Technical Paper by R.P. Hillman and T.D. Stark

SHEAR STRENGTH CHARACTERISTICS OF PVC GEOMEMBRANE-GEOSYNTHETIC INTERFACES

ABSTRACT: Torsional ring shear and large-scale direct shear tests were conducted to investigate the shear behavior of polyvinyl chloride (PVC) geomembrane-geosynthetic interfaces. Specifically, the smooth and faille-finished sides of a 0.75 mm-thick PVC geomembrane were sheared against five different nonwoven geotextiles, a drainage composite, a geonet, and an unreinforced geosynthetic clay liner (GCL). Test results indicate that the smooth side of the PVC geomembrane yields a higher interface shear resistance than the faille-finished side due to the larger contact area and higher pliability of the smooth side. The interface shear behavior of the PVC geomembrane is compared to that of a high density polyethylene (HDPE) geomembrane and two very flexible polyethylene (VFPE) geomembranes. Faille-finished PVC geomembrane-nonwoven geotextile interfaces experience a post-peak strength loss of less than 25% at normal stresses between 100 and 400 kPa and no post-peak strength loss at normal stresses of 50 kPa and below. This behavior is attributed to the pliability of the PVC geomembrane, which enables (i) the geomembrane surface to be roughened, (ii) the other interface component to embed into the geomembrane as shearing progresses, and (iii) no texturing to be used that can damage the overlying geosynthetic. The effects of nonwoven geotextile fiber type, mass per unit area, and calendering on PVC geomembrane-nonwoven geotextile interface strength are also investigated.

KEYWORDS: PVC, Geomembrane, Geotextile, Geosynthetic clay liner, Drainage composite, Direct shear test, Ring shear test, Shear strength, Slope stability.

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1 INTRODUCTION

The usual design objective for impoundments and waste containment facilities is to maximize storage capacity. Thus, it is important to construct their side slopes as steeply as possible. To reduce leakage from these facilities, a composite liner system that incorporates a geomembrane is usually installed. For example, municipal and hazardous waste containment facilities in the United States are required to have a composite liner and cover system that usually consists of a compacted clay liner and/or a geosynthetic clay liner (GCL) and other geosynthetic materials. The geosynthetic components of these systems routinely include layers of geonets or drainage composites, geotextile cushions and/or filters, and a geomembrane. An important characteristic of these composite liner systems with respect to slope stability is the shear resistance along the various component interfaces. A number of case histories (Byrne et al. 1992; Seed and Boulanger 1991; Seed et al. 1990; Stark 1999) suggest that a geomembrane can create a problematic interface due to low frictional resistance between it and another geosynthetic component or soil.

To date, data on the shear behavior and peak and residual shear strengths of PVC geomembrane-geosynthetic interfaces have not been published. To fill this need, torsional ring shear and large-scale direct shear tests were conducted on a variety of PVC geomembrane-geosynthetic interfaces. These test results are summarized herein and complement/differ from the extensive information available on HDPE geomembrane-geosynthetic and HDPE geomembrane-soil interfaces (Bove 1990; Dove and Frost 1999; Koerner et al. 1986; Martin et al. 1984; Mitchell et al. 1990; Negussey et al. 1989; O'Rourke et al. 1990; Saxena and Wong 1984, Stark and Poeppel 1994, Stark et al. 1996, Takasumi et al. 1991, Williams and Houlihan 1987; Yegian and Lahlaf 1992).

It will be shown that the higher pliability and sticky nature of PVC geomembranes results in a different interface shear behavior than HDPE geomembranes. This resulted in little similarities to the existing data on HDPE geomembranes and, thus, few linkages to the existing literature. A database of peak interface friction angles and shear displacements for a 0.75 mm-thick polyvinyl chloride (PVC) geomembrane with typical geosynthetic cover and liner system components is presented in Table 1. Each friction angle and shear displacement value corresponds to a particular normal stress. For example, the first interface listed, faille PVC-GT1, has a peak secant friction angle of 28, 28, 27, 25, and 24° at a normal stress of 17, 50, 100, 200, and 400 kPa, respectively. A database of the corresponding residual interface friction angles and shear displacements is shown in Table 2.

All of the values in Tables 1 and 2 were obtained from ring shear tests as the direct shear tests were performed only to verify the ring shear test results and to compare the two test methods. Details of the ring shear and direct shear test results are discussed throughout the present paper. The databases in Tables 1 and 2 provide designers and agencies with information for estimating the frictional performance of certain geosynthetic interfaces, as well as information for selecting the appropriate nonwoven geotextile for composite liner or cover systems that utilize a PVC geomembrane to maximize interface shear resistance. Since the shear resistance of geosynthetic interfaces is project specific and product dependent, presentation and discussion of the test

Table 1. Summary of peak geomembrane-geosynthetic interface friction angles and shear displacements from ring shear tests (for comparison purposes only [a]).

Geomembrane-geosynthetic interface	Secant peak friction angle for normal stresses of 17, 50, 100, 200, and 400 kPa, respectively, except as noted (°)	Shear displacement at peak friction angle for normal stresses of 17, 50, 100, 200, and 400 kPa, respectively, except as noted (mm)
Faille PVC-GT1	28, 28, 27, 25, 29	500, 505, 550, 150, 140
Faille PVC-GT2	37, 33, 31, 32, 33 [b]	1000, 500, 20, 18, 10 [b]
Faille PVC-GT3	25, 26, 28, 28, 27	500, 550, 480, 100, 15
Faille PVC-GT4	20, 21, 22, 23, 22	200, 225, 100, 25, 20
Smooth PVC-GT4	29, 30, 32, 30, 26	1000, 985, 990, 500, 400
Faille PVC-GT5	32, 30, 29, 31, 31	400, 455, 100, 80, 75
Smooth HDPE-GT2	11, 10, 11, 9, 9 [b]	4, 3, 3, 4, 2 [b]
Textured HDPE-GT2	55, 39, 32, 33, 31 [b]	12, 5, 7, 4, 6 [b]
Smooth VFPE-GT2	11, 9, 10, 7, 7 [b]	3, 1, 1, 1, 1 [b]
Textured VFPE-GT2	42, 32, 30, 27, 27 [b]	7, 6, 5, 7, 5 [b]
Faille PVC-drainage composite	34, 25, 28, 28, 27	500, 225, 35, 18, 17
Faille PVC-geonet	23, 25, 26, 24, 25	2, 2, 2, 3, 7
Faille PVC-smooth-backed GCL	27, 28, 22, 20, 14	1, 1, 1, 1, 1
Faille PVC-textured-backed GCL	27, 25, 25, 26, 24	1, 1, 1, 2, 3

Notes: (a) Site-specific interface testing should be conducted for design purposes. (b) Interface tested at normal stresses of 17, 48, 96, 192, and 285 kPa instead of 17, 50, 100, 200, and 400 kPa.

results herein are concentrated on shear behavior rather than providing specific shear strength values for use in design applications.

PVC geomembranes can be manufactured with a smooth side and an embossed side. The surface of the embossed side usually resembles that of a file and is called a "faille-finished" surface. Accordingly, a faille PVC geomembrane interface is one in which the faille-finished surface of a PVC geomembrane is sheared against another geosynthetic component (Tables 1 and 2). A smooth PVC geomembrane interface is one in which the smooth surface of a PVC geomembrane is sheared against another geosynthetic component.

2 TORSIONAL RING SHEAR APPARATUS

Stark and Poeppel (1994), Stark et al. (1996), and Eid and Stark (1997) describe the use of a torsional ring shear apparatus to measure the shear strength of geosynthetic-geosynthetic and geosynthetic-soil interfaces. In summary, the torsional ring shear

Table 2. Summary of residual geomembrane-geosynthetic interface friction angles and shear displacements from ring shear tests (for comparison purposes only [(a)]).

Geomembrane-geosynthetic interface	Secant residual friction angle for normal stresses of 17, 50, 100, 200, and 400 kPa, respectively, except as noted (°)	Shear displacement at residual friction angle for normal stresses of 17, 50, 100, 200, and 400 kPa, respectively, except as noted (mm)
Faille PVC-GT1	28, 28, 27, 24, 25	500, 505, 550, 585, 620
Faille PVC-GT2	37, 33, 26, 26, 26 [(b)]	1000, 500, 175, 160, 150 [(b)]
Faille PVC-GT3	25, 26, 27, 26, 24	500, 550, 580, 600, 615
Faille PVC-GT4	20, 21, 21, 20, 20	200, 225, 230, 310, 300
Smooth PVC-GT4	29, 30, 32, 30, 26	1000, 985, 990, 500, 400
Faille PVC-GT5	32, 30, 28, 30, 29	400, 455, 465, 505, 550
Smooth HDPE-GT2	7, 7, 5, 6, 5 [(b)]	55, 53, 45, 41, 35 [(b)]
Textured HDPE-GT2	25, 17, 16, 15, 16 [(b)]	205, 175, 145, 125, 100 [(b)]
Smooth VFPE-GT2	5, 4, 5, 5, 6 [(b)]	175, 140, 50, 40, 25 [(b)]
Textured VFPE-GT2	25, 22, 20, 19, 19 [(b)]	150, 145, 175, 180, 195 [(b)]
Faille PVC-drainage composite	34, 25, 23, 22, 21	500, 225, 200, 75, 65
Faille PVC-geonet	18, 20, 19, 21, 19	25, 20, 15, 40, 50
Faille PVC-smooth-backed GCL	21, 21, 11, 11, 10	30, 30, 18, 15, 10
Faille PVC-textured-backed GCL	21, 19, 18, 18, 18	13, 10, 12, 10, 15

Notes: (a) Site-specific interface testing should be conducted for design purposes. (b) Interface tested at normal stresses of 17, 48, 96, 192, and 285 kPa instead of 17, 50, 100, 200, and 400 kPa.

apparatus allows: (1) unlimited continuous shear displacement to occur in one direction, resulting in the development of a true residual strength condition; (2) a constant cross-sectional area during shear; (3) minimal laboratory supervision; and (4) data acquisition techniques to be readily used.

A modified Bromhead ring shear apparatus was used to measure the shear strength of the geomembrane-geosynthetic interfaces described herein. A modified specimen container was used to hold the bottom interface component in place. In tests on geosynthetic-geosynthetic interfaces, the knurled porous stone in the specimen container was replaced with a plastic insert to secure the appropriate geosynthetic. The insert was fastened to the specimen container using four screws. Specifically, an annular geomembrane or GCL specimen with an inside and outside diameter of 40 and 100 mm, respectively, was secured to the plastic insert using an adhesive. The other interface component was adhered to the top (loading) platen. The normal stress was applied to the top platen, which sits on top of the specimen container. During shearing, the bottom interface component moves with respect to the stationary top interface component. All of the shear dis-

placement values and shear displacement rates reported in the present paper were calculated using a diameter of 70 mm, which is the average diameter of the annular specimen.

3 RING SHEAR SPECIMEN PREPARATION AND TEST PROCEDURE

3.1 Geosynthetics Used in Shear Testing

The geosynthetics used in the interface shear testing are listed below. After each geosynthetic is an identifier in parentheses to facilitate comparison of the test results throughout the present paper.

- Polyvinyl chloride (PVC) geomembrane: A 0.75 mm-thick geomembrane with a faille-finished side and a smooth side. This geomembrane is manufactured by Canadian General-Tower, Ltd. of Cambridge, Ontario, Canada.
- Textured, high density polyethylene (T-HDPE) geomembrane: A 1.50 mm-thick, coextruded textured geomembrane that is manufactured by GSE Lining Technology, Inc. of Houston, Texas, USA.
- Smooth, high density polyethylene (S-HDPE) geomembrane: A 1.50 mm-thick, smooth geomembrane that is manufactured by GSE Lining Technology, Inc. of Houston, Texas, USA.
- Textured, very flexible polyethylene (T-VFPE) geomembrane: A 1.00 mm-thick, coextruded textured geomembrane that is manufactured by GSE Lining Technology, Inc. of Houston, Texas, USA.
- Smooth, very flexible polyethylene (S-VFPE) geomembrane: A 1.00 mm-thick, smooth geomembrane that is manufactured by GSE Lining Technology, Inc. of Houston, Texas, USA.
- Drainage composite (DC): A 5.6 mm-thick HDPE geonet heat-bonded to two nonwoven, polyester (PET) geotextiles, each with a mass per unit area of 270 g/m^2. This drainage composite is manufactured by Serrot International, Inc. of Henderson, Nevada, USA.
- Geonet (GN): A 5.6 mm-thick HDPE geonet heat-bonded to one nonwoven, PET geotextile with a mass per unit area of 270 g/m^2. This geonet composite is manufactured by Serrot International, Inc. of Henderson, Nevada, USA.
- Unreinforced geosynthetic clay liner (GCL): A 5 mm-thick layer of bentonite adhered to a 0.50 mm-thick smooth or a 1.00 mm-thick textured HDPE geomembrane. This GCL is manufactured by GSE Lining Technology, Inc. of Houston, Texas, USA.
- Nonwoven geotextile (GT1): A nonwoven, polypropylene (PP) geotextile with a mass per unit area of 540 g/m^2. This geotextile is manufactured by Amoco Fabrics & Fibers Company of Atlanta, Georgia, USA.
- Nonwoven geotextile (GT2): A nonwoven, PET geotextile with a mass per unit area of 540 g/m^2. This geotextile is manufactured by Johns Manville of Spartanburg, South Carolina, USA.
- Nonwoven geotextile (GT3): A nonwoven, PP geotextile with a mass per unit area

of 205 g/m^2. This geotextile was manufactured by Polyfelt Americas of Atlanta, Georgia, USA.

- Nonwoven geotextile (GT4): A nonwoven, PP geotextile with a mass per unit area of 540 g/m^2. This geotextile was manufactured by Polyfelt Americas of Atlanta, Georgia, USA.
- Nonwoven geotextile (GT5): A nonwoven, calendered, PP geotextile with a mass per unit area of 540 g/m^2. This geotextile is manufactured by Amoco Fabrics & Fibers Company of Atlanta, Georgia, USA.

3.2 PVC Geomembrane Specimen Preparation

PVC geomembrane specimens were cut into an annular shape and secured to a plastic insert in the specimen container for all of the interface tests except the unreinforced GCL-PVC geomembrane interface tests. In the unreinforced GCL interface tests, the PVC geomembrane was secured to the top platen and the unreinforced GCL was adhered to the plastic insert in the specimen container. A thin coat of epoxy was used to adhere the PVC geomembrane to either the plastic insert or the top platen. The epoxy was allowed to cure for 24 hours under a normal stress of 15 kPa for specimens that would be sheared at a normal stress of 17 kPa and a normal stress of 25 kPa for all other shearing normal stresses. As a result, the curing normal stress did not exceed the normal stress at which the test was conducted. The curing normal stress aided bonding of the geomembrane and minimized vertical displacement caused by the epoxy during testing. The geomembrane and specimen container/top platen were marked to ensure that the geomembrane did not slip during shearing.

3.3 Nonwoven Geotextile Specimen Preparation

All nonwoven geotextile specimens were secured to the top platen. To aid securing of a geotextile to the top platen, the geotextile was initially glued to a smooth HDPE geomembrane ring that was cut to the same size as the PVC geomembrane specimen. The geotextile was cut in a circle with a diameter of approximately 160 mm, which is larger than the outside diameter of the ring shear specimen (100 mm). A small circular hole (roughly 20 mm) was cut in the center of the geotextile specimen so that there was no interference with the ring shear apparatus centering pin. The HDPE geomembrane ring was then glued to the geotextile using a thin coat of epoxy. A 2 to 3 kg mass was placed on the geotextile-geomembrane ring to aid adhesion. After approximately 15 minutes of drying, the geotextile, extending beyond the edge of the geomembrane ring, was cut so that eight wedges or flaps of geotextile that were equal in size and spacing remained. Epoxy was applied to the back of the smooth geomembrane and the eight geotextile wedges were folded over and adhered to the back side of the smooth geomembrane. The 2 to 3 kg mass was reapplied for roughly 45 minutes. This wrapping of the geotextile around the geomembrane ring prevented geotextile fibers from readily pulling out during shearing.

The geotextile-geomembrane ring system was secured to the top platen using a thin coat of epoxy. The side with the eight wedges was adhered to the top platen. The top

platen with the attached geotextile specimen was then placed in the ring shear apparatus on top of the specimen container, to which the geomembrane was adhered. A sacrificial geotextile cushion was placed between the geomembrane and geotextile so that there was no contact between the interface components before shearing. The epoxy was allowed to cure for 24 hours under a normal stress (15 or 25 kPa) that did not exceed the normal stress at which the test was to be conducted. The top platen and geotextile were also marked to ensure that the geotextile did not slip during shearing.

After allowing the epoxy to cure for 24 hours, the sacrificial geotextile was removed and the two interface components were placed in contact such that no relative displacement occurred between them prior to shearing. The ring shear apparatus was then loaded to the shearing normal stress using a load increment ratio (LIR) of 1.0. Once the desired normal stress was applied, the interface system was allowed to equilibrate for approximately 20 minutes before shearing was started. A shear displacement rate of 0.37 mm/minute was used for all of the geomembrane-geotextile interface testing. The geomembrane-geotextile interfaces were sheared to a displacement of at least 1,000 mm before shearing was stopped.

3.4 Drainage Composite and Geonet Specimen Preparation

The drainage composite specimens were annular with a diameter of approximately 100 mm and a center circular hole of approximately 20 mm. Epoxy was applied to one of the geotextiles of the drainage composite to adhere the composite to the top platen. The epoxy was allowed to cure in the ring shear apparatus for 24 hours under a normal stress (15 or 25 kPa) that did not exceed the normal stress at which the test was to be conducted. A sacrificial geotextile was again used such that the interface components were not in contact prior to shearing. After the epoxy had cured for 24 hours, the sacrificial geotextile was removed and the two interface components were placed in contact such that no relative displacement occurred between them. The ring shear apparatus was then loaded to the shearing normal stress using an LIR of 1.0. Once the desired normal stress was applied, the interface system was allowed to equilibrate for approximately 20 minutes before shearing was started. A shear displacement rate of 0.37 mm/minute was used for all of the geomembrane-drainage composite interface testing and the interfaces were allowed to undergo shear displacements of at least 1,000 mm before shearing was stopped.

To prepare a geonet specimen, one of the geotextiles was removed from the drainage composite to expose the HDPE geonet. Afterwards, the geonet specimen preparation followed the procedure described previously for the drainage composite.

3.5 Unreinforced GCL Specimen Preparation

The unreinforced GCL specimen was attached to the plastic insert in the specimen container with the bentonite layer facing upwards. To simulate encapsulation of the bentonite in the field, the GCL specimens were tested at the manufactured water content and no hydration was allowed. The GCL specimens were annular with inside and outside diameters of 40 and 100 mm, respectively. Epoxy was applied to the HDPE geomembrane backing of the GCL to adhere it to the plastic insert. The epoxy was allowed to cure in the ring shear device for 24 hours under a normal stress of 15 kPa for all tests. A sacrificial geotextile was not used during the curing process because some of the bentonite may have adhered to the geotextile. After the epoxy cured for 24 hours, the specimen was loaded to the shearing normal stress using an LIR of 1.0. The interface was then allowed to equilibrate for 24 hours under this normal stress before shearing was started. A shear displacement rate of 0.015 mm/minute was used for all of the unreinforced GCL-geomembrane interface tests (Eid and Stark 1997).

4 COMPARISON OF RING SHEAR AND DIRECT SHEAR TEST RESULTS

To facilitate the required testing, it was desirable to use a ring shear device instead of the large-scale direct shear box required by ASTM D 5321. ASTM D 5321 allows other shear devices to be used for geosynthetic shear testing if they yield similar results as the large-scale direct shear box. To investigate this substitution, large-scale direct shear tests were conducted on the same PVC geomembrane interfaces that were tested in the torsional ring shear device. The direct shear tests were performed in accordance with ASTM D 5321. Specifically, the large-scale direct shear apparatus used in this study allows a 305 mm by 305 mm upper geosynthetic specimen to be sheared over a lower geosynthetic specimen that is 305 mm by 356 mm. The normal stresses are applied pneumatically and the same shear displacement rates used for the ring shear tests were used for the direct shear tests to avoid displacement rate-related discrepancies in the test results. The direct shear tests were also conducted at the same normal stresses used in the ring shear tests to ensure an accurate comparison of the shear stress-displacement relationships and peak and residual shear strengths.

Figure 1 presents a comparison between the shear stress-displacement relationships

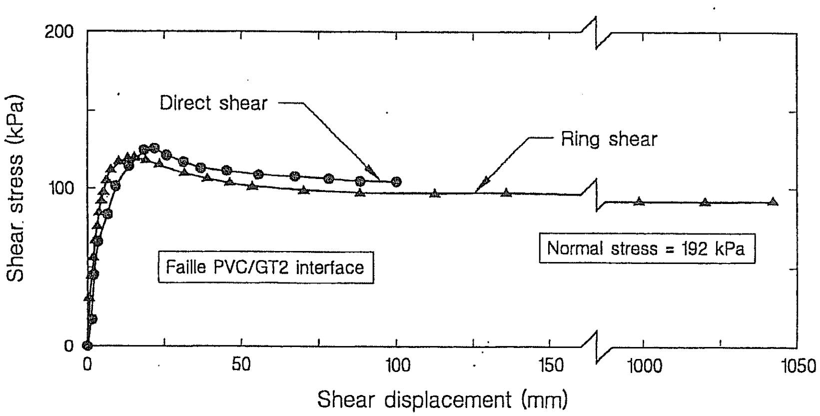

Figure 1. Comparison of shear stress-displacement relationships from ring shear and direct shear tests on a faille PVC geomembrane-GT2 geotextile interface.

obtained from ring shear and direct shear tests on a faille PVC geomembrane-GT2 geotextile interface at a normal stress of 192 kPa. It can be seen that both test procedures produce similar shear stress-displacement relationships. The ring shear test yielded secant peak and residual friction angles of approximately 32 and 26°, respectively, while the direct shear test yielded corresponding values of 34 and 28°, respectively. This agreement between the ring shear and direct shear test results on the faille PVC geomembrane-GT2 geotextile interface is typical for all of the interfaces that were compared (Table 3). The main difference between the ring shear and direct shear test methods is in the values obtained for the residual friction angle and shear displacement at the residual strength. The direct shear test terminates at a shear displacement of approximately 100 mm and, thus, the resulting friction angle is greater than the ring shear residual friction angle for many interfaces. Direct shear tests were conducted at one normal stress for each interface (either 192 or 200 kPa). Only one normal stress was tested because the focus of the present paper is PVC geomembrane-geosynthetic interface shear behavior, not a comparison of ring shear and direct shear test methods. Direct shear testing is being conducted at other normal stresses and the results will be the subject of a subsequent paper that compares the two devices. One normal stress was used to show agreement between the two testing methods, then, the more efficient ring shear device was used to obtain the test results that comprise the databases of Tables 1 and 2. Discussion of the ring shear data in Tables 1 and 2 is the focus of the remainder of the present paper.

In summary, it was assumed that the ring shear device yields similar results to the large-scale direct shear apparatus for the normal stresses and interfaces considered herein and could be used as a substitute for the direct shear apparatus as suggested in ASTM D 5321. The ring shear device was chosen because ring shear tests are easier

Table 3. Comparison of torsional ring shear and large-scale direct shear test results at a normal stress of 200 kPa (except as noted) (for comparison purposes only [a]).

Geomembrane-geosynthetic interface	Ring/direct shear secant peak friction angle, respectively (°)	Ring/direct shear displacement at peak, respectively (mm/mm)	Ring/direct shear secant residual friction angle, respectively (°)	Ring/direct shear displacement at residual, respectively (mm/mm)
Faille PVC-GT1	25/31	150/100	24/31	585/100
Faille PVC-GT2	32/34[b]	18/20 [b]	26/28 [b]	160/100 [b]
Faille PVC-GT3	28/28	100/30	26/28	600/30
Faille PVC-GT4	23/22	25/60	20/22	310/60
Faille PVC-drainage composite	28/32	18/27	22/26	75/80
Faille PVC-geonet	24/27	3/10	21/22	40/26

Notes: (a) Site-specific interface testing should be conducted for design purposes. (b) Interface tested at normal stresses of 17, 48, 96, 192, and 285 kPa instead of 17, 50, 100, 200, and 400 kPa.

and more cost effective to perform than large-scale direct shear tests. This is mainly due to the fact that a much larger specimen is required for a direct shear test. The larger specimen results in larger equipment and a longer specimen preparation time than for the ring shear device.

5 COMPARISON OF SMOOTH AND FAILLE PVC GEOMEMBRANE INTERFACE SHEAR STRENGTHS

Shear tests were performed to determine the effect of a faille finish on the shear strength of PVC geomembrane-nonwoven geotextile interfaces. Figure 2 shows the peak and residual failure envelopes for the smooth and faille sides of the PVC geomembrane sheared against the GT4 nonwoven geotextile. It is evident that the smooth side of the PVC geomembrane yielded significantly higher peak and residual interface shear strengths than the faille side. Furthermore, no noticeable post-peak strength loss was observed for the smooth PVC geomembrane interface, and the peak and residual failure envelopes are essentially the same. For example, at a normal stress of 200 kPa, the smooth PVC interface had a secant peak and residual friction angle of 30°. At this same normal stress, the faille PVC interface yielded secant peak and residual friction angles of 23 and 20°, respectively.

The post-peak shear behavior is further illustrated by the shear stress-displacement relationships shown in Figure 3. The faille PVC interface reached a peak strength condition and then experienced a post-peak strength loss of approximately 10%. However, the smooth PVC geomembrane interface exhibited a peak shear strength that was roughly 30% higher than that for the faille side and it reached this peak strength at a larger shear displacement. The smooth PVC geomembrane interface was tested to over 1,000 mm of shear displacement and no post-peak strength loss was observed. The higher frictional strength of the smooth side of a PVC geomembrane is attributed to its

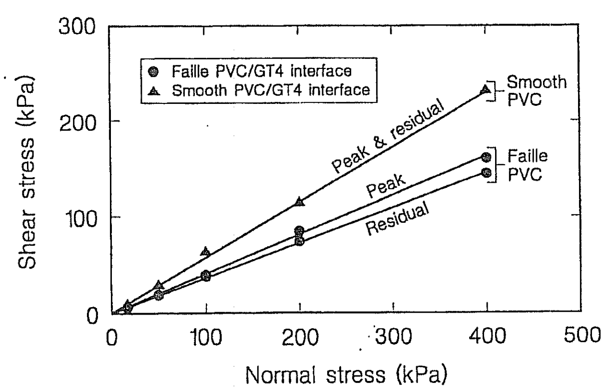

Figure 2. Comparison of failure envelopes for smooth and faille PVC geomembrane-GT4 geotextile interfaces.

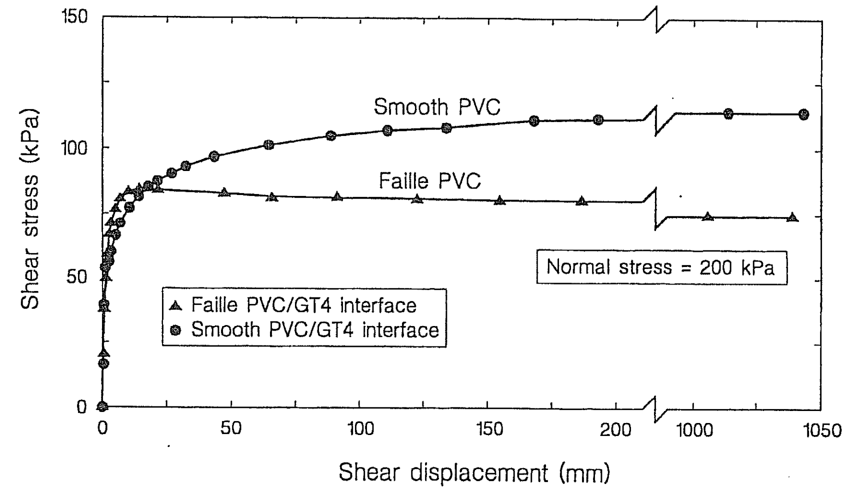

Figure 3. Comparison of shear stress-displacement relationships for smooth and faille PVC geomembrane-GT4 geotextile interfaces.

larger contact area and higher surface pliability than the faille side. The increased pliability results in a more ductile, malleable, or adaptable surface than the faille side. The difference in surface pliability is attributed to the embossing process, which results in the embossed pattern creating a less pliable surface. The smooth side allows for a greater area of contact between it and the other interface component because it does not possess the surface depressions of the faille side, which decrease the interface contact area. The faille side was estimated to have a contact surface area that is 20 to 30% lower than that of the smooth side because of the embossing. Furthermore, as shearing progresses, the higher surface pliability of the smooth side allows it to be: (1) roughened, and (2) embedded into by the other interface component, resulting in a larger shear resistance. The faille side also possesses a high pliability compared to an HDPE geomembrane; however, the other interface component cannot roughen and embed into the faille side as much as it can on the smooth side. This prevents the frictional resistance of the faille side from reaching that of the smooth side. This was evident from striations on the smooth side after shearing at all normal stresses (17 to 400 kPa). In contrast, the faille side did not exhibit any striations except after tests at normal stresses of 200 and 400 kPa.

In summary, the higher surface pliability of the smooth side enables the strength-increasing mechanisms discussed above to develop more readily than on the faille side, which accounts for the larger shear strength of the smooth side. This also explains why no post-peak strength loss was observed for the smooth PVC geomembrane-nonwoven geotextile interfaces. The strength-increasing mechanisms offset the strength-reducing effects, such as geotextile fibers being pulled or torn out, thereby preventing a loss of interface shear resistance with increasing shear displacement. This was not the case for the faille side because the strength-increasing mechanisms were not large enough to offset the strength-reducing effects. Thus, a post-peak strength loss was observed for the faille side.

Since the faille side of a PVC geomembrane renders a lower interface shear resistance than the smooth side, it was deemed appropriate to focus the present paper on the shear strength of faille PVC geomembrane interfaces. By doing this, lower bounds for PVC geomembrane peak and residual interface shear strengths were established. Accordingly, all of the PVC geomembrane data presented and discussed in the remainder of the present paper pertain to the faille PVC geomembrane interface.

6 COMPARISON OF PVC, HDPE, AND VFPE GEOMEMBRANE-NONWOVEN GEOTEXTILE INTERFACE SHEAR STRENGTHS

The peak and residual friction angles of textured and smooth HDPE geomembrane interfaces are compared to those of the faille PVC geomembrane interfaces in Tables 1 and 2, respectively. Additionally, peak and residual failure envelopes for faille PVC and textured HDPE geomembrane-GT2 nonwoven geotextile interfaces are shown in Figure 4. It can be seen that these two interfaces have similar peak failure envelopes. However, there is a significant difference in the post-peak strength loss experienced by the interfaces, as reflected in the residual failure envelopes. Specifically, the textured HDPE geomembrane interface underwent a larger post-peak strength loss compared to the faille PVC geomembrane interface. Stark et al. (1996) showed that a variety of textured HDPE geomembrane-nonwoven geotextile interfaces experienced a similar (50 to 60%) post-peak strength loss. The reason for this large strength loss is that the asperities of the textured HDPE geomembrane tore or pulled out the fibers of the geotextile and the geomembrane texturing was smoothed or polished (Stark et al. 1996). On the

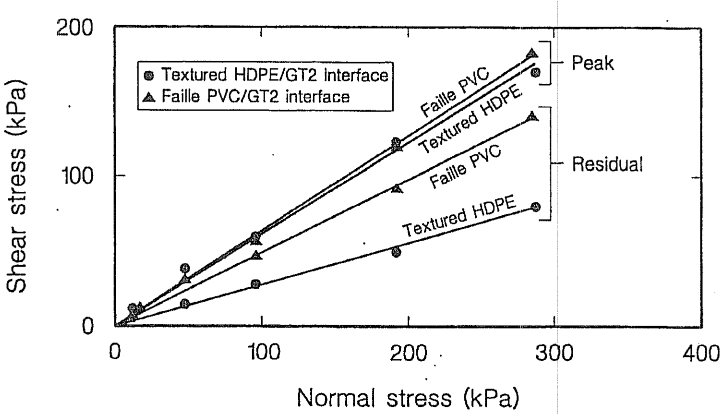

Figure 4. Comparison of failure envelopes for faille PVC and textured HDPE geomembrane-GT2 geotextile interfaces.

other hand, the faille PVC geomembrane tore or pulled out only a small quantity of fibers from the geotextile, which allowed the geotextile to stay relatively intact and maintain the interface strength. The failed specimens from the textured HDPE geomembrane-nonwoven geotextile interface tests reported by Stark et al. (1996) had been archived and were directly compared with the new PVC geomembrane-nonwoven geotextile interface test specimens to estimate the damage to the nonwoven geotextiles. After observing the small quantity of fibers that were removed from the geotextile by the PVC geomembrane, it could not be determined whether the fibers were torn from or pulled out of the geotextile. At normal stresses of 48 kPa and below, the PVC geomembrane extracted few, if any, fibers because the geotextile was unable to sufficiently embed into the PVC geomembrane. As a result, there was no noticeable post-peak strength loss at these normal stresses. In fact, a trend of no post-peak strength loss at low normal stresses was observed for all of the PVC geomembrane-nonwoven geotextile interfaces tested. This behavior has important design implications that are discussed below. At normal stresses between 96 and 285 kPa, the residual shear strength of the PVC geomembrane interface was only approximately 15 to 25% lower than its peak shear strength. These characteristics suggest that PVC geomembranes are well suited for applications in which low normal stresses are expected, such as landfill cover systems, or where seismically induced permanent deformations may result.

VFPE geomembrane-nonwoven geotextile interface shear behavior was also determined in the present study from a series of ring shear tests on the smooth and textured VFPE-GT2 geotextile interfaces. Figure 5 presents a comparison of the peak and residual failure envelopes for faille PVC, textured VFPE, and smooth VFPE geomembrane-GT2 geotextile interfaces. The failure envelopes indicate that the peak shear strength of this textured VFPE geomembrane interface was less than the faille PVC geomembrane interface. Additionally, this textured VFPE interface experienced a larger post-peak

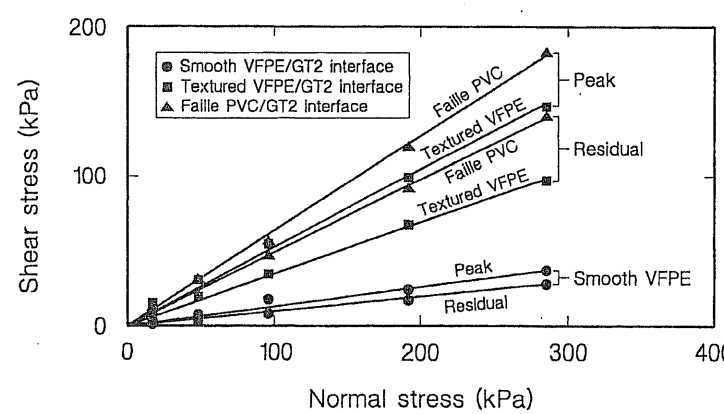

Figure 5. Comparison of failure envelopes for faille PVC, smooth VFPE, and textured VFPE geomembrane-GT2 geotextile interfaces.

strength loss than the faille PVC interface because the VFPE geomembrane texturing tore or pulled out more fibers from the nonwoven geotextile during shearing. As expected, the smooth VFPE geomembrane interface exhibited lower peak and residual shear strengths than the faille PVC and textured VFPE geomembrane interfaces. The reason that the smooth VFPE geomembrane interface exhibited a lower peak and residual shear strength than the faille PVC geomembrane interface is the difference in surface pliability. Even though the VFPE geomembrane is more pliable and flexible than an HDPE geomembrane, it is still less pliable than the faille or smooth sides of a PVC geomembrane and, thus, exhibits a lower interface strength.

As a final comparison, Figure 6 presents the shear stress-displacement relationships for faille PVC, textured HDPE, and textured VFPE geomembrane-GT2 geotextile interfaces at a normal stress of 192 kPa. The VFPE and HDPE geomembrane interfaces reached a peak strength condition after approximately 5 mm of shear displacement and then experienced a substantial post-peak strength loss (40 to 60%). On the other hand, the faille PVC interface peaked at a shear displacement of approximately 18 mm and lost only 20 to 25% of its peak shear strength. Additionally, a comparison of Figures 4 and 5 shows that textured HDPE geomembrane interfaces produced higher peak and lower residual failure envelopes than the corresponding textured VFPE geomembrane interfaces. In conclusion, faille PVC geomembrane-nonwoven geotextile interfaces appear to yield similar peak shear strengths and considerably higher residual shear strengths than similar textured HDPE and textured VFPE geomembrane-nonwoven geotextile interfaces.

7 SHEAR STRENGTH OF FAILLE PVC GEOMEMBRANE-NONWOVEN GEOTEXTILE INTERFACES

To study the effects of various nonwoven geotextile properties on PVC geomembrane-

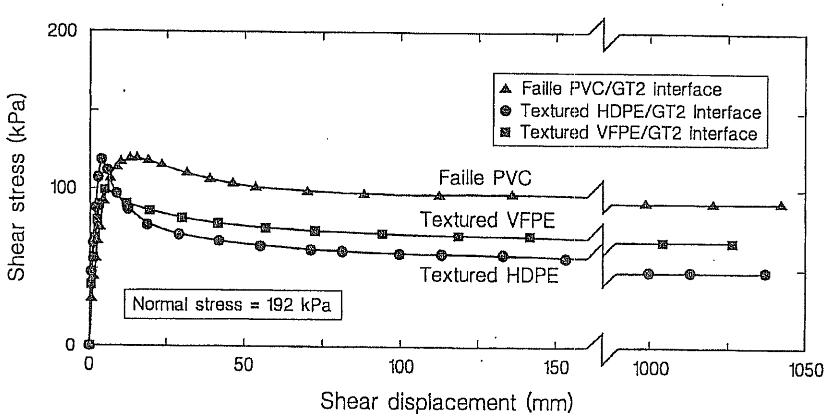

Figure 6. Comparison of shear stress-displacement relationships for faille PVC, textured HDPE, and textured VFPE geomembrane-GT2 geotextile interfaces.

nonwoven geotextile interface shear strengths, five different nonwoven geotextiles were sheared against the faille-finished side of a PVC geomembrane. The five nonwoven geotextiles were chosen such that the effects of nonwoven geotextile fiber type, mass per unit area, and calendering could be studied while maintaining the remaining nonwoven geotextile properties constant.

7.1 Effect of Nonwoven Geotextile Fiber Composition and Type on Interface Shear Strength

Nonwoven geotextiles can be manufactured with different base polymers, the two most common being PET and PP. To investigate the effect of fiber composition on interface shear strength, a PET geotextile (GT2) and a PP geotextile (GT4) were sheared against a faille PVC geomembrane. Since the two nonwoven geotextiles have different polymer compositions, the fibers themselves probably do not possess the same roughness and hardness. Additionally, the fibers most likely do not have the same diameter or weight. However, both geotextiles have a mass per unit area of 540 g/m^2 and are needle punched with continuous single fibers.

The peak and residual failure envelopes for the two interfaces are presented in Figure 7. It is apparent that the PET-based geotextile interface yielded higher peak and residual friction angles than the PP-based geotextile interface. For example, at a normal stress of 200 kPa, the secant peak and residual friction angles for the faille PVC-PET geotextile are 32 and 26°, respectively, while the secant peak and residual friction angles for the faille PVC geomembrane-PP geotextile interface are 23 and 20°, respectively. Polyester-based nonwoven geotextiles were also found to yield higher interface shear strengths than PP-based nonwoven geotextiles when sheared against the textured HDPE geomembrane (Stark et al. 1996). This trend is most likely caused by differences in fiber diameter, hardness, roughness, and weight as well as compositional properties.

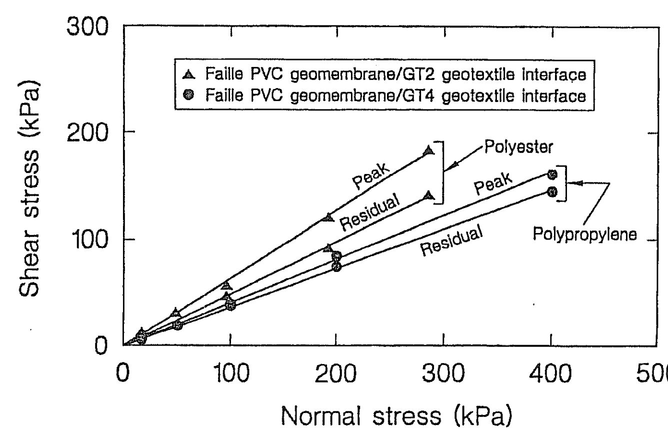

Figure 7. Effect of nonwoven geotextile fiber composition on interface shear strength.

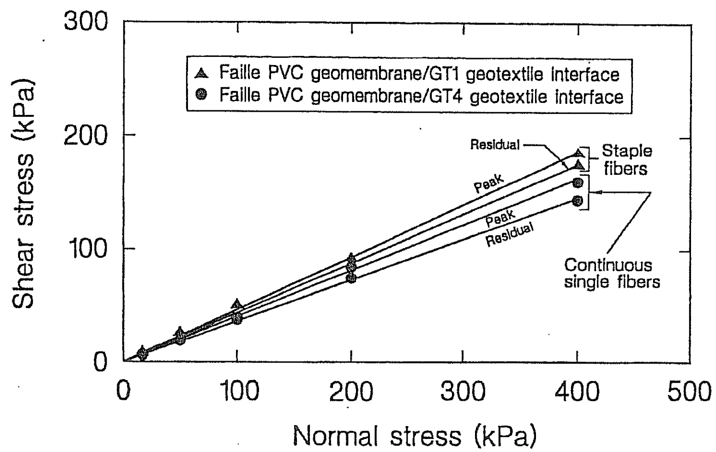

Figure 8. Effect of nonwoven geotextile fiber composition on interface shear strength.

Additionally, two nonwoven, PP geotextiles (GT1 and GT4) were used to determine the effect of geotextile fiber type (staple versus continuous) on the shear strength of faille PVC geomembrane interfaces. Both geotextiles are needle punched and have a mass per unit area of 540 g/m^2. However, the GT1 geotextile utilizes staple fibers while the GT4 geotextile utilizes continuous single fibers. Figure 8 shows the peak and residual failure envelopes for the faille PVC geomembrane-GT1 and GT4 interfaces. The failure envelopes indicate that the staple fiber geotextile yielded greater peak and residual interface strengths when sheared against a faille PVC geomembrane. Another important characteristic inferred from Figure 8 is that the staple fiber geotextile did not undergo as large a post-peak strength loss as the continuous single fiber geotextile. A possible explanation for this behavior is that the staple fibers are too small or fine to embed into the PVC geomembrane to the same degree as the longer and larger continuous single fibers. It was observed after shearing that fewer staple fibers were torn out during shear, which enabled the staple fiber geotextile to stay more intact than the continuous single fiber geotextile and prevented the interface from undergoing a large post-peak strength loss. This may be attributed to the continuous single fibers being longer and having more contact area with the PVC geomembrane. The greater contact area may have increased the shear force on the continuous fiber resulting in tearing or pulling out. Once the continuous fiber is removed from the geotextile, it is oriented parallel to the direction of shear. The long nature of the fiber results in a larger reduction in the interface shear resistance than a staple fiber. In addition, the continuous single fibers were able to embed into the PVC geomembrane at high normal stresses, allowing the continuous single fibers to be torn or pulled out and the interface shear strength to decrease as shearing progressed. Thus, the mechanical properties of the fibers appear to influence the PVC geomembrane-nonwoven geotextile shear behavior.

7.2 Effect of Nonwoven Geotextile Mass Per Unit Area on Interface Shear Strength

Two nonwoven, PP geotextiles, one with a mass per unit area of 205 g/m^2 (GT3) and the other with a mass per unit area of 540 g/m^2 (GT4), were sheared against a faille PVC geomembrane to examine the effects of mass per unit area on interface shear resistance. Both of the geotextiles are needle punched and have continuous single fibers. The 205 g/m^2 geotextile yielded a greater interface shear resistance than the 540 g/m^2 geotextile, as indicated by the failure envelopes of Figure 9. For example, at a normal stress of 200 kPa, the 205 g/m^2 geotextile interface exhibited secant peak and residual friction angles of 28 and 25°, respectively, compared to 23 and 20°, respectively, for the 540 g/m^2 geotextile. This may be caused by the fibers of the 540 g/m^2 geotextile being more easily torn or pulled out during shear than the fibers of the 205 g/m^2 geotextile and the increased number of fibers in the heavier geotextile placing more fibers in contact with the surface of the PVC geomembrane. The increased number of fibers in contact with the surface of the PVC geomembrane increases the number of fibers that can actually be removed from the geotextile. Once a fiber is removed, it is oriented parallel to the direction of shear, which reduces the interface shear resistance. Therefore, the mass per unit area appears to slightly influence the faille PVC geomembrane-nonwoven geotextile interface shear strength.

7.3 Effect of Nonwoven Geotextile Calendering on Interface Shear Strength

To investigate the effect of nonwoven geotextile calendering on interface shear strength, a faille PVC geomembrane was sheared against a nonwoven, calendered geo-

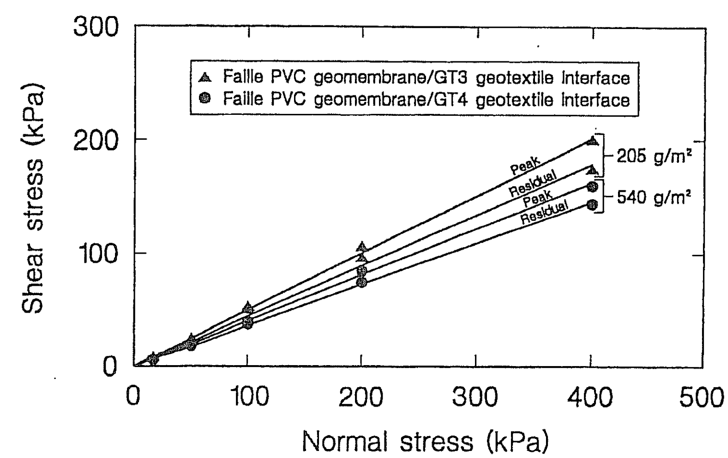

Figure 9. Effect of nonwoven geotextile mass per unit area on interface shear strength.

textile (GT5). This geotextile possesses the same properties as the GT1 nonwoven geotextile except that it is calendered. The peak and residual failure envelopes for the faille PVC geomembrane-GT5 and -GT1 geotextile interfaces are shown in Figure 10. It can be seen that the calendered geotextile interface yielded larger peak and residual interface shear strengths than the non-calendered geotextile. This trend is attributed to the surface of the calendered geotextile being rougher and more rigid than that of the non-calendered geotextile. This roughness and rigidity may enable the calendered geotextile to embed into the PVC geomembrane to a greater degree and prevent the fibers from being pulled or torn out and oriented parallel to the direction of shear. Additionally, the calendered geotextile, like the non-calendered geotextile, experienced approximately 5% post-peak strength loss at normal stresses of 200 and 400 kPa and no post-peak strength loss at normal stresses between 17 and 100 kPa. This behavior is probably due to the rough surface of the calendered geotextile being smoothed at high normal stresses, thereby causing some loss of shear strength. The smoothing of the calendered geotextile at high normal stresses was determined by visually comparing the original/presheared material with the calendered geotextile after shearing to the residual condition. It could be seen that some of the matted finish of the original calendered geotextile had been removed resulting in a more pliable surface. However, at lower normal stresses, the calendered surface is not smoothed significantly, which accounts for the absence of a post-peak strength loss. In summary, nonwoven geotextile calendering appears to have an impact on peak and residual interface shear strengths.

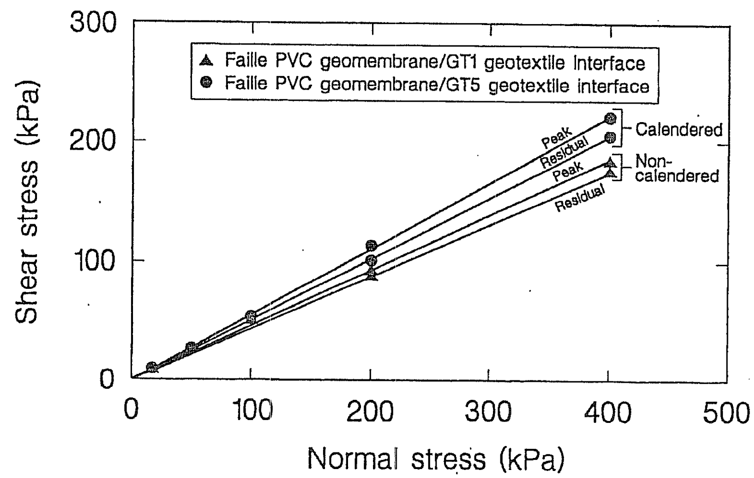

Figure 10. Effect of nonwoven geotextile calendering on interface shear strength.

8 SHEAR STRENGTH OF FAILLE PVC GEOMEMBRANE-DRAINAGE COMPOSITE AND GEONET INTERFACES

8.1 Introduction

Drainage composites and geonets are commonly used to facilitate lateral drainage in landfill liner and cover systems and other applications. Therefore, the shear behavior of PVC geomembrane-drainage composite and geonet interfaces was examined in this study. As discussed previously, the drainage composite and geonet have two and one nonwoven geotextiles, respectively, heat-bonded to the geonet. Figure 11 presents a comparison of the peak and residual failure envelopes for faille PVC geomembrane-drainage composite and geonet (without a geotextile in contact with the PVC geomembrane) interfaces. The drainage composite and geonet interfaces exhibited a 20 and 45% post-peak strength loss, respectively, at a normal stress of 400 kPa. This strength loss is higher than the post-peak strength losses observed for the various PVC geomembrane-nonwoven geotextile interfaces. One of the reasons for these larger strength losses is that the relatively rigid geonet embeds in the soft PVC geomembrane surface under all of the applied normal stresses. Thus, as interface shearing began, relatively high shear stresses were required to dislodge the geonet from its initial embedded position. Once the geonet had been dislodged, it sheared across the surface of the PVC geomembrane without being able to embed, thereby resulting in a significant amount of post-peak strength loss.

The failure envelopes in Figure 11 also show the effect of having a nonwoven geotextile between the PVC geomembrane and the geonet in a drainage composite interface.

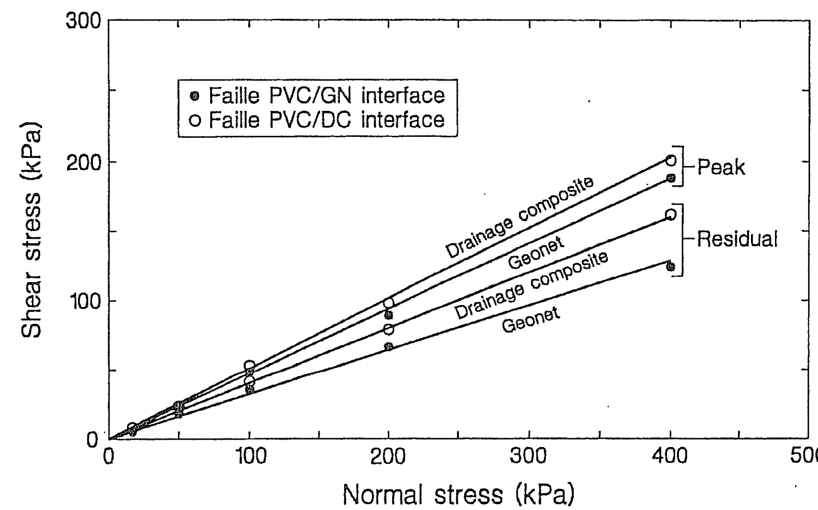

Figure 11. Comparison of failure envelopes for faille PVC geomembrane-drainage composite and -geonet interfaces.

This geotextile is the same as the GT2 geotextile except the mass per unit area is 270 g/m^2 instead of 540 g/m^2. It can be seen that the faille PVC geomembrane-drainage composite interface yielded average peak and residual friction angles of approximately 27 and 22°, respectively. The corresponding values for the faille PVC geomembrane-geonet interface are approximately 25 and 20°, respectively. To explain this difference, it is noted that the faille PVC geomembrane-GT2 interface yielded substantially higher interface strengths (average peak and residual friction angles of 32 and 26°, respectively) than the faille PVC geomembrane-drainage composite interface. The higher interface shear strengths for the PVC geomembrane-GT2 interface than the drainage composite interface is attributed to the larger contact area for the GT2 geotextile versus the area corresponding to the geonet in the drainage composite. The higher shear strength of the faille PVC geomembrane-drainage composite interface versus the geonet interface is attributed to the higher frictional resistance for the faille PVC geomembrane-nonwoven GT2 interface than the faille PVC geomembrane-HDPE geonet interface.

8.2 Comparison of Faille PVC and Textured HDPE Geomembrane-Drainage Composite Interface Shear Strengths

Figure 12 presents the failure envelopes for textured HDPE and faille PVC geomembrane-drainage composite interfaces. As was the case for the nonwoven geotextile interfaces, the faille PVC geomembrane interface exhibited a peak shear strength similar to that of the textured HDPE geomembrane interface. Also, a larger post-peak strength loss (50 to 60%) was observed for the textured HDPE interface than for the

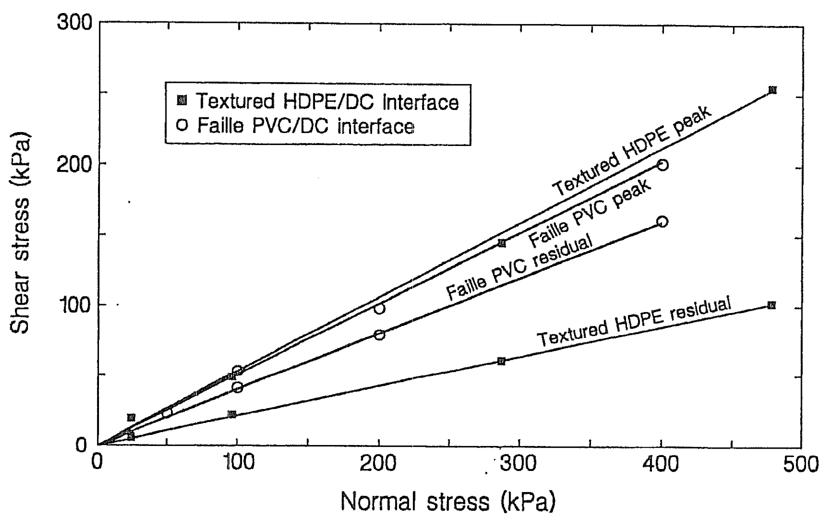

Figure 12. Comparison of failure envelopes for textured HDPE and faille PVC geomembrane-drainage composite interfaces.

faille PVC interface (30 to 35%). Since a geonet cannot substantially embed in a HDPE geomembrane at normal stresses under 500 kPa (Stark et al. 1996), the same mechanisms responsible for the large post-peak strength losses in textured HDPE geomembrane-nonwoven geotextile interfaces probably produce a similar shear behavior in textured HDPE geomembrane-drainage composite interfaces. In addition, the geonet damages and smooths the asperities of the textured HDPE geomembrane during shearing, thereby decreasing the roughness of the textured surface and further reducing the interface strength. However, the surface of a faille PVC geomembrane was actually roughened by the geonet as shearing progressed. This was determined by visually comparing the sheared PVC geomembrane to a piece of the original material. The sheared material had striations caused by the geonet ribs that were parallel to the shear direction. All of these factors account for the lower post-peak strength loss in a faille PVC geomembrane-drainage composite interface as compared to that in the corresponding textured HDPE interface.

9 SHEAR STRENGTH OF AN UNREINFORCED GCL-FAILLE PVC GEOMEMBRANE INTERFACE

9.1 Introduction

A GCL can be used in landfill cover and liner systems to partially or completely replace a compacted clay liner. A faille PVC geomembrane was sheared against an unreinforced GCL to determine the shear behavior of this interface. As mentioned previously, the GCL was not allowed to hydrate. Figure 13 presents the results of shear tests performed on the unreinforced, smooth HDPE geomembrane-backed GCL-faille PVC geomembrane interface. At a normal stress between 50 and 100 kPa, the critical shear surface shifted from the dry bentonite-faille PVC geomembrane interface to the

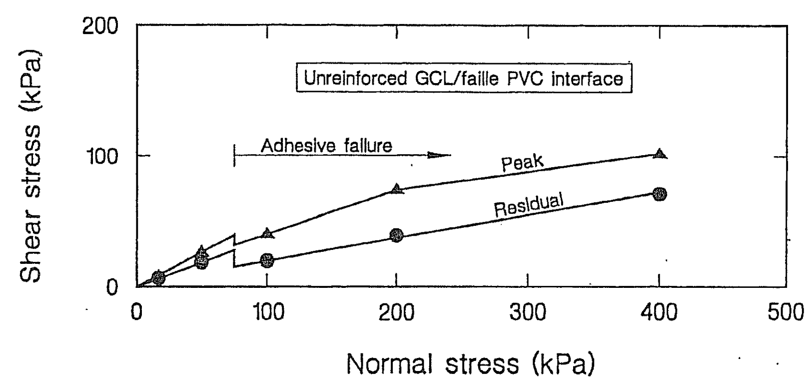

Figure 13. Peak and residual failure envelopes for an unreinforced, smooth HDPE geomembrane-backed GCL-faille PVC geomembrane interface.

smooth HDPE geomembrane backing-dry bentonite interface. In other words, at normal stresses greater than approximately 100 kPa, the unreinforced GCL experienced an internal adhesive failure because the adhesive bonding the dry bentonite to the smooth geomembrane backing failed in shear. This behavior was also observed by Eid and Stark (1997) for an unreinforced, smooth HDPE geomembrane-backed GCL-textured HDPE geomembrane interface. An adhesive failure takes place when the adhesive used to bond the dry bentonite to the smooth geomembrane backing is weaker in shear than the dry bentonite-faille PVC geomembrane interface. Therefore, the failure surface shifts to the bottom of the unreinforced bentonite layer and the peak and residual friction angles decrease, as indicated by the discontinuities in the failure envelopes shown in Figure 13. At normal stresses of 50 kPa and below, the adhesive does not fail and the interface has average peak and residual friction angles of 27 and 21°, respectively. When an adhesive failure occurs at a normal stress between 50 and 100 kPa, the average peak and residual friction angles are reduced to 17 and 11°, respectively. In summary, the unreinforced, smooth HDPE geomembrane-backed GCL-faille PVC geomembrane interface strength is stress dependent and this characteristic should be considered in the design process. For example, a typical landfill cover system is subjected to normal stresses less than 50 kPa, which suggests that failure will occur at the dry bentonite-PVC geomembrane interface. However, an adhesive failure may occur in a landfill liner system since normal stresses on a liner usually exceed 100 kPa.

The unreinforced GCL discussed in the previous paragraph is also manufactured with a textured HDPE geomembrane backing. The unreinforced, textured HDPE geomembrane-backed GCL-faille PVC geomembrane interface was tested to determine if a textured geomembrane backing has an effect on the interface failure mode and shear strength. The peak and residual failure envelopes for this interface are presented in Figure 14. It can be seen that the textured geomembrane backing prevented an adhesive failure from occurring at normal stresses ranging from 17 to 400 kPa. To verify this

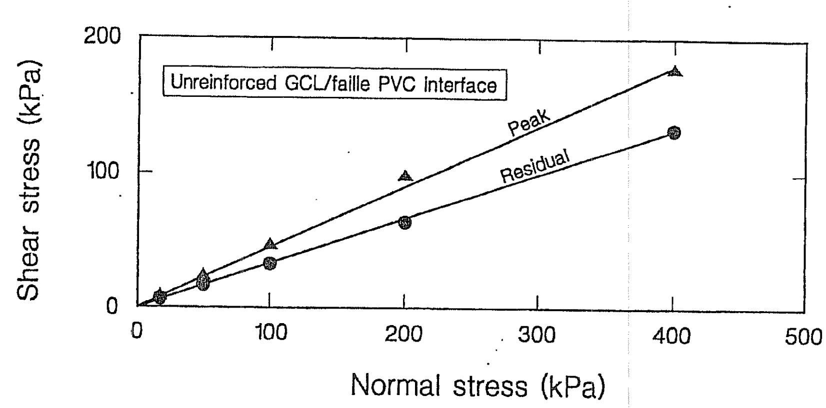

Figure 14. Peak and residual failure envelopes for an unreinforced, textured, HDPE geomembrane-backed GCL-faille PVC geomembrane interface.

conclusion, the secant peak and residual friction angles at a normal stress of 400 kPa for the unreinforced, textured geomembrane-backed GCL-faille PVC geomembrane interface are 24 and 18°, respectively. However, the corresponding values are only 14 and 10°, respectively, for the unreinforced, smooth geomembrane-backed GCL interface. To experience an adhesive failure with a textured geomembrane backing, the dry bentonite particles would have to shear over the asperities of the geomembrane, which would require a shear stress greater than the shear strength of the dry bentonite-faille PVC geomembrane interface. Therefore, a textured HDPE geomembrane backing increases interface shear strengths at normal stresses greater than approximately 100 kPa by mobilizing a larger shear resistance between the geomembrane backing and the dry bentonite. This helps to prevent an adhesive failure in the unreinforced GCL for normal stresses less than and equal to 400 kPa. This differs from results presented by Stark and Eid (1997) for the unreinforced, textured HDPE geomembrane-backed GCL-textured HDPE geomembrane interface, as discussed below.

9.2 Comparison of Unreinforced, Textured HDPE Geomembrane-Backed GCL-Faille PVC and Textured HDPE Geomembrane Interface Shear Strengths

A comparison of peak and residual failure envelopes for the unreinforced, textured HDPE geomembrane-backed GCL-faille PVC and textured HDPE geomembrane interfaces is presented in Figure 15. This illustrates the effect of the encapsulating geomembrane on the shear behavior of the unreinforced GCL. The textured HDPE geomembrane interface mobilizes a slightly higher shear strength than the faille PVC geomembrane interface at normal stresses less than approximately 175 kPa. This is

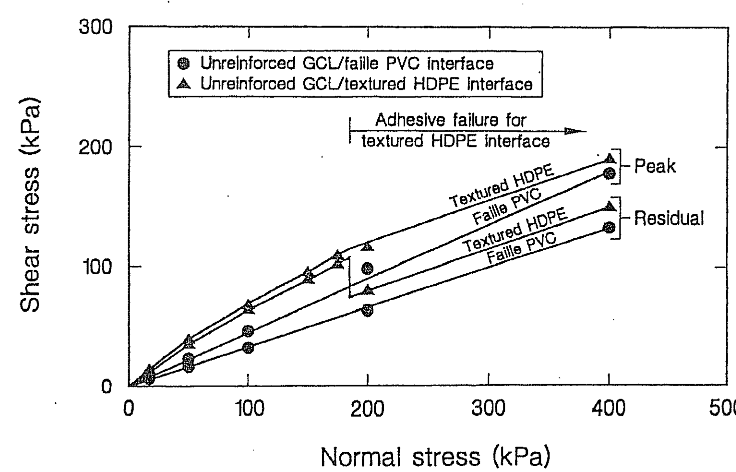

Figure 15. Comparison of failure envelopes for unreinforced, textured HDPE geomembrane-backed GCL-faille PVC and textured HDPE geomembrane interfaces.

probably caused by the asperities of the textured HDPE geomembrane embedding into the dry bentonite layer of the GCL. As shearing begins, a relatively high shear stress must develop to shear the asperities over the dry bentonite particles. The faille PVC geomembrane is relatively smooth and flexible compared to the textured HDPE geomembrane, and it does not embed into the dry bentonite layer to the extent of the textured HDPE geomembrane. Thus, the faille PVC geomembrane did not develop as much frictional resistance when sheared over the unreinforced GCL. Also, as discussed above, the unreinforced, textured geomembrane-backed GCL-faille PVC geomembrane interface did not experience an adhesive failure for normal stresses of 400 kPa and below. However, at normal stresses above roughly 175 kPa, an adhesive failure occurred in the unreinforced, textured geomembrane-backed GCL-textured HDPE geomembrane interface (Eid and Stark 1997). The faille PVC geomembrane mobilizes less shear resistance with the dry bentonite, which does not allow enough shear stress to develop to cause an adhesive failure. However, the textured HDPE geomembrane possesses a greater shear resistance with the dry bentonite, enabling the shear stress required for an adhesive failure to develop. As a result, the adhesive failure in the unreinforced GCL-textured HDPE geomembrane interface reduces the peak and residual shear strengths so, at normal stresses greater than approximately 175 kPa, the unreinforced, textured HDPE geomembrane-backed GCL-textured HDPE and faille PVC geomembrane interfaces yield similar peak and residual friction angles.

10 CONCLUSIONS

The present paper describes torsional ring shear and large-scale direct shear test results on PVC geomembrane-geosynthetic interfaces. Tables 1 and 2 present a database of peak and residual PVC geomembrane interface strengths, respectively, that can be used for comparison purposes. The following conclusions are based on the data and interpretations presented in the present paper:

1. The interface shear strengths obtained from torsional ring shear tests are in agreement with those obtained from large-scale direct shear tests at a normal stress of 192 or 200 kPa for the interfaces considered. Therefore, it was assumed that the ring shear device could be used as a substitute for the large-scale direct shear apparatus as permitted by ASTM D 5321 for the other normal stresses tested during this research.
2. The smooth side of a PVC geomembrane provides higher peak and residual interface shear resistances than the faille side. Additionally, there was no noticeable post-peak strength loss for the smooth PVC geomembrane interfaces. The greater frictional resistance of the smooth side of a PVC geomembrane is attributed to a higher pliability/flexibility and larger contact area with the overlying geosynthetic than the faille side. The higher pliability of the smooth side also accounts for the negligible post-peak strength loss in smooth PVC geomembrane-nonwoven geotextile interfaces. Since the faille side yielded lower interface shear resistances than the smooth side, the databases in Tables 1 and 2 focus on faille PVC geomembrane interfaces in order to provide lower bound values of peak and residual interface strengths.

3. Faille PVC geomembrane-nonwoven geotextile interfaces exhibit smaller post-peak strength losses than the textured HDPE and textured VFPE geomembrane interfaces tested during the present study. Textured HDPE geomembrane-nonwoven geotextile interfaces exhibit post-peak strength losses of 50 to 60% and textured VFPE geomembrane-nonwoven geotextile interfaces 35 to 45% as compared to less than 25% for the faille PVC geomembrane-nonwoven geotextile interfaces considered in the present paper. The textured geomembranes exhibit a larger post-peak strength loss because the texturing tears or pulls out more geotextile fibers and the texturing is smoothed or polished during shear (Stark et al. 1996). Faille PVC geomembrane-nonwoven geotextile interfaces do not exhibit a post-peak strength loss at normal stresses less than 50 kPa. The post-peak strength loss at higher normal stresses (100 to 400 kPa) appears to be caused by the tearing or pulling out of geotextile fibers that have embedded into the pliable faille PVC geomembrane. At low normal stresses, the geotextile fibers are unable to sufficiently embed into the faille PVC geomembrane, which reduces fiber damage and post-peak strength loss.
4. Fiber composition and type appears to impact the PVC geomembrane-nonwoven geotextile interface shear strength. A PET-based nonwoven geotextile yielded higher peak and residual interface shear strengths when sheared against the faille PVC geomembrane surface than a PP-based nonwoven geotextile of the same weight. This is probably caused by differences in fiber properties, such as hardness, roughness, weight, and diameter. This trend has also been observed for textured HDPE geomembrane-nonwoven geotextile interfaces (Stark et al. 1996). Additionally, a staple fiber nonwoven geotextile yielded higher interface strengths than continuous single fiber nonwoven geotextiles for the faille PVC geomembrane interfaces tested herein. This result is the subject of additional research but one possible explanation for this result is that the continuous single fiber is longer and larger than a staple fiber and, thus, has a higher contact area with the PVC geomembrane, which causes more fibers to be removed from the geotextile.
5. A nonwoven geotextile with a mass per unit area of 205 g/m^2 yields higher peak interface strengths than a 540 g/m^2 geotextile for the faille PVC geomembrane surface tested herein. This result is attributed to the heavier geotextile having more fibers in contact with the PVC geomembrane, which results in a greater number of fibers being pulled out and oriented parallel to the direction of shear than the 205 g/m^2 geotextile.
6. Calendering a nonwoven geotextile produces greater interface shear strength with the faille PVC geomembrane tested herein than a nonwoven geotextile that is not calendered. This appears to be caused by the rougher surface of the calendered geotextile being able to embed further into the pliable PVC geomembrane surface than the non-calendered geotextile.
7. The faille PVC geomembrane-drainage composite interface yields higher shear strengths than the faille PVC geomembrane-geonet (without a geotextile) interface. The extra geotextile in the drainage composite interface results in a higher shear resistance than the geonet interface. The higher interface strength appears to be caused by a greater contact area (geonet ribs acting through the geotextile plus the

geotextile) than only the geonet ribs.

8. The faille PVC geomembrane-drainage composite interface yields a similar peak shear strength as the corresponding textured HDPE geomembrane interface and undergoes a smaller post-peak strength loss because of less damage to the geotextile bonded to the geonet.
9. The use of a PVC geomembrane to encapsulate an unreinforced, smooth HDPE geomembrane-backed GCL results in an interface strength that is stress dependent. At normal stresses of 50 kPa and below, failure occurs at the dry bentonite-faille PVC geomembrane interface and results in average peak and residual friction angles of approximately 26 and 21°, respectively. However, at normal stresses greater than approximately 100 kPa, the failure surface shifts to the smooth geomembrane backing-dry bentonite interface because an adhesive failure occurs within the unreinforced GCL. This adhesive failure reduces the average interface peak and residual friction angles to approximately 16 and 11°, respectively. Use of a textured HDPE geomembrane backing in the unreinforced GCL mobilizes a larger shear resistance on the geomembrane backing-dry bentonite interface. This allows higher peak and residual shear strengths to develop than for the smooth geomembrane-backed GCL interface.

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Technical Paper by J.P. Gourc, R. Arab, and H. Giraud

Calibration and Validation of Design Methods for Geosynthetic-Reinforced Retaining Structures Using Partial Factors

ABSTRACT: The technique for constructing geosynthetic-reinforced soil retaining structures is now in widespread use. Since its first use in the late 1960s, construction processes have become more technologically advanced, and the number of alternatives has reduced, with most of the construction techniques being standardised. This type of reinforced structure has been in use for nearly 30 years, during which time its reliability has been proved. At the same time, work is in progress to standardise the design of these structures using the new international format of Ultimate Limit States and Serviceability Limit States calculations and associated partial factors. This study presents the procedure currently being prepared for the future standard in France. First, a preliminary parametric calibration based on typical structure profiles is described, comparing different stability calculation methods and different partial factor combinations. Second, design validation of instrumented case histories is performed.

KEYWORDS: Soil reinforcement, Geosynthetic, Standard, Design, Case history, Partial factor.

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