BENTONITE MIGRATION IN GEOSYNTHETIC CLAY LINERS

Timothy D. Stark
Associate Professor, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

ABSTRACT: Since the introduction of geosynthetic clay liners (GCLs) to waste containment facilities, one of the major concerns about their use has been the hydraulic equivalency to a compacted clay liner. Field observations and laboratory test results show that the thickness, or mass per unit area, of hydrated GCLs can decrease under normal stress, especially around zones of stress concentration, such as a sump or wrinkles in an overlying geomembrane. In a liner system, this decrease in GCL thickness can lead to an increase in fluid flux, regulatory non-compliance, and a decrease in leachate attenuation capacity and containment time. In a cover system, a reduced thickness of bentonite may lead to an increase in infiltration or gas migration through the GCL. Suggestions for protecting hydrated bentonite from stress concentrations are presented.

KEYWORDS: Geosynthetic Clay Liners, Flow Rates, Fluid Barrier, Permeability, Shear Strength

1 INTRODUCTION

In recent years, geosynthetic clay liners (GCLs) are increasingly being selected to replace compacted clay liners (CCLs) in composite liner and cover systems for waste containment facilities. Some of the advantages of GCLs over CCLs are: (1) lower and more predictable cost, (2) prefabricated/manufactured quality, (3) easier and faster construction, (4) reduced need for field hydraulic conductivity testing, (5) availability of engineering properties, (6) more resistance to the effects of wetting/drying and freeze/thaw cycles, (7) increased airspace resulting from smaller thickness, and (8) easier repair. Some of the disadvantages of GCLs versus CCLs include: (1) a potential for lower internal and interface shear strength, (2) a possible large post-peak shear strength loss in reinforced GCLs, (3) lower puncture resistance, (4) smaller leachate attenuation capacity, (5) shorter containment time, and (6) possibly higher long-term flux because of a reduction in hydrated bentonite thickness under the applied normal stress (Anderson and Allen 1995 and Anderson 1996). Koerner and Daniel (1995) concluded that GCLs can be considered hydraulically equivalent to CCLs if puncture and bentonite thinning do not occur.

2 BENTONITE MIGRATION IN GCLs

Field experiences, including the GCL slope stability research project in Cincinnati, Ohio (Koerner et al. 1996), show that bentonite will absorb moisture because of its high matric suction potential. An increase in water content is accompanied by an increase in compressibility regardless of the normal stress at which hydration occurs (Terzaghi et al. 1996).

Koerner and Narejo (1995) showed that if a circular piston is applied to a hydrated GCL, the bentonite will flow away from the load and the hydrated thickness of the GCL beneath the applied load will decrease. They concluded that the soil covering a GCL must have a thickness (H) greater than or equal to the diameter (D) of the loaded area to adequately protect the GCL. Fox et al. (1996) presented results of similar GCL bearing capacity tests using three cover soils: a clean sand, a fine gravel, and a medium gravel. They recommended an H/D ratio between 1 and 2 to protect the GCL for this range of cover soils. The U.S. Army Corps of Engineers (United States 1995) requires a minimum cover soil thickness of 0.45 m, instead of an H/D ratio, before construction equipment can operate on top of a GCL.

The thickness of hydrated bentonite also may decrease under nonuniform normal stresses that may be imposed by the waste placed above the liner system. Stress concentrations in a liner system can cause hydrated bentonite to migrate to zones of lower stress. Stress concentrations are ubiquitous in a liner system, especially around a sump, under leachate collection pipes, at the edge of an anchor trench, at slope transitions, and around slope benches. Bentonite migration may be particularly important in sump areas because high hydraulic heads in a sump can increase leakage rates. In fact, Tedder (1997) recommended additional protection for sump areas. Stress concentrations can also be induced in a cover or liner system by a subgrade that contains stones or is uneven and/or contains ruts prior to GCL placement. Another possible mechanism for stress concentration development is local differential settlement caused by natural variations in foundation compressibility and shear strength, i.e., bearing capacity.

3 MIGRATION AT GEOMEMBRANE WRINKLES

The presence of wrinkles in an overlying geomembrane creates zones of nonuniform normal stress, which can cause hydrated bentonite to migrate into the airspace under the wrinkle. Figure 1 presents a typical pattern of wrinkles in a recently installed black, smooth high density polyethylene (HDPE) geomembrane. It can be seen that the liner has a number of wrinkles, especially around the sump located in the foreground. (Note: sandbags in middle of photograph for scale.) The photograph was taken in the morning which probably reduced the number of wrinkles. In addition, there are a number of places around the sump and subsequent piping that lead to stress concentrations.

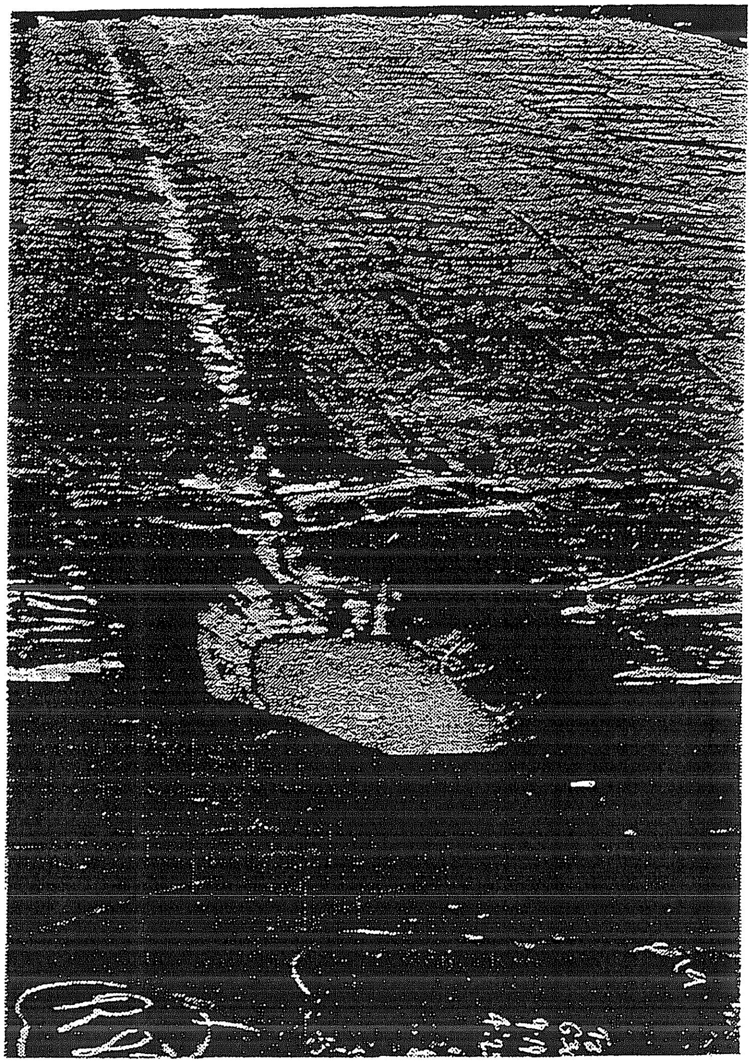

Figure 1. Typical pattern of wrinkles in a smooth HDPE geomembrane liner and around a sump.

Koerner (1996) and Soong and Koerner (1997) discussed the progress of a current research project investigating the fate of wrinkles in geomembranes. Current results indicate that the shape of a wrinkle or wave can change with time and normal stress, but the height does not appear to reduce substantially under a range of normal stresses. In addition, Eith and Koerner (1996) and Koerner et al. (1997) described a municipal solid waste landfill double liner system that was exhumed after eight years of service. The double liner system was constructed in 1988 and exhumed for a lateral expansion. After exhumation, a number of large wrinkles were found in the geomembrane. These observations show that wrinkles are not removed after installation, and can be long-term zones of nonuniform normal stress acting on an underlying GCL. The lack of intimate contact due to wrinkles can result in hydrated bentonite migrating into the airspace under the wrinkle.

Anderson and Allen (1995) and Anderson (1996) showed that the thickness of a hydrated GCL can be reduced significantly in the vicinity of a geomembrane wrinkle. A normal stress of 958 kPa was applied to a hydrated GCL in the presence of a geomembrane wrinkle using a one-dimensional compression apparatus. These tests were conducted using a steel and plexiglass consolidometer measuring 0.3 m by 0.3 m. Two needle-punched GCLs were used in these compression tests. Both products consisted of woven upper geotextiles and nonwoven lower geotextiles. The non-woven geotextile of the GCL was placed on a horizontal layer of compacted sand while the woven geotextile was in contact with the geomembrane.

Both GCLs were hydrated under a normal stress of 9.6 kPa for 72 hours. The moisture content of the bentonite after hydration ranged from 100 to 150%. A 1.5 mm thick smooth HDPE geomembrane with a 50 mm wrinkle, as suggested by Giroud (1995), was placed on top of the GCL. Sand was then compacted along the sides and top of the wrinkle.

The normal stress was applied using a loading frame with a load cell at an average rate of 4.5 kN/min in one-dimensional compression. The normal force was increased for approximately 3.5 hours until a normal stress of 958 kPa was achieved. This normal stress was maintained for 3 hours and observations of the bentonite behavior were made. The shape or width of the wrinkle changed slightly but it did not disappear due to the normal stress of 958 kPa.

The hydrated bentonite migrated toward the void under the geomembrane wrinkle where the normal stress was at or near zero. The thickness of the GCLs under the wrinkle was 20 to 25 mm while the thickness farthest away from the wrinkle was less than 2.5 mm. The nominal manufactured thickness of the GCL was 7.0 mm. In addition, the upper woven geotextile separated from the GCL under the wrinkle and conformed to the shape of the wrinkle. This was caused by the additional pressure of the migrating bentonite breaking or pulling the needle-punched fibers out from the woven geotextile in the low confining stress area under the wrinkle. Along the edges of the GCL, where the bentonite was in compression, the needle-punched fibers remained intact.

In summary, the test results presented by Anderson and Allen (1995) indicate that migration of hydrated bentonite toward the area under a wrinkle in the 1.5 mm thick smooth HDPE geomembrane can occur. The migration of bentonite into the wrinkles of a geomembrane also has been observed at an operating landfill in Ohio (Evans 1997).

The migration of hydrated bentonite has implications for meeting regulatory requirements, including mass of bentonite per unit area and hydraulic performance. Thus, it seems prudent to ensure a minimum long-term thickness or mass per unit area of hydrated bentonite to maintain hydraulic performance, leachate attenuation capacity, and leachate containment time in a GCL liner system. In a cover system, a minimum long-term thickness of hydrated bentonite should be maintained to reduce water infiltration and/or gas migration out of the landfill. The reduced thickness in a cover could be caused by vehicle traffic, slope transitions or benches, and geomembrane wrinkles.

4 POSSIBLE SOLUTIONS

A number of possible solutions were considered to eliminate or reduce the potential migration of hydrated bentonite in a liner system. One possible solution is to use a CCL because of the low compressibility of the highly compacted soil. Another solution is to encapsulate the bentonite between two geomembranes to reduce the amount of hydration and the resulting increase in compressibility. This can be accomplished with planar geomembranes or geomembranes with protrusions. Multiple layers of GCL also can be installed at known points of stress concentration, e.g., sumps and changes in slope. The multiple layers of GCL initially provide a thicker layer of bentonite. Another possible solution involves reducing stress concentrations in the subgrade by smoothing changes in the geometry, reducing ruts, and removing rocks. The geomembrane also should be installed with a limited number of wrinkles. This can be accomplished by using geomembranes that are light-colored (white), exhibit a high friction coefficient (textured), and/or are flexible (Giroud 1995).

5 MODIFICATION OF EXISTING GCLs

Another technique to ensure a minimum long-term thickness of hydrated bentonite is to modify existing GCLs to include an internal structure or stabilizer element. The stabilizer element would reduce the compression, and thus lateral squeezing, of hydrated bentonite in response to the stress concentrations in a liner or cover system. The internal structure would also protect the bentonite from concentrated stresses applied during handling, stockpiling, and construction, and may provide additional resistance to accidental puncture. Confining the bentonite in an internal structure will provide better assurance of the thickness or integrity of the bentonite. This protection is already provided in some bentonite waterproofing applications. It is anticipated that the bentonite would fill the entire depth of the internal structure. Therefore, the initial thickness of the GCL, or internal structure, would correspond to the desired bentonite thickness.

The modified GCL described herein utilizes a geonet as the internal structure or stabilizer element. This modified GCL is fabricated by bonding one nonwoven geotextile to the geonet, filling the geonet with bentonite, and bonding the second geotextile. The internal structure facilitates bonding of the geotextiles and protects the bentonite, or other impermeable material, from the overlying normal stress. Heat bonding usually results in a strong bond between a geotextile and geonet, which has been observed for geosynthetic drainage composites. This bonding significantly reduces the potential for internal failure or shear through the bentonite. The internal structure also provides some puncture and tensile resistance to the GCL. If additional tensile resistance is required, the geonet could be replaced with a thick geogrid. Other variations of the modified GCL include the use of an internal configuration or structure that differs from a geonet or using a geomembrane that incorporates an internal structure (Stark 1997).

5.1 Hydraulic Conductivity of Modified GCL

Stalcup and Rad (1994) conducted a falling head hydraulic conductivity test in accordance with ASTM D5084 (Standard 1993a) to evaluate the hydraulic conductivity of the modified GCL. The modified GCL described herein consisted of two 265 g/m^2 nonwoven geotextiles heat bonded to a geonet. The geonet was filled with 5 kg/m^2 of bentonite.

The modified GCL was consolidated at a confining stress of 35 kPa and then hydrated. The hydraulic conductivity value of 4×10^{-11} m/sec was measured using falling head hydraulic gradients ranging from 27 to 5. This value is in agreement with values (2 to 5×10^{-11} m/s) reported for existing fabric encased GCLs (Geotechnical Fabrics Report 1997).

5.2 Shear Strength of Modified GCL

Swan (1994) conducted 0.3 m by 0.3 m direct shear tests in accordance with ASTM D5321 (Standard 1993b) to evaluate the shear strength of the modified GCL. The modified GCL was hydrated and sheared at the same normal stress. Two normal stresses, 100 and 290 kPa, were used in the tests. The modified GCL was allowed to hydrate for 24 hours under tap water immersion. The shear stress was applied at the rate of 1.0 mm/minute, as indicated in ASTM D5321. In both tests, failure occurred between the upper geotextile and a special direct shear gripping surface. The bond between the upper and lower geotextiles and the geonet did not fail or show any degradation. Table 1 presents the peak shear stress and secant friction angle for each test. These angles of internal friction correspond to a linear failure envelope that passes through the origin and the peak shear stress. The resulting friction angles are large, and comparable to the peak friction angle of a textured geomembrane/nonwoven geotextile (265 g/m^2) interface

(Stark et al. 1996).

Table 1. Direct shear test results on modified GCL.

Normal stress (kPa)	Peak shear stress (kPa)	Peak secant friction angle (degrees)
100	115	49
200	174	31

Figure 2 presents the shear force-displacement relationships from the two 0.3 m by 0.3 m direct shear tests on the modified GCL. No post-peak strength loss was observed in the test at a normal stress of 100 kPa. In fact, the shear force-displacement relationship increases with increasing shear displacement due to necking or stretching of the geonet. The test at a normal stress of 290 kPa exhibited a reduction in shear force and friction angle of approximately 6 kN and 9 degrees, respectively. The post-peak strength loss is mainly attributed to the pulling out and/or tearing of the filaments from the nonwoven geotextile during shear (Stark et al. 1996). The geonet also necked or stretched during this test.

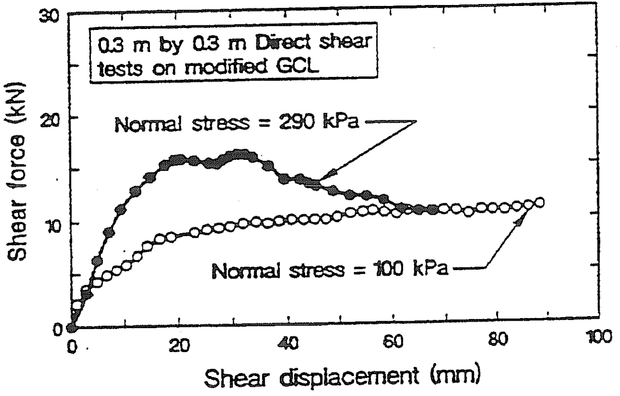

Figure 2. Shear strength of modified GCL after hydration (after Swan 1994).

5.3 Compressibility of Modified GCL

One-dimensional compression tests were conducted on the modified GCL in the 0.3 m by 0.3 m consolidometer used by Anderson and Allen (1995). The tests were conducted in the presence of a geomembrane wrinkle to demonstrate protection of the hydrated bentonite. The testing was performed both with and without bentonite in the geonet to distinguish between bentonite and geosynthetic compressibility.

For comparison purposes, the normal stress (958 kPa) and duration of the maximum normal stress (3 hours) used in the previously described tests by Anderson and Allen (1995) were used to test the modified GCL. However, to better simulate landfill loading rates, the normal stress was applied at an average rate of about 2.5 kPa/min, instead of 4.5 kPa/min, until a normal stress of 958 kPa was achieved. As a result, approximately 6 hours of loading was required to obtain a normal stress of 958 kPa. However, this loading rate is still probably faster than actual landfilling.

Both modified GCL specimens were hydrated using the procedure described by Anderson and Allen (1995). The water content of the bentonite in the modified GCL after hydration was 172%. The specimen without bentonite was also hydrated, but moisture contents of the geosynthetics were not measured. After the normal stress was removed, the specimens with and without bentonite were measured to determine the variation of thickness across the specimen in the presence of a wrinkle.

5.3.1 Modified GCL with bentonite

Table 2 presents the thicknesses of the GCL specimen with bentonite before and after loading to a normal stress of 958 kPa. The thickness of the GCL prior to hydration under a normal stress of 9.6 kPa for 72 hours was about 5.5 mm.

The thickness of the modified GCL increased slightly from approximately 5.5 mm to 5.8 and 5.9 mm along the right and left edges, respectively, during the hydration phase of the test. This is attributed to bentonite swelling into the nonwoven geotextile at a normal stress of 9.6 kPa. The thickness also increased slightly under the wrinkle at the center of the specimen. It is anticipated that this increase in thickness is also due to expansion of the bentonite during hydration.

Table 2. Thickness of modified GCL with bentonite.

Test Condition	Thickness at left edge (mm)	Thickness under wrinkle at center (mm)	Thickness at right edge (mm)
After hydration & prior to loading	5.9	5.7	5.8
After application of normal stress of 958 kPa	5.4	10.1	5.5
Change in thickness after loading	-0.5	+4.4	-0.3

Under a normal stress of 958 kPa, the GCL thickness at the outer edges decreased slightly to approximately the original thickness of 5.5 mm. This decrease is attributed to compression of the geotextile, compression of the geonet, and possible squeezing of hydrated bentonite through the upper nonwoven geotextile toward the wrinkle or into the underlying bentonite. The bentonite probably initially migrated into the upper nonwoven geotextile during hydration under a normal stress of 9.6 kPa.

The interesting behavior occurred under the wrinkle near the center of the specimen where the thickness increased by 4.4 mm. Examination of the specimen after testing indicated that the increase in thickness was caused by bentonite swelling vertically into the nonwoven geotextile, the geotextile and geonet not being compressed under the wrinkle, and the geonet being slightly compressed along the edges and forcing hydrated bentonite toward the wrinkle area. It is also possible that hydrated bentonite in the nonwoven geotextile was squeezed or pushed from the left and right edges to the area under the wrinkle. It is important to note that the nonwoven geotextile remained bonded to the top of the geonet in the vicinity of the wrinkle instead of separating from the GCL as was observed in tests performed on a needle-punched GCL by Anderson and Allen (1995).

In summary, the modified GCL maintained a minimum thickness of 5.4 mm (near the initial thickness of 5.5 mm) after hydration and loading to a normal stress of 958 kPa in the presence of a geomembrane wrinkle.

5.3.2 Modified GCL without bentonite

Table 3 presents the thickness of the modified GCL specimen without bentonite before and after loading. The thickness of the GCL after hydration for 72 hours under a normal stress of 9.6 kPa was approximately 5.6 mm. As expected, the thickness of the modified GCL remained approximately constant during the hydration phase of the test because no bentonite was placed in the geonet. After loading to a normal stress of 958 kPa, the thickness at the left and right edges of the modified GCL showed little, if any, compression which is similar to the modified GCL with bentonite. The GCL thickness under the wrinkle remained essentially unchanged.

Comparison of Tables 2 and 3 shows that the modified GCL with and without bentonite exhibited similar thicknesses along the edges after loading to a normal stress of 958 kPa. The only discrepancy appears to be the area under the wrinkle where some hydrated bentonite swelled into the nonwoven geotextile and may have been pushed from the edges through the nonwoven geotextile to the wrinkle area.

In summary, the use of an internal structure in a GCL may provide some assurance of the minimum thickness or mass per unit area of the bentonite after installation. The long-term thickness can be prescribed by using an internal structure height that meets the desired thickness or mass per unit area. In addition, stress concentrations caused by handling, installation, uneven subgrades, rocks, sumps, piping, slope transitions, and geomembrane wrinkles will not have to be reduced or modified because the bentonite is protected by the internal structure. The modified GCL also utilizes materials already approved and accepted for waste containment facilities.

Table 3. Thickness of modified GCL without bentonite.

Test Condition	Thickness at left edge (mm)	Thickness under wrinkle at center (mm)	Thickness at right edge (mm)
After hydration & prior to loading	5.6	5.5	5.7
After application of normal stress of 958 kPa	5.4	5.7	5.3
Change in thickness after loading	-0.2	+0.2	-0.4

6 CONCLUSIONS

Hydrated bentonite can migrate to areas of lower normal stress due to stress concentrations. Stress concentrations are ubiquitous in a liner system, especially around a sump and pipe locations, at the edge of an anchor trench, around slope transitions and slope benches, under geomembrane wrinkles, and above an uneven subgrade or rock. Possible solutions to eliminate or reduce the migration of hydrated bentonite include using a compacted clay liner, encapsulating the bentonite between two geomembranes to reduce the amount of hydration and the resulting increase in compressibility, installing multiple layers of GCL at known stress concentrations, eliminating stress concentrations in the subgrade by smoothing changes in geometry, reducing ruts and removing rocks, and/or installing geomembranes with a limited number of wrinkles. The number of wrinkles could be reduced using a geomembrane that is light-colored (white), exhibits a high coefficient of friction (textured), and/or is flexible (Giroud 1995). Another alternative is to modify existing GCLs to include an internal structure or stabilizer element as described herein. The stabilizer element appears to protect the bentonite from stress concentrations thereby reducing bentonite migration and provide additional puncture resistance.

ACKNOWLEDGMENTS

Sam R. Allen of TRI/Environmental in Austin, Texas supervised the 0.3 m by 0.3 m one-dimensional compression tests on the modified GCL. The author also acknowledges James D. Anderson of JANCO Engineering for his extensive review of this paper. The author invented the modified GCL. Patent rights have been assigned to Geosynthetics, Incorporated to which the author is a paid technical consultant.

REFERENCES

Anderson, J.D. (1996) "Are Geosynthetic Clay Liners (GCLs) Really Equivalent to Compacted Clay Liners", *Geotechnical News*, BiTech Publishing, Ltd., British Columbia, Canada, Vol. 14, No. 2, June, pp. 20-23.

Anderson, J.D. and Allen, S.R. (1995) "What Are the Real Design Considerations When Using a Geosynthetic Clay Liner (GCL)", *Proceedings of the 9th Annual Municipal Solid Waste Management Conference*, Austin, TX.

Eith, A.W. and Koerner, G.R. (1996) "Assessment of HDPE Geomembrane Performance in a Municipal Waste Landfill Double Liner System after Eight Years of Service", *Proceedings of 10th GRI Conf. on Field Performance of Geosynthetics and Geosynthetic Related Systems*, Drexel Univ., Philadelphia, PA, pp. 97-109.

Evans, W.D. (1997). "Advisory on Structural Integrity Considerations for Incorporating Geosynthetic Clay Liners in Solid Waste Landfill Facility Designs," Div. of Solid and Infectious Waste Management, Ohio Environmental Protection Agency, August, 14 pp.

Fox, P.J., DeBattista, D.J. and Chen, S.H. (1996) "Bearing Capacity of Geosynthetic Clay Liners for Cover Soils of Varying Particle Size", *Geosynthetics International*, Industrial Fabrics Assoc. International, St. Paul, MN, Vol. 3, No. 4, pp. 447-461.

Geotechnical Fabrics Report (1997) "Specifier's Guide", Industrial Fabric Assoc. Intl., St. Paul, MN, pp. 144-145.

Giroud, J.P. (1995) "Wrinkle Management for Polyethylene Geomembranes Requires Active Approach", *Geotechnical Fabric Report*, April, Vol. 13, No. 3, pp. 14-17.

Koerner, G.R., Eith, A.W., and Tanese, M. (1997) "Properties of Exhumed HDPE Field Waves and Selected Aspects of Wave Management", *Proceedings of 11th GRI Conf. on Field Installation of Geosynthetics*, Drexel Univ., Philadelphia, PA, pp. 152-162.

Koerner, R.M. (1996) *The GSI Newsletter/Report*, Geosynthetic Institute, Drexel University, Philadelphia, PA, Vol. 10, No. 2, June.

Koerner, R.M., Daniel, D.E. and Bonaparte, R. (1996) "Current Status of the Cincinnati GCL Test Plots", *Proceedings of 10th GRI Conference on Field Performance of Geosynthetics and Geosynthetic Related Systems*, Drexel Univ., Philadelphia, PA, pp. 147-175.

Koerner, R.M. and Daniel, D.E. (1995) "A Suggested Methodology for Assessing the Technical Equivalency of GCLs to CCLs", *Geosynthetic Clay Liners*, edited by Koerner, R.M., Gartung, E., and Zanzinger, H., A.A. Balkema, Rotterdam/Brookfield, pp. 73-98.

Koerner, R.M. and Narejo, D. (1995) "Bearing Capacity of Hydrated Geosynthetic Clay Liners", *Journal of Geotechnical Engineering*, American Society of Civil Engineers, Vol. 121, No. 1, pp. 82-85.

Soong, T.-Y. and Koerner, R.M. (1997) "Behavior of Waves in High Density Polyethylene Geomembranes: A Laboratory Study", *Proceedings of 11th GRI Conf. on Field Installation of Geosynthetics*, Drexel Univ., Philadelphia, PA, pp. 128-151.

Stalcup, J.M. and Rad, N.S. (1994) "GCL Permeability Testing", Laboratory Testing Report prepared by GeoSyntec Consultants, Atlanta, GA, 6 pp.

"Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter - D5084", (1993a) American Society for Testing and Materials, Philadelphia, PA, Annual Book of Standards, Vol. 04.09, pp. 63-70.

"Standard Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method - D5321", (1993b) American Soc. for Testing and Materials, Philadelphia, PA, Annual Book of Standards, Vol. 04.09, pp. 110-114.

Stark, T.D. (1997) "Effect of Swell Pressure on GCL Cover Stability", *Proceedings of Symposium Testing and Acceptance Criteria for Geosynthetic Clay Liners*, Amer. Soc. for Testing and Materials, Special Technical Publication 1308, Larry W. Well, ed., pp. 30-44.

Stark, T.D., Williamson, T.A. and Eid, H.T. (1996) "Effect of Textured HDPE Geomembrane/Geotextile Interface Shear Strengths", *J. of Geotechnical Engineering*, Amer. Soc. of Civil Engineers, Vol. 122, No. 3, pp. 197-203.

Swan, R.H., Jr. (1994) "GCL Direct Shear Testing", Laboratory Testing Report prepared by GeoSyntec Consultants, Atlanta, GA, 8 pp.

Tedder, R.B. (1997) "Evaluating the Performance of Florida Double-Lined Landfills", *Proceedings Geosynthetics '97 Conference*, Industrial Fabrics Association International, St. Paul, MN, Vol. 1, pp. 425-438.

Terzaghi, K., Peck, R.B., and Mesri, G. (1996) *Soil Mechanics in Engineering Practice*, Third Edition, John Wiley & Sons, Inc., New York, NY, 549 pp.

United States Army Corps of Engineers (1995) "Guide Specification for Military Construction: Geosynthetic Clay Liners - Section 02442", CEGS-02442, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, August, 10 pp.