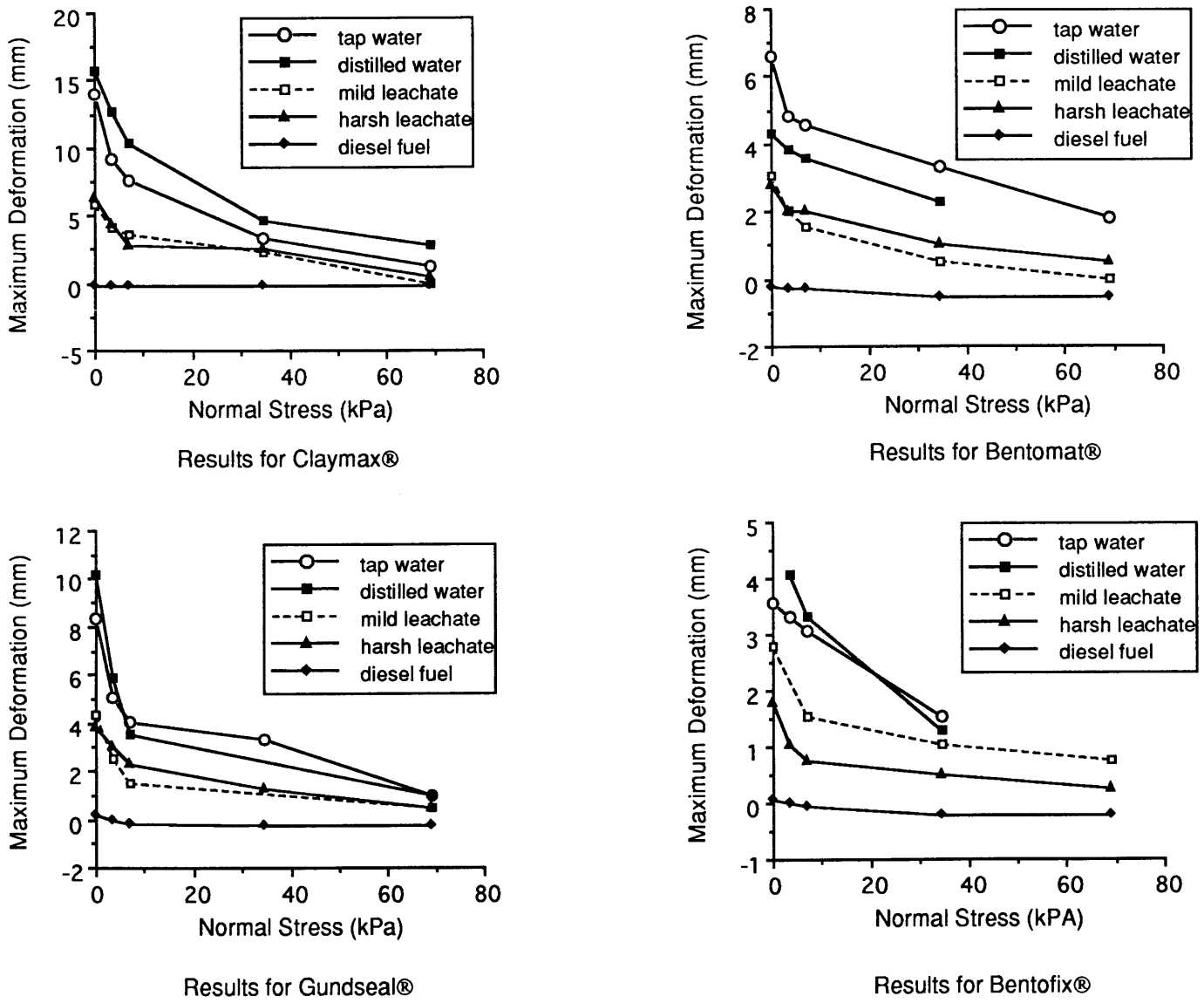


Figure 6.18 Hydration of GCLs Using Different Liquids

0.9 mm/min and were designated as "constrained-swell" tests. Direct shear tests were conducted on all samples and counterpointed against parallel sets of tests in the dry (or as received) state and also against "free-swell" tests in which the test specimens were hydrated in the same liquids but without any normal stress. The direct shear tests produced the shear strength parameters Φ and c shown in Table 6.1. The data indicate the following trends.

- The products are strongest in the dry "as-received" condition and the weakest in the free-swell condition. The constrained-swell condition is intermediate between the two extremes.
- Needle-punching significantly increases shear strength.
- The hydrating liquid can affect strength.
- Hydration with distilled water yields the lowest shear strength and can be used as a conservative liquid.
- Products with fiber reinforcement required much larger displacements than unreinforced products to reach their limiting shear stress.

Table 6.1 Direct Shear Test Results Summary (Drexel University)

Hydrating Fluid	GCL Type	Measured Property	Dry*	Constrained Swell**	Free Swell***
Distilled Water	Claymax	Ø (degrees)	37	16	0
		C(kPa)	6.9	3	4
	Gundseal	Ø (degrees)	26	19	0
		C(kPa)	50	5	3
	Bentomat	Ø (degrees)	42	37	23
		C(kPa)	14	6	5
	Bentofix	Ø (degrees)	36	31	10
		C(kPa)	68	7	9.0
Tap Water	Claymax	Ø (degrees)	37	18	0
		C(kPa)	6.9	3	3
	Gundseal	Ø (degrees)	26	18	0
		C(kPa)	50	5	3
	Bentomat	Ø (degrees)	42	43	26
		C(kPa)	14	6	10
	Bentofix	Ø (degrees)	36	34	15
		C(kPa)	68	6.9	7
Mild Leachate	Claymax	Ø (degrees)	37	24	4
		C(kPa)	6.9	6	3
	Gundseal	Ø (degrees)	26	18	13
		C(kPa)	50	5	4
	Bentomat	Ø (degrees)	42	39	25
		C(kPa)	14	8.3	14
	Bentofix	Ø (degrees)	36	43	20
		C(kPa)	68	5	12
Harsh Leachate	Claymax	Ø (degrees)	37	19	0
		C(kPa)	6.9	6	3
	Gundseal	Ø (degrees)	26	13	0
		C(kPa)	50	7.6	3
	Bentomat	Ø (degrees)	42	45	32
		C(kPa)	14	5	12
	Bentofix	Ø (degrees)	36	39	30
		C(kPa)	68	4	8.3
Diesel Fuel	Claymax	Ø (degrees)	37	44	38
		C(kPa)	6.9	4	6
	Gundseal	Ø (degrees)	26	24	29
		C(kPa)	50	4	6
	Bentomat	Ø (degrees)	42	42	40
		C(kPa)	14	6	5
	Bentofix	Ø (degrees)	36	51	46
		C(kPa)	68	4	5

Notes:

* Dry refers to product as-received, placed under desired normal stress, then sheared at midplane.

** Constrained swell refers to product hydrated under desired normal stress, i.e., constrained swell, then sheared at midplane.

*** Free swell refers to product hydrated under zero normal stress, then placed under desired normal stress, and then sheared at midplane.

CHAPTER 7
EQUIVALENCY

7.1 Equivalency (By David Daniel, University of Texas)

7.1.1 Potential Applications

If one wants to substitute a geosynthetic clay liner (GCL) for a required compacted clay liner (CCL), one will generally have to demonstrate that the proposed GCL will provide equivalent or better performance to a CCL. Equivalency analyses may be required for:

- Final Cover Systems:
  - Single GCL Versus Single CCL Liner
  - Geomembrane/GCL Composite Liner Versus Geomembrane/CCL Composite Liner

- Single Liner Systems:
  - Single GCL Versus Single CCL Liner
  - Geomembrane/GCL Composite Liner Versus Geomembrane/CCL Composite Liner

- Double Liner Systems:
  - Geomembrane/GCL Composite Liner Versus Geomembrane/CCL Composite Liner in Primary Liner
  - Geomembrane/GCL Composite Liner Versus Geomembrane/CCL Composite Liner in Secondary Liner

The Solid Waste Disposal Facility Criteria found at 40 CFR Part 258 apply to municipal solid waste landfills and treat the area of "equivalency" differently for final covers and liners. Final cover systems are to be designed to minimize infiltration and erosion, therefore, designs other than the minimum requirements of §258.60 (a) could be approved using an "equivalency" demonstration. However, alternatives to the composite liner design in §258.40 (a) (2) are not approved based on "equivalency" demonstrations but must meet the performance standard at §258.40 (a) (1). Different standards apply to facilities

that receive hazardous waste regulated under Subtitle C of RCRA and to CERCLA clean-up sites.

The designs for Subtitle C and CERCLA are evaluated based on the site-specific design. Innovative use of modern materials is encouraged, providing they meet the requirements of the law.

7.1.2 Differences Between CCLs and GCLs

Some of the differences between compacted clay liners and geosynthetic clay liners are listed in Table 7.1. Some of the potentially important (depending upon specific application) relative advantages of CCLs and GCLs may be summarized as follows:

- Advantages of compacted clay liners (CCLs):
    - The large thickness of CCLs makes them virtually puncture proof
    - The large thickness of CCLs makes them relatively insensitive to small imperfections in any one lift
    - The large thickness of CCLs gives them substantial capacity for adsorption of leachate
    - The large thickness of CCLs delays the discharge of water and solutes from the base of liners
    - There is a long history of use of CCLs
    - Intimate hydraulic contact with a geomembrane is not an issue for CCLs
    - Many regulatory agencies require CCLs; use of another type of liner may require demonstration of equivalency to a CCL.
    - A CCL is a logical choice if suitable clay is available locally
    - Testing procedures are reasonably well established for CCLs.
- Advantages of geosynthetic clay liners (GCLs):
    - Small thickness of GCLs leads to low consumption of space
    - Construction of GCLs is rapid and simple
    - Heavy equipment is not needed to install a GCL, which is beneficial if the GCL is underlain by a geosynthetic material

Table 7.1 Differences Between GCLs and CCLs

Characteristic	Geosynthetic Clay Liner	Compacted Clay Liner
Materials	Bentonite Clay, Adhesives, Geotextiles, and Geomembranes	Native Soils or Blend of Soil and Bentonite
Construction	Manufactured and Then Installed in the Field	Constructed in the Field
Thickness	Approximately 10 mm	Approximately 0.5 to 1.0 m
Hydraulic Conductivity of Clay	10^{-10} to 10^{-8} cm/s (Typical)	10^{-8} to 10^{-7} cm/s (Typical)
Speed and Ease Construction	Rapid, Simple Installation	Slow, Complicated Construction
Water Content at Time of Construction	Essentially Dry; Cannot Desiccate During Construction and Produces No Consolidation Water	Nearly Saturated; Can Desiccate and Can Produce Consolidation Water
Cost	$5 to $11 per Square Meter	Highly Variable (Estimated Range: $8 to $32 per Square Meter)
Experience Level	Limited Due to Newness	Has Been Used for Many Decades

- Some inclement weather delays (e.g., freezing temperatures) that stop construction of CCLs are not experienced with GCLs
- Because a GCL is a manufactured material, a consistent and uniform material can be produced
- Because GCLs are manufactured materials many of the specialized performance properties can be determined and need not be repeatedly re-determined
- GCLs can accommodate large differential settlement
- Quality assurance is simpler for a GCL compared to a CCL
- GCLs are more easily repaired than CCLs
- GCLs can probably better withstand freeze/thaw and wet/dry cycles than CCLs
- Unlike CCLs, GCLs are not vulnerable to desiccation damage during construction

7.1.3 Criteria for Equivalency

Three issues should be addressed when one compares a GCL to a CCL and considers the equivalency of a GCL to a CCL:

1. Hydraulic issues
2. Physical/mechanical issues
3. Construction issues

The specific issues that might have to be addressed for a specific site are listed in Table 7.2.

7.1.4 Hydraulic Issues

Hydraulic issues are the easiest to quantify. The criteria are discussed separately.

7.1.4.1 Steady Flux of Water

Flux of water is usually assessed by comparing the long-term, steady state water flux for the CCL and GCL. The flux of water (v) through an individual layer of porous material is defined from Darcy's Law as:

Table 7.2 Potential Equivalency Issues

Category	Criterion for Evaluation	Relevant for: Liners	Covers
Hydraulic Issues	Steady Flux of Water	X	X
	Steady Solute Flux	X	
	Adsorption Capacity	X	
	Breakout Time:		
	-Water	X	X
	-Solute	X	
	Production of Consolidation Water	X	X
Physical/ Mechanical Issues	Freeze-Thaw	X*	X
	Wet-Dry		X
	Total Settlement	X**	X
	Differential Settlement	X**	X
	Slope Stability	X***	X
	Erosion		X
	Bearing Capacity	X	
Construction Issues	Puncture Resistance	X	X
	Subgrade Condition	X	X
	Ease of Placement	X	X
	Speed of Construction	X	X
	Availability of Materials	X	X
	Weather Constraints	X	X
	Quality Assurance	X	X

Notes:

* Relevant only until liner is covered sufficiently to prevent freezing

** Settlement of liners usually of concern only in certain circumstances, e.g., vertical expansions

*** Stability of liner may not be relevant after filling (except canyon landfills)

$$v = k \frac{H+L}{L} \tag{7.1}$$

where k is the hydraulic conductivity, H is the depth of liquid ponded on the liner, and L is the thickness of the liner. The water pressure on the base of the liner is assumed to be zero in Eq. 7.1.

For a GCL, Eq. 7.1 is applicable only for flow through the bentonite component; if the GCL contains a geomembrane, water flux will be controlled by water vapor diffusion through the geomembrane component. The geomembrane component, if present, should be considered in the equivalency analysis and in computation of water flux. Also, Eq. 7.1 applies to a CCL or GCL liner alone; composite action with a geomembrane is considered later.

The flux ratio for water, F_W, is defined as:

$$F_w = \frac{v_{GCL}}{v_{CCL}} \tag{7.2}$$

or:

$$F_w = \frac{k_{GCL} \dfrac{H+L_{GCL}}{L_{GCL}}}{k_{CCL} \dfrac{H+L_{CCL}}{L_{CCL}}} \tag{7.3}$$

For example, for a GCL without a geomembrane component, if:

$k_{GCL} = 1 \times 10^{-9}$ cm/s = 1×10^{-11} m/s
H = 0.3 m (1 ft)
L_{GCL} = 7 mm = 0.007 m
$K_{CCL} = 1 \times 10^{-7}$ cm/s = 1×10^{-9} m/s
L_{CCL} = 0.9 m (3 ft)

then F_W from Eq. 7.3 equals 0.3. So long as $F_W \leq 1$, equivalency in terms of water flux is demonstrated, i.e., the rate of water flow through the GCL is less than or equal to that through the CCL. Most GCLs can be shown to be equivalent to a CCL that has a hydraulic conductivity of 1×10^{-7} cm/s in terms of steady water

flux. If the GCL contains a geomembrane, the flux ratio will be even less than that computed from Eq. 7.3.

A composite liner consists of a geomembrane placed in contact with a low-permeability soil. A geomembrane/GCL composite may be considered as an alternate to a geomembrane/CCL composite. If so, flow through the composite should be analyzed. Flow through a flaw in a geomembrane in a composite liner depends on the hydraulic conductivity of the clay component, the hydraulic gradient across the clay component, the hydraulic contact between the geomembrane and the clay component, and the presence of a geomembrane within the GCL. No equations have been published for computing flow rates through a defect in a geomembrane component of a geomembrane/GCL composite liner. However, published information can be used to make comparative estimates. Equivalency evaluations would clearly be product and perhaps site specific.

7.1.4.2 Steady Solute Flux

The maximum flux is the steady-state flux. Long-term, steady solute flux, which is relevant only for liners, may be analyzed on the basis of advection alone, diffusion alone, or advection plus diffusion. As will be seen later, the assumptions necessary to analyze steady diffusion and steady advection-plus-diffusion are inconsistent with the processes themselves, and only the case of advection is relevant for steady-state conditions. Nevertheless, for completeness, the methods for analyzing steady diffusion and steady diffusion-plus-advection are presented so that these processes can be understood.

It is assumed that the concentration of a solute of concern in the leachate remains constant. The advective mass flux, $v_{m,A}$, is:

$$v_{m,A} = c_{leachate}\, k \frac{H + L}{L} \tag{7.4}$$

where $c_{leachate}$ is the concentration of the solute of interest in the leachate. The advective mass flux ratio, $F_{m,A}$ is defined as:

$$F_{m,A} = \frac{v_{m\,A(GCL)}}{v_{m\,A(CCL)}} \tag{7.5}$$

or:

$$F_{m,A} = \frac{c_{leachate}\, k_{GCL}\, \dfrac{H + L_{GCL}}{L_{GCL}}}{c_{leachate}\, k_{CCL}\, \dfrac{H + L_{CCL}}{L_{CCL}}} \tag{7.6}$$

or:

$$F_{m,A} = \frac{k_{GCL}\, \dfrac{H+L_{GCL}}{L_{GCL}}}{k_{CCL}\, \dfrac{H+L_{CCL}}{L_{CCL}}} = F_w \tag{7.7}$$

It is noted that $c_{leachate}$ cancels out of Eq. 7.6. Because $F_{m,A} = F_w$ (Eq. 7.7), if one has demonstrated equivalency of steady water flux, one has also demonstrated equivalency of steady mass flux of solute caused by advection.

Solutes in leachate can also migrate through clay liners by molecular diffusion. Steady diffusion of solutes is usually analyzed with Fick's first law, which states that:

$$v_D = D\, \theta\, \frac{\Delta c}{L} \tag{7.8}$$

where v_D is the diffusive mass flux, D is the diffusion coefficient for the solute of interest, θ is the volumetric water content, Δc is the difference in concentration of the solute between the top and bottom of the liner, and L is the thickness of the liner.

The diffusive mass flux ratio ($F_{m,D}$) is defined as

$$F_{m,D} = \frac{F_{m\,D(GCL)}}{F_{m\,D(CCL)}} \tag{7.9}$$

or:

$$F_{m,D} = \frac{D_{GCL}\, \theta_{GCL}\, \dfrac{\Delta c}{L_{GCL}}}{D_{CCL}\, \theta_{CCL}\, \dfrac{\Delta c}{L_{CCL}}} \tag{7.10}$$

or:

$$F_{m,D} = \frac{D_{GCL}}{D_{CCL}} \frac{\theta_{GCL}}{\theta_{CCL}} \frac{L_{CCL}}{L_{GCL}} \qquad (7.11)$$

Limited data exist on diffusion coefficients in clay liners. Data developed for compacted kaolinite at the University of Texas indicate that $D \approx 6 \times 10^{-10}$ m^2/s for the non-reactive solute chlorine. For one GCL tested, the diffusion coefficient for the bentonite in the GCL was approximately 2×10^{-10} m^2/s. If, for example, one assumes:

$$\frac{D_{GCL}}{D_{CCL}} = \frac{2 \times 10^{-10}}{6 \times 10^{-10}} = 0.33$$

$$\frac{\theta_{GCL}}{\theta_{CCL}} = \frac{0.6}{0.4} = 1.5$$

$$\frac{L_{CCL}}{L_{GCL}} = \frac{0.9\ m}{0.007\ m} = 129$$

then one computes a diffusive mass flux ratio of:

$$F_{m,D} = (0.33)\ (1.5)\ (129) = 64$$

In this example, the GCL is not equivalent to the CCL since there would be more diffusive mass flux through the GCL than CCL. In general the calculated steady, diffusive mass flux through the bentonite within the GCL is always expected to be greater than the steady, diffusive mass flux through the CCL. However, for those GCLs that have a geomembrane component, the geomembrane, which has an extremely low diffusion coefficient for most solutes, should be considered and will tend to greatly reduce the steady, diffusive mass flux.

As mentioned earlier, the assumptions necessary for computing steady diffusive flux are inconsistent with the process itself. The problem is that a contradiction exists in the boundary conditions. Diffusion is driven by a concentration gradient, Δc. Over time, the solute of interest in the leachate will

diffuse to the base of the liner, and the concentration at the base of the liner will eventually equal the concentration on top of the liner, i.e., the concentration in the leachate (which is assumed to be constant). Thus, the diffusion-driving concentration gradient becomes zero and diffusive transport ceases. The only way that steady diffusion could develop through a liner would be for fresh water to continually flush the underside of the liner to maintain a concentration gradient across the liner. For nearly all sites, the case of steady diffusion will be irrelevant and need not be considered.

It may be argued that neither advection alone nor diffusion alone is important -- solutes will migrate through soil liners by advection plus diffusion. The total mass flux due to advection plus diffusion ($v_{m,A+D}$) is generally assumed to be:

$$v_{m,A+D} = v_{m,A} + v_{m,D} \tag{7.12}$$

and the ratio of advective plus diffusive mass flux, $F_{m,A+D}$, may be defined as:

$$F_{m,A+D} = \frac{v_{m\ A+D\ (GCL)}}{v_{m\ A+D\ (CCL)}} \tag{7.13}$$

Although Eq. 7.13 can be applied, it should not be applied because the assumed conditions are physically impossible for long-term, steady conditions. If advection carries solutes downward through the liner, then at steady state the base of the liner must necessarily be saturated with leachate. If the base is saturated with leachate, then $\Delta c = 0$ and $v_{m,D} = 0$. Thus, when one analyzes long-term, steady mass flux of a solute through a GCL or CCL, only advective transport need generally be considered.

In some cases, one may wish to analyze transient conditions that lead up to steady conditions, in which case both advective and diffusive transport should be considered. If the GCL contains a geomembrane, the presence of the geomembrane should be taken into account.

7.1.4.3 Adsorption Capacity

The adsorption capacity of a clay liner may be relevant only for liners (not covers). Regulations generally have no specific adsorption requirements.

Adsorption of organics tends to be different from adsorption by inorganics. Adsorption of inorganics is controlled by cation exchange reactions and geochemical processes such as precipitation. Adsorption of organic solutes is generally assumed to be controlled by the amount of organic carbon in the soil and a partition coefficient for the solute (which is characterized by the octanol-water partition coefficient or water solubility of the organic species).

For inorganics, the maximum adsorbed mass per unit cross-sectional area of liner (C) resulting from cation exchange processes may be defined as follows:

$$C = CEC\ \rho_d\ L \tag{7.14}$$

where CEC is the cation exchange capacity (maximum mass of solute sorbed per unit mass of dry soil), ρ_d is the dry mass density of the soil, and L is the thickness of the liner. The ratio of thickness of a typical GCL to a CCL is small (on the order of 0.01). Thus, in order for a GCL to have equivalent cation adsorption capacity to a CCL, the adsorption coefficient of the GCL would have to be at least 100 times that of the CCL.

The cation exchange capacity of bentonite clay is typically on the order of 100 to 150 meq/100g. Natural soil materials used to construct CCLs have typical CECs in the range of 3 to 30 meq/100g. The ratio of cation adsorption capacities, denoted F_{CEC}, is:

$$F_{CEC} = \frac{C_{GCL}}{C_{CCL}} = \frac{CEC_{GCL}}{CEC_{CCL}} \frac{\rho_{d\,GCL}}{\rho_{d\,CCL}} \frac{L_{GCL}}{L_{CCL}} \tag{7.15}$$

For the typical range of values, F_{CEC} would be expected to be in the range of 0.03 to 0.75. It appears unlikely that equivalency can be demonstrated for cation adsorption capacity using the expressions just presented. However, it must be understood that adsorption of inorganic species is a complex process. Cation exchange is just one of several processes that can affect adsorption. Precipitation of inorganic solutes can be a far more important mechanism than cation exchange, and pH is often a dominant variable controlling precipitation processes in many geochemical environments. Thus, site-specific factors, and not just simple comparisons of CECs and relative soil masses, will often need to be considered when relative adsorption capacities are compared.

Non-polar organic solutes are sorbed by carbon present in the soil. The carbon content of bentonite in GCLs is capable of estimation, but CCLs will be highly variable in their organic carbon content. Although site-specific assessments would be required (due to variability of CCLs), equivalency of a GCL to a CCL probably cannot be demonstrated in terms of capacity to adsorb non-polar constituents in leachate to the bentonite because the mass of bentonite present in a GCL is far less than the mass of soil present in a CCL.

Adsorption is only relevant in the short term. When steady state mass transport is reached, adsorption capacity is exhausted. Equivalency in terms of adsorption, if evaluated at all, should be evaluated in terms of a specified performance period. For example, suppose the performance period being considered is 30 years. If the adsorption capacity of neither the CCL nor the GCL is exhausted after 30 years, both types of liner have "reserve" adsorption capacity and may be considered equivalent for the performance period. Alternatively, if either or both is exceeded, breakthrough of solute will occur and other issues, e.g., steady state solute flux, will require consideration.

7.1.4.4 Time to Initiate Discharge of Water from Base of Liner

GCLs are initially unsaturated with water whereas CCLs are often very close to saturation. When liquid first enters the upper surface of the liner, no liquid initially discharges from the base of the liner. The GCL might be compared to the CCL in terms of time to achieve discharge of water from the bottom of the liner. Again, for those GCLs that contain a geomembrane, the presence of the geomembrane should be taken into account.

The time to achieve discharge of water from the base is difficult to describe in general terms. For CCLs, the time depends greatly upon the hydraulic conductivity, initial water content, and tendency to swell. For GCLs, the time is usually fairly short (a few weeks), although for GCLs that contain a geomembrane, the time may be much greater. A comparison of time to initiate discharge of water from the base of the liner would have to be performed on a site specific basis.

The time to initiate discharge of water from the base of a liner is not relevant in the long term and often will not be relevant even in the short term. Most designs assume that water will be discharged from the base of a liner and do not make any assumptions about how long this process will take.

7.1.4.5 Breakthrough Time for Solute

The breakthrough time for a solute, which is not relevant for covers, is the time required for a solute to travel from the top to the bottom of a liner. However, theoretically, the time required for an infinitely small concentration of solute to breakthrough to the base of a liner is zero for a thick or thin liner. Thus, breakthrough time is not a uniquely defined parameter -- the time depends upon the concentration of interest. In this section, it is assumed that the breakthrough time for a GCL is compared to that of a CCL for the same concentration at the base of the clay liner.

Because of the thinness of GCLs, diffusion will generally cause the breakthrough time of a thin layer of bentonite to be less than for a CCL. Even for GCLs that contain a geomembrane, diffusion of organic solutes across the geomembrane tends to occur quickly, but at a very low mass flux. However, diffusion of inorganics through the geomembrane would be nil. Equivalency depends on the GCL and the chemicals of concern.

One must carefully consider whether the breakthrough time for solutes is relevant. In the long term, breakthrough time is irrelevant -- breakthrough will eventually occur in all liner systems with an outward gradient. The important long-term issue is solute flux.

Steady-state flux represents a worst-case scenario, i.e., largest mass flux. Time-dependent flux, before steady state, also may need to be considered in certain situations.

7.1.4.6 Production of Consolidation Water

When clayey soils are loaded, water tends to be slowly squeezed out of the soil via a process known as "consolidation." The production of consolidation may or may not be of any concern, depending upon site-specific conditions. Examples of potential problems associated with the production of consolidation water include reduced stability at the geomembrane/clay liner interface (the consolidation water from the clay liner tends to reduce stability through increased water pressure at the interface) and collection of liquids in a leak detection layer for double composite liners.

Compacted clay liners are nearly saturated with water at the time of construction. When CCLs are loaded, substantial quantities of water are often squeezed out of the liner. For example, if a 1-m-thick liner is saturated with

water and compresses just 2 percent of its original thickness due to consolidation, the amount of water squeezed out of the liner would be approximately 200,000 liters of water per hectare (20,000 gallons per acre).

Geosynthetic clay liners are essentially dry when they are constructed and cannot produce consolidation water unless they are first soaked with water and then compressed. Normally, GCLs do not have an opportunity to become saturated before they are loaded. However, a saturated GCL will produce far less consolidation water than a saturated CCL. Thus, GCLs are superior to CCLs in terms of minimizing production of consolidation water.

7.1.5 Physical/Mechanical Issues

The physical/mechanical issues that might be considered in an equivalency analysis include freeze/thaw effects, wet/dry effects, response to total settlement, response to differential settlement, stability on slopes, and vulnerability to erosion. Some issues are relevant for liners but all are relevant for covers (Table 7.2).

7.1.5.1 Freeze/Thaw Resistance

Compacted clay liners are known to be vulnerable to large increases in hydraulic conductivity from freeze/thaw. Limited laboratory data indicate that GCLs do not undergo increases in hydraulic conductivity as a result of freeze/thaw (Shan and Daniel, 1991). In addition, for those GCLs that contain a geomembrane, the geomembrane is unaffected by freeze/thaw. Thus, from the available data, GCLs appear to be superior to CCLs in terms of freeze/thaw resistance.

7.1.5.2 Wet/Dry Effects

Wetting and drying of CCLs and GCLs can cause either type of clay liner to swell or shrink. The main concern with clay liners that are wet and then dry out, is that desiccation can lead to cracking and an increase in hydraulic conductivity.

Limited laboratory data indicate that when dry, cracked CCLs are rewetted, the clay swells and any cracks are partially closed, leading to partial recovery of the original, low hydraulic conductivity. In contrast, the available data show that the high swelling of bentonite results in full self healing and full

recovery of the original, low hydraulic conductivity when dried, cracked GCLs are rewetted. In addition, for those GCLs that contain a geomembrane, the geomembrane is insensitive to wet/dry effects. Thus, GCLs appear to be more than equivalent to CCLs in terms of ability to self-heal if the material is wetted, dried, and then rewetted.

7.1.5.3 Response to Total Settlement

Total settlement refers to block-like settlement without significant bending or distortion. It is believed that GCLs and CCLs would respond similarly to total settlement.

7.1.5.4 Response to Differential Settlement

Recent research by LaGatta (1992) indicates that some GCLs maintain their low hydraulic conductivity even when subjected to large differential settlements. In all probability, GCLs are more resistant to damage from differential settlement than CCLs (LaGatta, 1992). For example, for a depression with a diameter of 1 m that subsides 0.5 m, the liner will undergo approximately 10% tensile strain. While the data discussed in LaGatta (1992) suggests that GCLs can function under such conditions, it is known that CCLs cannot and will suffer tension cracks at 1% tensile strain or less.

7.1.5.5 Stability on Slopes

The shear strength of GCLs is very sensitive to the water content and type of GCL (Shan and Daniel, 1991; and Daniel and Shan, 1992). Water-saturated GCLs that have adhesive-bonded bentonite have angles of internal friction for consolidated-drained conditions of approximately 10 degrees. Dry materials are 2 to 3 times as strong as water-saturated GCLs. Also, needle-punched and stitch-bonded GCLs tend to have high strengths. The shear strength of CCLs varies widely, depending on materials, water content, and compaction conditions.

In stability analyses, one often must consider not only internal shear failure but interfacial shear with an adjacent layer, e.g., a geomembrane. Also, shear strength may be of short-or long-term concern, or both. No general statement can be made about probable equivalency of a GCL to a CCL because the assessment depends on specific materials, the degree to which the bentonite

can wet, consolidation water generated by CCLs, the slope angle, and other site-specific conditions.

7.1.5.6 Vulnerability to Erosion

Erosion resistance may be of concern in final covers if inadequate cover soil is present. Because of the presence of erosion-resistant geosynthetic materials in GCLs, GCLs can potentially be more resistant to erosion than CCLs. However, if the clay liner is exposed to erosive forces, the bentonite may be washed out of some GCL materials. Thus, equivalency depends upon the specific materials being considered. For many sites, erosion will not be of any concern, e.g., for a GCL underlying a geomembrane or a GCL containing a geomembrane that overlies the bentonite.

7.1.5.7 Bearing Capacity

A clay liner must have adequate bearing capacity to support loads, e.g., wheel loads from construction equipment. The clay liner must not thin or pump clay into adjacent layers under static or dynamic (e.g., traffic) loads. Hydrated bentonite is not as strong as most materials used in constructing CCLs. Equivalency is heavily dependent upon site-specific conditions.

7.1.6 Construction Issues

The construction issues that might be considered in an equivalency analysis include puncture resistance, effect of subgrade condition on constructability, ease of placement, speed of construction, availability of materials, weather constraints, and quality assurance requirements.

7.1.6.1 Puncture Resistance

Thick CCLs cannot be accidentally punctured during construction, but thin GCLs can. Some GCLs have the capability of self-sealing around certain types of puncture objects, e.g., penetration of the GCL with a sharp object such as a nail. The swelling capacity of bentonite gives GCLs this self-healing capability.

The more significant type of puncture for a GCL would be puncture caused by construction equipment. For example, if the corner of the blade of a bulldozer accidentally punctures the GCL during spreading of cover material, the GCL would probably not self seal at the puncture. A thick CCL could not be

punctured by a piece of construction equipment. Thus, GCLs will not have equivalent puncture resistance to CCLs. However, quality assurance and quality control procedures can be established and implemented to make the probability of a puncture during construction extremely low. Ultimately, site-specific conditions and quality assurance procedures will determine whether puncture is a relevant issue that deserves serious consideration.

7.1.6.2 Effect of Subgrade Condition

Compacted clay liners are constructed with heavy equipment. If the subgrade is compressible (e.g, solid waste), the GCL, which can be installed with light-weight equipment, will be easier to construct. On the other hand, stones and rocks can puncture a GCL but not a CCL; if the subgrade contains stones or rocks, the integrity of the GCL may be compromised. Thus, equivalency of a GCL to a CCL in terms of the effect of subgrade depends on the condition of the subgrade and will have to be evaluated on a site-specific basis.

7.1.6.3 Ease of Placement or Construction

A GCL will always be easier to place than a CCL, unless weather conditions are adverse (e.g., constant rain), in which case even a CCL will also be difficult to construct. In general, GCLs are equivalent to or better than CCLs in terms of ease of placement or construction.

7.1.6.4 Speed of Construction

Geosynthetic clay liners can be placed much more quickly than CCLs. Equivalency is obvious.

7.1.6.5 Availability of Materials

Suitable clays for construction of a CCL may or may not be available locally, depending on the site. Because GCLs are a manufactured material, they are readily available and can be shipped to a site quickly. The cost of shipment is not a large percentage of the total cost of a GCL. Thus, GCLs will often be superior to CCLs in terms of availability of materials.

7.1.6.6 Weather Constraints

Compacted clay liners are difficult to construct when soils are wet, heavy precipitation is occurring, the weather is extremely dry (clay desiccates), the soil is frozen, or the temperature is below freezing. Geosynthetic clay liners are difficult to construct during precipitation. Weather constraints generally favor GCLs.

Some GCLs must be covered before they get wet. If a geomembrane will be placed over the GCL, the GCL must be covered almost immediately with the geomembrane. Additional weather constraints, e.g., wind speed, may apply to the geomembrane and, indirectly, influence the GCL. The fact that many GCLs must be covered before they are hydrated is a significant weather constraint for GCLs that does not exist for CCLs. However, CCLs have weather constraints, too: CCLs must not be allowed to freeze or desiccate (GCLs cannot desiccate during construction because they are dry, and dry GCLs are unaffected by freezing temperatures).

Equivalency in terms of weather constraints must be considered on a site-specific basis, but weather constraints generally favor GCLs over CCLs.

7.1.6.7 Quality Assurance Requirements

Quality assurance (QA) requirements are less extensive for GCLs compared to CCLs, but no less critical. There is no reason to suspect that QA is more difficult for a GCL than a CCL. However, testing procedures and observational techniques are well established for CCLs but are not for GCLs. The GCL industry and the Geosynthetic Research Institute (GRI) are working hard through GRI and ASTM to established testing methods. While it would appear that GCLs and CCLs are equivalent in terms of QA requirements, more work needs to be done to establish standard test methods for GCLs.

7.1.7 Summary of Equivalency Issues

Table 7.3 summarizes the preceding discussion of equivalency. Equivalency can be demonstrated generically in many categories. However, in two categories, equivalency probably cannot be demonstrated: (1) GCLs do not have adsorption capacity equivalent to CCLs; and (2) GCLs do not have the puncture resistance of CCLs. The adsorption capacity has no relevancy to covers.

Table 7.3 Summary of Equivalency Assessment

		Equivalency of GCL to CCL		
Category	Criterion for Evaluation	Probably Equivalent	Probably Not Equivalent	Product or Site Specific
Hydraulic Issues	Steady Flux of Water			X
	Steady Solute Flux			X
	Adsorption Capacity		X	
	Breakthrough Time:			
	-Water			X
	-Solute		X	
	Consolidation Water	X		
Physical/ Mechanical Issues	Freeze-Thaw	X		
	Wet-Dry	X		
	Total Settlement	X		
	Differential Settlement	X		
	Slope Stability			X
	Erosion			X
	Bearing Capacity			X
Construction Issues	Puncture Resistance		X	
	Subgrade Condition			X
	Ease of Placement	X		
	Speed of Construction	X		
	Availability of Materials	X		
	Weather Constraints	X		
	Quality Assurance	X		

For liners, the issue of adsorption capacity may or may not be relevant, depending on project-specific details. Although thin GCLs can be punctured during construction, the problem is of more concern for liners (due to higher stresses), and careful QA may be capable of addressing this potential problem for both liners and covers.

As suggested by Table 7.3, many equivalency issues depend on the GCL product and the particular conditions unique to a given site. Equivalency will clearly have to be evaluated on a case-by-case basis.

7.2 Discussion

A brief discussion took place after the presentation. Comments were made that there is a large need to establish criteria for analysis of equivalency. The potential criteria are numerous, but many may not apply. Also, differences in liners and covers were emphasized and the special problems in analyzing geomembrane/clay liner composites were briefly discussed.

CHAPTER 8
TECHNICAL CONCERNS

Even though a wide variety of research has been performed on geosynthetic clay liners (GCLs), many people expressed concern about how GCLs will perform in the field. The research, while providing some insight into the properties of GCLs, can often be difficult to interpret and relate back to a real-life field condition. Because of this, there are still unanswered questions and concerns relating to the full-scale field behavior of GCLs. In an effort to identify and address specific concerns, an open discussion was held.

8.1 The Effect of Freezing on Saturated Sodium Bentonite

The hydraulic conductivity of one GCL incorporating sodium bentonite has been shown to be unaffected by several freeze/thaw cycles in one series of laboratory experiments (Shan and Daniel, 1991). Similar results have been obtained for other GCLs in tests performed in commercial laboratories. Thus, the limited laboratory data show no detrimental effects from freeze-thaw but there have been no full scale field tests performed to verify the results of laboratory tests.

8.2 The Flow of Bentonite out of a GCL on a Side Slope

Bentonite would most likely not flow out of a GCL on a slope because:

- If a GCL is installed with an overlying geomembrane, the chances are that the GCL will never get sufficiently hydrated to allow the clay to "flow".

- If the GCL did become hydrated, consolidation would take place due to the stress of cover soils, and the internal shear strength of the GCL would go up.

- If a needle punched or stitch bonded GCL is used it is difficult to imagine the clay moving between the confining geotextiles.

8.3 Designing for Side Slopes

Two sets of data are needed to design for side slope stability when using GCLs:

1) Shear strength test data simulating the failure mode deemed important by the designing engineer:

    - Short term direct shear tests
    - Long term creep tests

2) Wide width tensile strength data. When conducting this test, one must consider the effect of confining stress on the results. Research at Drexel University (1992) has shown that the confining stress will not influence the tensile strength of a GCL incorporating a woven slit film geotextile.

8.4 Possibility of Overlaps Pulling Apart Due to Wet/Dry Cycles

This is why GCLs should always be installed with some sort of overburden stress. Not only can the overburden soil prevent damage to the GCL, but over burden will also prevent the overlap width from changing if moist GCLs dry and shrink. The GCL products can also be modified to prevent overlap movement. Bentofix® can be made with a velcro strip along the overlap, Claymax® or Bentomat® can be sewn (by hand) along the overlap as a prayer seam with a strong monofilament thread, and the geomembrane components of Gundseal can be welded together.

8.5 Steep Slopes

The use of geogrids and high strength geotextiles should be considered, as the long term shear and tensile strength of a GCL is questionable.

8.6 Long Term Physical Stability

Which will physically last longer, a GCL or a CCL? This depends on the environment to which the liner will be exposed. While CCLs have traditionally had problems due to desiccation cracking in hot, arid climates, GCLs have shown the ability to quickly swell and self-heal even after being dried out. The mineral components of both the CCL and GCL would hypothetically last forever as clay is in the final stage of weathering. The long-term performance of the geotextiles and needle punching is questionable, though.

8.7 Long Term Shear Strength

The internal shear strength of a GCL will go down as the bentonite hydrates. How long will it take for a GCL to become hydrated? Is it reasonable to assume that the entire GCL becomes hydrated?

8.8 Biotic Instabilities

How does one prevent animals and plants from burrowing into the final cover? While a thick CCL could prevent damage, how can a thin GCL prevent damage from occurring? One could possibly place a wire screen in the upper layer, but how effective would this really be?

CHAPTER 9
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