Technical Paper by H.T. Eid and T.D. Stark

SHEAR BEHAVIOR OF AN UNREINFORCED GEOSYNTHETIC CLAY LINER

ABSTRACT: Dry and hydrated specimens of an unreinforced geomembrane-backed geosynthetic clay liner (GCL) were sheared against a textured geomembrane using a torsional ring shear apparatus to study the shear behavior of geomembrane encapsulated bentonite. Shearing of the dry GCL against a textured geomembrane at high normal stresses resulted in failure occurring within the GCL adhesive that attaches the bentonite to the geomembrane backing and not the GCL bentonite/geomembrane interface. This type of failure occurred when both smooth and textured geomembranes were used as the GCL backing material. Conversely, shearing of the hydrated GCL against a textured geomembrane resulted in failure occurring at the GCL bentonite/textured geomembrane interface. The order of hydration and normal stress application was found to significantly affect the GCL/textured geomembrane interface shear strength. The mobilized shear strength of the GCL/textured geomembrane interface does not equal the drained shear strength of bentonite because of the effect of geomembrane texturing and the lack of drainage during dry and hydrated GCL testing, respectively. Finally, the hydrated GCL/textured geomembrane interface exhibits an increase in peak shear strength of approximately 13% per log cycle of the shear rate. Therefore, the selection of a shear displacement rate is important for unreinforced geomembrane-backed GCL/textured geomembrane interface shear tests.

KEYWORDS: Geosynthetic clay liner, Strength, Stability, Slope, Shear box test, Shear rate.

AUTHORS: H.T. Eid, Post-Doctoral Research Associate, b213 Newmark Civil Engineering Laboratory, University of Illinois, 205 N. Mathews Ave., Urbana, Illinois 61801, USA, Telephone: 1/217-333-6990, Telefax: 1/217-333-9464, E-mail: h-eid@uiuc.edu; and T.D. Stark, Associate Professor of Civil Engineering, 2217 Newmark Civil Engineering Laboratory, University of Illinois, 205 N. Mathews Ave., Urbana, Illinois 61801, USA, Telephone: 1/217-333-7394, Telefax: 1/217-333-9464, E-mail: t-stark1@uiuc.edu.

PUBLICATION: *Geosynthetics International* is published by the Industrial Fabrics Association International, 1801 County Road B West, Roseville, Minnesota 55113-4061, USA, Telephone: 1/612-222-2508, Telefax: 1/612-631-9334. *Geosynthetics International* is registered under ISSN 1072-6349.

DATES: Original manuscript received 3 June 1997, revised version received 29 October 1997 and accepted 5 December 1997. Discussion open until 1 July 1998.

REFERENCE: Eid, H.T. and Stark, T.D., 1997, "Shear Behavior of an Unreinforced Geosynthetic Clay Liner", *Geosynthetics International*, Vol. 4, No. 6, pp. 645-659.

---

1 INTRODUCTION

Geosynthetic clay liners (GCLs) have been used in recent years to replace or reduce the thickness of compacted clay liners (CCLs) required in composite liner or cover systems for waste containment facilities or landfills. GCLs are a cost effective substitute for CCLs because they are easier to construct and repair, and smaller in thickness which results in more waste containment capacity. In addition, GCLs have more resistance to the effects of wetting/drying and freeze/thaw cycles on hydraulic conductivity. However, CCLs have advantages over GCLs including larger leachate attenuation capacity, smaller post-peak shear strength loss, and possibly higher internal and interface shear strength.

GCL products are continuously being developed to improve their hydraulic and shear characteristics. The two main types of unreinforced GCLs are comprised of: (i) a thin layer of granulated bentonite (approximately 3 to 4 mm thick) adhered to a high density polyethylene (HDPE) geomembrane (Figure 1a); or (ii) a thin layer of granulated bentonite (approximately 3 to 5 mm thick) encased between two geotextiles that are not connected (Figure 1b). Reinforced GCLs are also available and are comprised of geotextile-encapsulated bentonite that is stitch-bonded or needle-punched to connect the backing geotextiles. The reinforcement is designed to increase the internal shear strength of the GCL.

Hydrated bentonite is one of the weakest soil/clay materials in terms of shear strength (Mesri 1969). Precipitation and/or the moisture from the underlying soil can hydrate the bentonite within a GCL. Bentonite can be encapsulated between two geomembranes to maintain shear strength and bearing capacity by reducing the amount of hydration. This is often accomplished by using a geomembrane-backed GCL covered with a textured geomembrane (the bentonite surface of the GCL is in contact with the textured geomembrane surface). Therefore, the interface between the bentonite of an unreinforced GCL and a textured geomembrane is of particular interest.

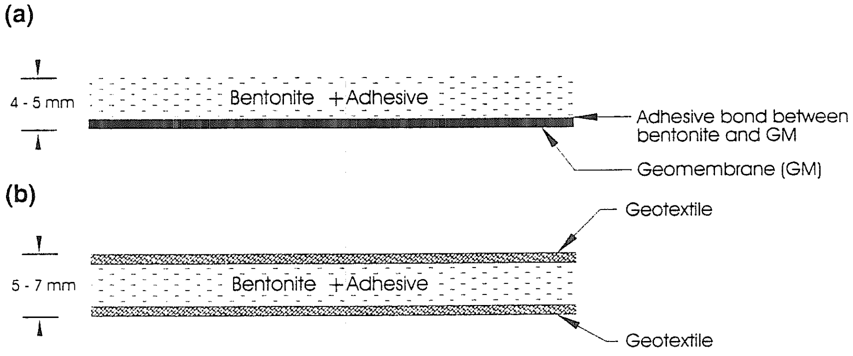

Figure 1. Cross sections of currently available unreinforced GCLs: (a) adhesive bound bentonite adhered to a geomembrane; (b) adhesive bound bentonite between two geotextiles.

This paper describes the torsional ring shear tests that were performed to study the shear behavior of the interface between a textured geomembrane and the bentonite in a geomembrane-backed GCL. The effect of shear rate, normal stress, bentonite hydration, and an undrained condition, due to bentonite encapsulation, on the shear behavior of the interface was investigated. The interface shear strength is project specific and product dependent, thus, the discussion of the test results and their applications focused on analyzing the shear behavior rather than determining the specific shear strength values required for the design of landfill liner or cover systems using an unreinforced GCL.

2 SPECIMEN PREPARATION AND TEST METHOD

A modified Bromhead ring shear apparatus that utilizes an annular specimen with an inside and outside diameter of 40 and 100 mm, respectively, was used for the testing described herein. For each test, a 1.5 mm (60 mil) thick textured high density polyethylene (HDPE) geomembrane was glued to the top platen. The textured geomembrane was manufactured by GSE Lining Technology, Inc. of Houston, Texas, USA using a coextrusion process. A geomembrane-backed GCL was glued to the bottom platen of the ring shear apparatus with the unreinforced bentonite facing the top platen (loading platen) to form a geomembrane-backed GCL/textured geomembrane interface (Figure 2). The GCL was also manufactured by GSE Lining Technology and consists of a 3 to 4 mm thick layer of bentonite attached to a smooth or textured HDPE geomembrane. The following steps describe the geomembrane-backed GCL manufacturing process: (i) adhesive is sprayed onto a geomembrane; (ii) granulated bentonite is rained on the wet adhesive; (iii) adhesive is sprayed onto the adhered bentonite; and (iv) granulated bentonite is rained on the wet adhesive. Combinations of adhesive and granulated bentonite are continuously applied until a 3 to 4 mm thick layer of bentonite, or a mass per unit area of 4.9 kg/m^2, is reached. The bentonite typically used in this GCL is Wyoming bentonite with a liquid limit of 300 to 450, and a plasticity index of 260 to 390 (Mesri 1969; Mesri and Olson 1970). Figure 3 shows the assembled specimen container prior to installation in the ring shear apparatus. The specimen was placed in the ring shear apparatus and then loaded in increments to a maximum normal stress of 17 kPa, and the glue was allowed to cure for 24 hours.

The geomembrane-backed GCL/textured geomembrane interface was tested under two different bentonite conditions: dry and hydrated. The dry condition corresponds to the as-received water content. The as-received water content of the bentonite ranged from 10 to 15% in this study. For the hydrated condition, the specimen was inundated with distilled water and allowed to hydrate until the end of primary swell or vertical deformation ceased. The standard test method ASTM D 4546 was used to estimate the end of primary swelling of the bentonite. The dry and hydrated specimens were sheared until the residual strength was reached which typically required 30 and 70 mm of displacement, respectively.

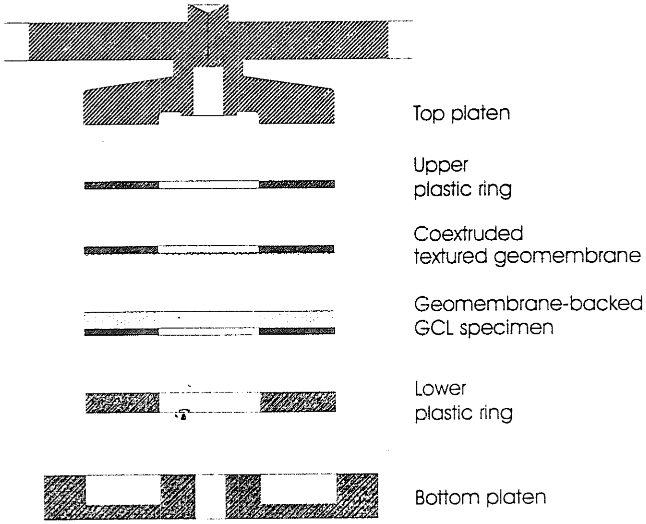

Figure 2. Schematic of the torsional ring shear specimen container.

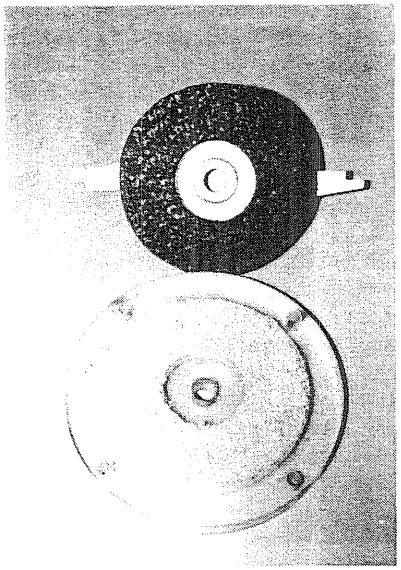

Figure 3. An unreinforced geomembrane-backed GCL/textured geomembrane specimen before ring shear testing.

3 EFFECT OF SHEAR DISPLACEMENT RATE ON GCL/TEXTURED GEOMEMBRANE INTERFACE STRENGTH

The shear displacement rate used in the laboratory tests may have important implications for the estimation of interface shear strength and the cost and scheduling of commercial testing. Two series of ring shear tests were conducted to investigate the effects of shear displacement rate on the measured geomembrane-backed GCL/textured geomembrane interface shear strength. In each series of tests, six different specimens were sheared at displacement rates of 0.015, 0.045, 0.15, 0.5, 1.5, and 18.5 mm/minute. These rates were converted from the corresponding rotation rates using an average annular specimen diameter of 70 mm. All of the tests were conducted at a normal stress of 17 kPa to simulate a landfill cover system.

In the first test series, the water content of the GCL bentonite was maintained at the as-received value during shearing. The specimen was loaded under a normal stress of 17 kPa for 24 hours and then sheared at the desired displacement rate. In the second series of tests, the specimen was hydrated and sheared under a normal stress of 17 kPa. Hydration usually required three weeks and was assumed to be complete by the end of primary swell as defined in ASTM D 4546.

Visual inspection of the failed dry and hydrated specimens revealed that shearing occurred at the interface between the textured geomembrane and the bentonite at a normal stress of 17 kPa for the six displacement rates (Figure 4). The peak and residual shear strengths were typically reached at a shear displacement of 8 and 30 mm, respectively, for the dry specimens, and at 5 and 70 mm, respectively, for the hydrated specimens. The granular particles of dry bentonite require less shear displacement to achieve an

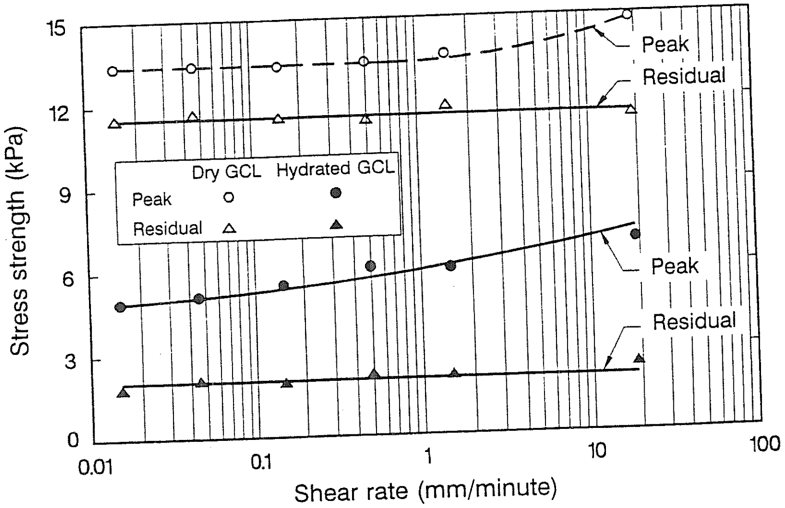

Figure 4. The effect of shear displacement rate on the interface strength of dry and hydrated smooth geomembrane-backed GCL/textured geomembrane specimens at a normal stress of 17 kPa.

orientation parallel to the direction of shear and a residual strength condition than the plate-shaped particles of hydrated bentonite (Lupini et al. 1981).

Figure 4 presents the peak and residual interface shear strengths for the dry and hydrated GCL specimens tested at shear displacement rates ranging from 0.015 to 18.5 mm/minute. The peak interface strength of the dry specimens is approximately constant at shearing rates less than approximately 1.0 mm/minute. The standard test method ASTM D 5321 recommends that the same shear rate of 1.0 mm/minute be used for large direct shear box tests when excess pore pressures are not anticipated. Therefore, a shear displacement rate of 1.0 mm/minute appears suitable for ring shear and direct shear tests on dry unreinforced GCL specimens. It can also be seen from Figure 4 that the peak interface shear strength of the hydrated specimen increases with increasing shear displacement rate. The peak interface strength of the hydrated specimens increases by approximately 13% per log cycle of shear rate. A similar increase of undrained peak shear strength was reported by Graham et al. (1983) and Lefebvre and Pfendler (1996) using direct simple shear tests on a variety of clay soils. The increase in the measured peak interface shear strength at faster shear rates is attributed to the increase in geometric interference because there was no time for contractive particle rearrangement. For slow shear rates, more interparticle bonds were broken and more contractive particle rearrangement occurred before failure (Terzagi et al. 1996).

The data in Figure 4 also suggests that the residual interface shear strength is independent of the shear rate for the dry and hydrated specimens. A residual shear strength condition is reached after a relatively large displacement which causes particle orientation parallel to the direction of shear. The mobilization of this condition in the interface appears to be unaffected by the shear rate. However, the significant decrease in interface shear strength caused by GCL hydration and shear displacement must be considered in landfill slope design.

A shear displacement rate of 0.015 mm/minute was used for the tests presented in the remainder of the paper. This is the slowest possible displacement rate of the modified Bromhead ring shear apparatus and may be faster than the field shear displacement rate prior to failure. However, according to the data presented in Figure 4, a slower shear displacement rate only appears to slightly influence the measured peak interface strength of a hydrated specimen. The effect of shear displacement rate can be approximately quantified by using a peak interface strength reduction of 13% per log cycle of shear rate.

The ring shear specimen configuration used in this testing program simulates field conditions of a layer of bentonite encapsulated by two geomembranes. Geomembrane encapsulation may prevent drainage from the top and bottom edges of the bentonite layer; however, lateral drainage may occur in the laboratory tests. The low permeability of hydrated bentonite and the encapsulating geomembrane may result in an undrained or partially-drained shearing condition, regardless of the displacement rate. The undrained condition may be especially applicable to the peak shear strength because the peak shear strength is rapidly mobilized after shearing is initiated.

4 DRY GCL/TEXTURED GEOMEMBRANE INTERFACE BEHAVIOR

4.1 Introduction

This section discusses the shear behavior of a dry GCL/textured geomembrane interface (i.e. geomembrane-encapsulated bentonite). As mentioned in Section 2, the dry condition refers to the as-received water content. Ring shear specimens were sheared under normal stresses of 17, 50, 75, 100, 150, 175, 200, and 400 kPa to simulate the loading conditions in landfill cover and liner systems. The interface components were marked prior to ring shear testing to facilitate locating the failure surface after shear. Each dry specimen was compressed under the test normal stress for 24 hours and then sheared until a residual shear strength condition was achieved. Figure 5 presents the shear stress-displacement relationships for a smooth geomembrane-backed GCL/textured geomembrane interface test at a normal stress of 17 kPa. The stress ratio is defined as the measured shear stress, τ, divided by the effective normal stress, σ'_n. The secant peak and residual friction angles of the interface were approximately 38 and 35°, respectively. Figure 5 also shows the shear stress-displacement relationship for a 0.3 m by 0.3 m direct shear test (ASTM D 5321) on a similar interface reported by Daniel and Scranton (1996). The normal stress and shear rate were 18 kPa and 1.0 mm/minute, respectively. It should be noted that the geosynthetics used in the ring shear and direct shear tests were from the same manufacturer, but not from the same production lot. In Figure 5, the term "as received" is used to report the water content of the bentonite for the direct shear test because the initial water content was not reported. The peak and residual friction angles measured during the direct shear interface test were approximately 37 and 35°, respectively.

Visual inspection of the ring shear specimen after shearing showed that failure occurred at the dry bentonite/textured geomembrane interface. Daniel and Scranton

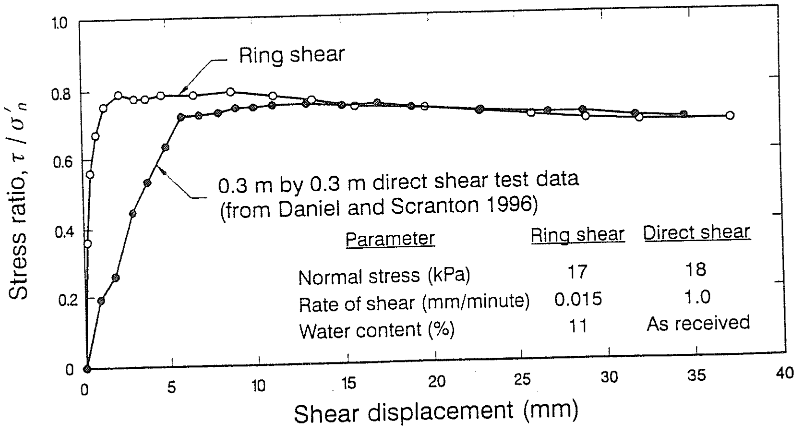

Figure 5. Ring and direct shear test results for a dry smooth geomembrane-backed GCL/textured geomembrane specimen interface.

(1996) also reported that the failure surface was located at the dry bentonite/textured geomembrane interface for the direct shear test specimen in Figure 5. Figure 5 shows that the peak stress ratios measured in the ring shear and 0.3 m by 0.3 m direct shear tests are in a close agreement. It is interesting to note that the ring shear and direct shear tests also resulted in similar residual shear stress ratios. It is anticipated that this similarity was caused by the relatively small displacement required to orient the dry granular bentonite particles parallel to the shear direction. Larger continuous shear displacements were required to orient hydrated bentonite particles parallel to the shear direction. These displacements may not be achieved by some direct shear apparatuses.

4.2 Effect of Normal Stress

Figure 6 presents two stress ratio-shear displacement relationships for two ring shear tests (normal stresses of 50 and 100 kPa) on a dry, smooth geomembrane-backed GCL/textured geomembrane specimen interface. For a normal stress of 50 kPa, the failure occurred at the dry bentonite/textured geomembrane interface; however, for a normal stress of 100 kPa, the failure occurred at the adhesive bond between the dry bentonite and the smooth geomembrane in the GCL. This failure mode is termed an "adhesive failure", whereby the bentonite layer was completely sheared off of the smooth geomembrane. This results in an intact annular layer of bentonite shearing against the surface of the smooth geomembrane. The dry bentonite remains intact because the adhesive in the bentonite is still functioning, and the intact annular layer of bentonite polishes the surface of the smooth geomembrane.

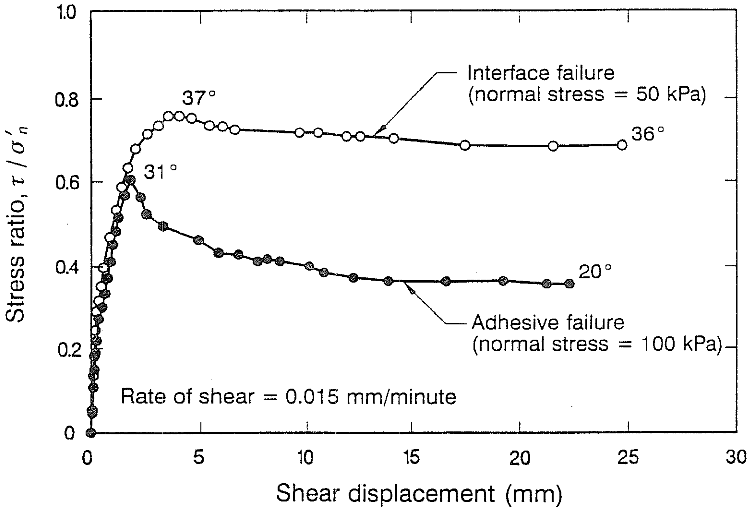

Figure 6. Ring shear test results for interface and adhesive failure modes of a dry, smooth geomembrane-backed GCL/textured geomembrane specimen interface.

Figure 7 presents the peak and residual failure envelopes for the dry smooth geomembrane-backed GCL/textured geomembrane interface shear tests. The dry bentonite/textured geomembrane interface has a friction angle of approximately 37° at normal stresses less than or equal to 50 kPa. This large shear strength is caused by failure occurring at the dry bentonite/textured geomembrane interface. The granular nature of the dry bentonite also caused a small post-peak strength loss and, thus, the peak and residual failure envelopes are similar at normal stresses less than or equal to 50 kPa.

At a normal stress of 100 kPa, the peak shear strength is lower than the corresponding peak shear strength at a normal stress of 50 kPa and a friction angle of 37°. Also, the residual friction angle was considerably lower than the residual friction angle measured at normal stresses less than or equal to 50 kPa. The decrease in the measured peak and residual friction angles was approximately 6 and 16°, respectively (Figures 6 and 7). An adhesive failure mode was also observed in tests using normal stresses of 200 and 400 kPa. Therefore, at a normal stress between 50 and 100 kPa, the failure mode of the encapsulated dry bentonite changed from the bentonite/textured geomembrane interface to the bentonite adhesive/smooth geomembrane bond. A subsequent test was conducted at a normal stress of 75 kPa to better define the normal stress at which the change in failure mode occurs: failure occurred at the bentonite adhesive/smooth geomembrane bond. Thus, the transition in failure mode was assumed to occur at a normal stress between 50 and 75 kPa (Figure 7).

4.3 Effect of Textured Geomembrane Backing

The geomembrane-backed GCL can be manufactured using a textured geomembrane as well as a smooth geomembrane. A similar series of tests was conducted to determine if a textured geomembrane-backing could prevent an adhesive failure. Figure 8 presents the peak and residual failure envelopes for the dry, textured geomembrane-backed

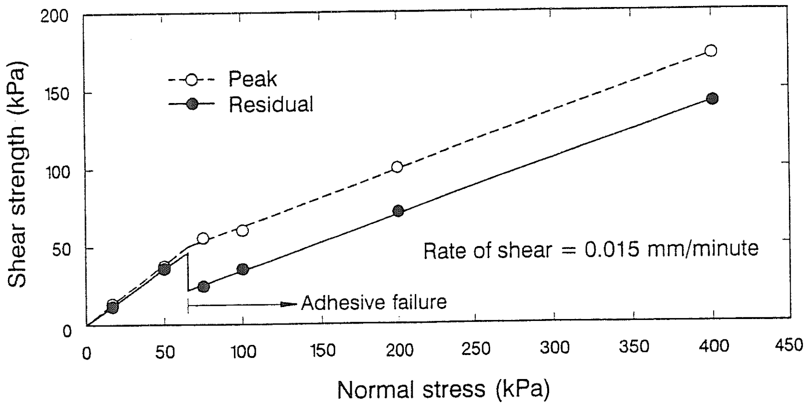

Figure 7. Peak and residual failure envelopes from interface shear tests on dry smooth geomembrane-backed GCL/textured geomembrane specimens.

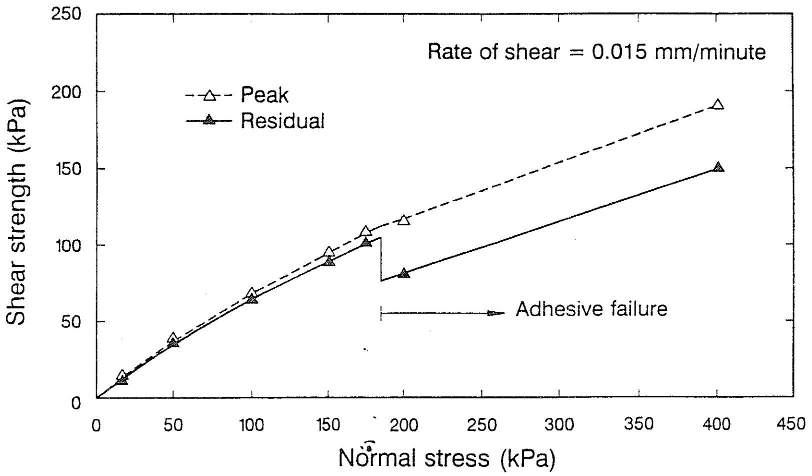

Figure 8. Peak and residual failure envelopes from interface shear tests on dry textured geomembrane-backed GCL/textured geomembrane specimens.

GCL/textured geomembrane interface shear tests. At a normal stress of 200 and 400 kPa, failure again occurred at the bentonite adhesive/textured geomembrane backing interface. A subsequent test was conducted at a normal stress of 175 kPa to better define the normal stress at which the failure mode changes. In this test, failure occurred at the bentonite/textured geomembrane interface and not at the adhesive bond. As a result, the failure mode transition is assumed to occur at a normal stress between 175 and 200 kPa. The adhesive failure at a normal stress of 200 kPa resulted in a peak and residual secant friction angle of 30 and 22°, respectively. The decrease in the measured peak and residual friction angles after the adhesive failure was 2 and 9°, respectively. This reduction is less than that observed for the smooth geomembrane-backed GCL. The difference in friction angle reduction was caused by the textured backing providing more shear resistance with the intact granular bentonite than the smooth geomembrane backing.

The adhesive failure described in Section 4.2 has not been reported in previous studies that measured and described the shear strength of a dry geomembrane-backed GCL using a direct shear apparatus (e.g. Shan 1993; Daniel et al. 1993). This may be attributed to the fact that, in some direct shear tests, shear failure is forced to occur through the bentonite (Figure 9). Figure 9 shows the dry bentonite centered on the gap between the upper and lower halves of the shear box. This prevents failure from occurring at the bentonite adhesive/geomembrane interface which is located in the upper half of the shear box. In contrast, a ring shear specimen simulates all of the interfaces in the geomembrane-encapsulated bentonite system and allows failure to occur along the weakest interface (Figure 2). As a result, failure can occur through the bentonite/textured geomembrane interface, the bentonite, or the bentonite/backing geomembrane interface. Direct shear tests should be conducted with a large enough gap between the upper and lower halves of the shear box so that failure can occur along the weakest interface.

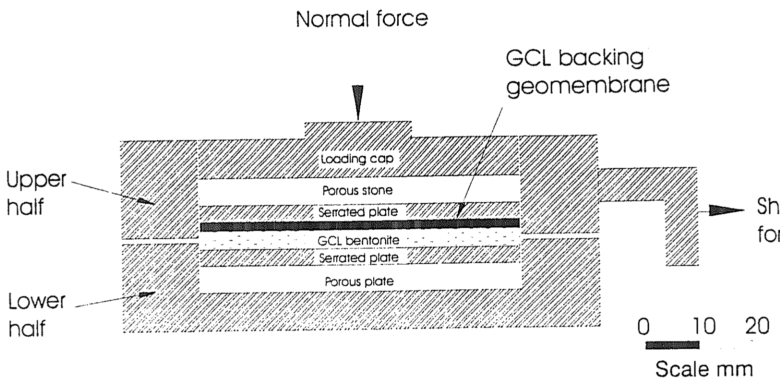

Figure 9. The direct shear test specimen configuration required to force a shear failure through the bentonite layer (after Daniel and Shan 1992).

In summary, forcing the shear failure to only occur through the dry bentonite can overestimate the shear strength of the geomembrane-backed GCL at normal stresses greater than approximately 50 and 175 kPa for smooth and textured backing geomembranes, respectively. An overestimation of shear strength occurs because the shear resistance of the dry bentonite is higher than the shear strength of the adhesive/bond between the backing HDPE geomembrane and bentonite in these normal stress ranges.

According to the data presented in Figures 7 and 8, design shear strength parameters for the dry geomembrane-backed GCL/textured geomembrane interface depend on the magnitude of the normal stress. Clearly, laboratory interface tests should simulate the geomembrane-encapsulated bentonite system so that failure can occur along the weakest interface. For example, in a typical landfill cover system, the normal stress is approximately 17 kPa; therefore, failure will occur at the geomembrane-backed GCL/textured geomembrane interface, and peak and residual friction angles of 38 and 35°, respectively, may result for the dry or as-received condition. The normal stresses on landfill liner systems can exceed 200 kPa, therefore, an adhesive failure may occur. The recommended peak and residual friction shear strength parameters for a dry geomembrane-backed GCL/textured geomembrane interface depend on what type of backing geomembrane (smooth or textured) is used to support the GCL bentonite and the effectiveness of the adhesive. Site-specific interface testing should be conducted because of the variability of the GCL components and adhesive used in the GCL.

5 HYDRATED GCL/TEXTURED GEOMEMBRANE INTERFACE BEHAVIOR

5.1 Introduction

Hydration of the geomembrane-backed GCL/textured geomembrane specimen had a significant effect on the bentonite/textured geomembrane interface shear strength. To investigate this effect, two series of ring shear tests were conducted. The first test series involved ring shear specimens being hydrated and sheared at the same normal stress. The second test series involved hydrating ring shear specimens under a normal stress of 17 kPa and then increasing the normal stress to the desired value at which shearing was to occur. The difference in the results of these two series of tests clearly illustrates the importance of carefully simulating the field hydration and shearing conditions. In each test, the specimen was hydrated until the vertical deformation (swelling or compression) equilibrated under the applied normal stress (hydration normal stress). The hydration stage usually required three weeks to complete. The water content of the bentonite was determined at the end of each test. For the two test series, examination of the failed specimens revealed that failure occurred at the hydrated bentonite/textured geomembrane interface.

5.2 Shearing at Hydration Normal Stress

Figure 10 presents the failure envelopes for the first test series in which the GCL bentonite is hydrated and sheared at the same normal stress. The peak and residual failure envelopes are linear and, as a result, a peak and residual strength ratio of 0.34 and 0.18, respectively, can be estimated. The measured value of the peak strength ratio (0.34) is close to the undrained strength ratio that is expected for this type of soil using a direct simple shear test (Terzaghi et al. 1996). In addition, the peak failure envelope shown in Figure 10 does not exhibit the nonlinearity that is expected from shear testing on such high plasticity material under drained conditions (Mesri 1969; Stark and Eid 1997). As a result, it may be concluded that shearing hydrated bentonite that is encapsulated by two geomembrane layers can result in an undrained or partially-drained condition in the ring shear test. Partial lateral drainage through the specimen may have occurred during ring shear tests. However, vertical and lateral drainage are not likely to occur in the field due to geomembrane encapsulation of the bentonite and the long lateral drainage path of the extended bentonite layer, respectively. Thus, it is recommended that an undrained shear strength be used in design for hydrated bentonite that is encapsulated by two geomembrane layers in the field.

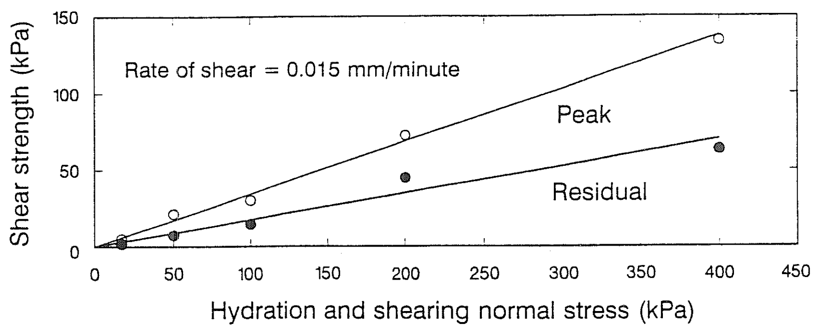

Figure 10. Peak and residual failure envelopes from interface shear tests on hydrated geomembrane-backed GCL/textured geomembrane specimens.

It should be noted that the water content of the bentonite at the end of the test depends on the applied normal stress. For example, the water content was 49 and 158% at the end of tests using normal stresses of 400 and 17 kPa, respectively. The peak and residual shear strengths were typically reached at shear displacements of approximately 4 and 60 mm, respectively.

5.3 Shearing at a Normal Stress Larger than the Hydration Normal Stress

Figure 11 presents the shear strengths for the second series of tests in which four specimens were allowed to hydrate under a normal stress of 17 kPa until the end of primary swelling was reached. Each specimen was then loaded to a higher normal stress and sheared until a residual strength condition was reached. Applied normal stresses of 50, 100, 200, and 400 kPa were used during shear. The application of a larger normal stress usually required a substantial amount of time because the stress was increased in small increments to ensure that hydrated bentonite was not squeezed out of the GCL. Shearing was started after the vertical deformation (compression) ceased under the final normal stress. The water content of the hydrated bentonite was 80 and 127% at the end of the tests at normal stresses of 400 and 50 kPa, respectively. The peak and residual shear strengths were usually reached at a shear displacement of approximately 3 and 45 mm, respectively.

For comparison purposes, Figure 11 presents the peak and residual failure envelopes from Figure 10, which were derived by hydrating and shearing at the same normal stress. It can be seen from Figure 11 that a significant reduction in measured shear strength occurred due to hydration under a low normal stress (17 kPa) and then shearing at a higher normal stress. The reduction in the measured peak and residual friction angles due to hydration at a normal stress of 17 kPa is approximately 30 and 25%, respectively. Hydration at 17 kPa probably results in more water being adsorbed into the double-layer of the bentonite particles. Not all of this water is expelled at higher normal stresses because of molecular attractive forces. This results in a higher water content and void ratio and consequently more shear strength reduction for specimens in the sec-

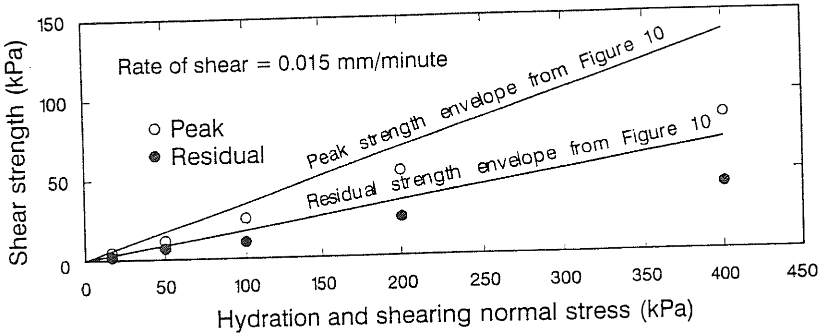

Figure 11. Peak and residual shear strengths from interface shear tests on hydrated geomembrane-backed GCL/textured geomembrane specimens (hydration normal stress = 17 kPa).

ond series of tests than that in the first series. In summary, the order of hydration and normal stress application affects the hydrated geomembrane-backed GCL/textured geomembrane interface shear strength. As a result, laboratory shear tests should carefully simulate the field hydration and shearing conditions.

6 CONCLUSIONS

Dry and hydrated unreinforced geomembrane-backed geosynthetic clay liners (GCLs) were sheared against a textured geomembrane using a torsional ring shear apparatus to study the shear behavior of geomembrane-encapsulated unreinforced bentonite. The following conclusions are made based on the data and interpretations presented in this paper:

1. It is recommended that a shear displacement rate of 1.0 mm/minute or less be used for laboratory testing of a dry unreinforced GCL/textured geomembrane interface. For the hydrated unreinforced GCL/textured geomembrane interface, the hydrated peak strength increases by 13% per log cycle of shear rate, while the residual shear strength of the unreinforced GCL/textured geomembrane interface appears to be independent of the shear displacement rate. This recommendation and information is based on tests conducted at a normal stress of 17 kPa to simulate a landfill cover system.
2. Shearing the dry unreinforced geomembrane-backed GCL against a textured geomembrane at high normal stresses can result in failure occurring through the adhesive that attaches the bentonite to the backing geomembrane. This was observed when both smooth and textured geomembranes were used as the backing material. As a result, it is recommended that laboratory testing of an unreinforced geomembrane-backed GCL/textured geomembrane interface be conducted so that failure can occur along the weakest interface, not a predetermined plane.
3. Mobilized shear strength of the geomembrane-backed GCL/textured geomembrane interface was significantly reduced by GCL hydration. In addition, the hydrated interface strength did not equal the drained shear strength of bentonite because of the effect of geomembrane texturing and the undrained or partially-drained condition in dry and hydrated GCL testing, respectively.
4. Dry bentonite at the GCL/textured geomembrane interface can draw water even under high normal stresses. However, excess pore-water pressure due to further normal stress loading and shearing may not dissipate because of the low permeability of hydrated bentonite and the lack of drainage faces. This pore-water pressure can result in a reduced effective normal stress acting on a potential slip surface and, consequently, a lower mobilized shear strength. Therefore, care should be taken to avoid bentonite hydration under low normal stresses in the field.

ACKNOWLEDGMENTS

This study was funded by the National Science Foundation, Grant Number BCS-93-00043. The second author also acknowledges the support provided by the William J. and Elaine F. Hall Scholar award. GSE Lining Technology, Inc. supplied the material for the laboratory testing. This support is gratefully acknowledged. The authors also appreciate the helpful review comments provided by J.D. Anderson of Janco Engineering. The contents and views in this paper are the authors' and do not necessarily reflect those of any of the contributors.

REFERENCES

ASTM D 4546, "*Standard Test Method for One-Dimensional Swell or Settlement Potential of Cohesive Soil*", American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.

ASTM D 5321, "*Standard Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method*", American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.

Daniel, D.E. and Scranton, H.B., 1996, "*Report of 1995 Workshop on Geosynthetic Clay Liner*", Report Prepared for U.S. Environmental Protection Agency, Report No. EPA/600/R-96/149, 217 p.

Daniel, D.E. and Shan, H.-Y., 1992, "*Effect of Partial Wetting of Gundseal on Strength and Hydrocarbon Permeability*", Research Report Prepared for Gundle Lining System, Inc., University of Texas at Austin, Austin, Texas, USA, 13 p.

Daniel, D.E., Shan, H.-Y. and Anderson, J.D., 1993, "Effect of Partial Wetting on the Performance of the Bentonite Component of a Geosynthetic Clay Liner", *Proceedings of Geosynthetics '93*, IFAI, Vol. 3, Vancouver, British Colombia, Canada, March 1993, pp. 1483-1496.

Graham, J., Crooks, J.H.A. and Bell, A.L., 1993, "Time Effects on the Stress-strain Behavior of Natural Soft Clays", *Geotechnique*, Vol. 33, No. 4, pp. 327-340.

Lefebvre, G. and Pfendler, P., 1996, "Strain Rate and Preshear Effects in Cyclic Resistance of Soft Clay", *Journal of Geotechnical Engineering*, Vol. 122, No. 1, pp. 21-26.

Lupini, J.F., Shinner, A.E. and Vaughan, P.R., 1981, "The Drained Residual Strength of Cohesive Soils", *Geotechnique*, Vol. 31, No. 2, pp. 181-213.

Mesri, G., 1969, "*Engineering Properties of Montmorillonite*", Ph. D. dissertation, University of Illinois at Urbana-Champaign, Urbana-Champaign, Illinois, USA, 90 p.

Mesri, G. and Olson, R.E., 1970, "Shear Strength of Montmorillonite", *Geotechnique*, Vol. 20, No. 3, pp. 261-270.

Shan, H.-Y., 1993, "Stability of Final Cover Placed on Slopes Containing Geosynthetic Clay Liners", Ph. D. dissertation. University of Texas, Austin, Texas, USA, 269 p.

Stark, T.D. and Eid, H.T., 1997, "Slope Stability Analyses in Stiff Fissured Clays", *Journal of Geotechnical Engineering*, Vol. 123, No. 4, pp. 335-343.

Terzaghi, K., Peck, R. and Mesri, G., 1996, "*Soil Mechanics in Engineering Practice*", Third Edition, John Wiley & Sons, New York, New York, USA, 549 p.