HDPE GEOMEMBRANE/GEOTEXTILE INTERFACE SHEAR STRENGTH

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ABSTRACT: This paper describes torsional ring shear tests on interfaces composed of high-density polyethylene (HDPE) geomembranes/nonwoven geotextiles and a drainage geocomposite. Flow textured geomembrane with three different manufacturing techniques are utilized to investigate the effect of geomembrane texturing on interface shear resistance. In addition, the effects of geotextile fiber type, fabric style, polymer composition, calendaring, and mass per unit area on textured HDPE geomembrane interface strengths are investigated. The textured HDPE geomembrane/nonwoven geotextile and drainage geocomposite interfaces exhibit a large postpeak strength loss. This strength loss is attributed to pulling out or tearing of filaments from the nonwoven geotextile and entangling them parallel to shear, and polishing of the texturing on the geomembrane. At high normal stresses, the strength loss can be caused by damage to or removal of the texturing on the geomembrane surface.

INTRODUCTION

Municipal and hazardous waste containment facilities in this country are required to have liner and cover systems containing components of low-permeability liners and liquid collecting (divisive) layers. These systems usually contain compacted clay, granular soils, and geosynthetic materials. Geosynthetic components of these layered systems routinely include layers of geomembrane or geocomposite drainage layers, geotextile cushions and filters, and geomembrane liners. The most common type of geomembrane used in waste containment facilities is manufactured from medium- or high-density polyethylene (HDPE). An important characteristic of these liner systems with respect to stability is the shear resistance along the interface between the various liner or cover system components. This importance was illustrated by the 1988 failure in Unit B-19 at the Kentlem Mills Class I hazardous waste treatment and storage facility in Kentlemown, Calif. (Byrne et al. 1992). The HDPE geomembranes installed at this facility had smooth surfaces, which resulted in a low interface shear resistance. To increase the shear resistance of geomembrane interfaces used in liner and cover systems, manufacturers developed textured HDPE geomembranes. A textured HDPE geomembrane has roughened top and/or bottom surfaces that increase the shear resistance between soil or geosynthetics in comparison to a smooth resistance developed along smooth geomembrane interfaces. At present, there are three main techniques for manufacturing textured geomembranes: (1) coextrusion; (2) lamination; and (3) imprinting. The coextrusion method uses a blowing agent in the molten extrudate. As the extrudate meets cool air and the confining pressure provided by the extruding equipment is removed, the blowing agent expands, opens to the atmosphere, and creates a textured surface. The lamination method involves an HDPE foam on a previously manufactured smooth sheet. In this method, a foaming agent contained within molten HDPE provides a froth, that produces a rough textured laminate adhered to the previously manufactured smooth sheet. The imprinting method also adheres textures to a previously manufactured smooth sheet. In this process, hot particles are projected onto the previously manufactured smooth sheet. This paper describes the results of torsional ring shear tests on textured geomembrane/nonwoven geotextile and textured geomembrane/drainage geocomposite interfaces. These results can be used to quantify the efficiency of textured geomembrane interfaces with respect to slope stability. The results also provide designers with information for selecting the appropriate nonwoven geotextile for waste containment facility liner and cover systems that utilize textured geomembranes.

TORSIONAL RING SHEAR APPARATUS

Stark and Poppel (1994) 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 apparatus allows: (1) unlimited continuous shear displacement to occur in one direction and the development of a residual or minimum interface strength condition; (2) the same interface to be sheared throughout the test; (3) a constant cross-sectional area during shearing; (4) minimal laboratory supervision; and (5) data acquisition techniques to be readily used. Other advantages of the ring shear device include no machine friction over the full range of normal stresses, no eccentric shear loading, and low cost. Disadvantages of the apparatus include changing the direction of shear with respect to the manufacturer's directions.

A modified Bromhead ring shear apparatus is used to measure the shear strength of the textured geomembrane/geosynthetic interfaces described herein. The Bromhead ring shear apparatus is based on a design presented by Bromhead (1979) and manufactured by Wyckham-Farrance Ltd., Slough, U.K. As manufactured, the annular specimen has an inner diameter of 70 mm and outside diameter of 100 mm. The specimen is contained radially by the specimen container, which is 5 mm deep. An enlarged specimen container that can accommodate an annular specimen with an inside diameter of 40 mm and an outside diameter of 100 mm was fabricated and used for the interface tests described in this paper. The enlarged specimen is contained radially by an enlarged specimen container, which is 10 mm deep. During the shear test, the top loading piston is in contact with the rotating specimen container. The normal stress is applied to the loading piston and a geotextile or drainage geocomposite is usually secured to the loading piston. The specimen container is designed to securely a geomembrane. In tests on geosynthetic/geosynthetic interfaces the bottom knurled porous stone in the specimen container is replaced with a plastic ring to secure the geomembrane. Plastic rings are used to facilitate the procedure.
securing the geosynthetics with an adhesive. The knotted po-
rous stone attached to the loading plate is also replaced with a
plastic ring for tests on geosynthetic/geosynthetic interfaces.
The plastic rings are secured to the loading plate and bottom-
of the specimen container using four screws. Therefore, the
ring shear tests are conducted with the interface between two
rigid substrata.
All of the interface tests described herein were conducted
dry or without water added to the specimen container. The
vertical displacements and shear stress are measured during the
test. Average shear displacements are calculated using the
number of degrees traveled by the specimen container and the
average specimen radius (70 mm), or the shear displacement
rate multiplied by the elapsed time. The shear force is mea-
sured using two proving rings or load cells attached to the
stationary loading plate. The specimen container rotates past
the stationary loading plate at a constant shear displacement
rate.
RING SHEAR SPECIMEN PREPARATION AND TEST
PROCEDURE
Geosynthetics Used in Ring Shear Testing
The geosynthetics used in the interface shear testing are
described next:
- Coextruded Textured Geomembrane (Co-GMX): 1.5-mm
  thick textured HDPE geomembranes manufactured by
  Gundle Lining Systems, Inc., Houston, (Co-GMX1) and
  Poly-Flx, Inc., Grand Prairie, Texas (Co-GMX2).
- Laminated Textured Geomembrane (Lam-GMX): 1.5-
  mm thick HDPE textured geomembrane manufactured by
  National Seal Co., Aurora, Ill.
- Impinged Textured Geomembrane (Imp-GMX): 1.5-
  mm thick HDPE textured geomembrane manufactured by
  SLT North America, Inc., Conroe, Tex.
- Smooth Geomembrane (GM): 1.5-mm thick HDPE smooth
  geomembrane manufactured by Gundle Lining Systems,
  Inc.
- Drainage Geocomposite (GQ): 5.6-mm thick HDPE geo-
  net is heat bonded to two polyester nonwoven continuous
  single filament needle punched geotextiles each with a
  mass per unit area of 270 g/m². This geocomposite is
  manufactured by National Seal Co.
- Nonwoven Geotextile (GT1): polypropylene nonwoven
  staple filament needle punched geotextile with a mass per
  unit area of 540 g/m². This geotextile is manufactured by
  Amoco, Atlanta.
- Nonwoven Geotextile (GT2): polyester nonwoven contin-
  uous single filament needle punched geotextile with
  a mass per unit area of 540 g/m². This geotextile is
  manufactured by Hoechst-Celanese, Sparta, N. J.
- Nonwoven Geotextile (GT3): polypropylene nonwoven
  continuous single filament needle punched geotextile with
  large denier filaments and a mass per unit area of 270 g/
  m². This geotextile is manufactured by Polyfelt America,
  Atlanta.
- Nonwoven Geotextile (GT4): polypropylene nonwoven
  continuous single filament needle punched geotextile with
  large denier filaments and a mass per unit area of 546 g/
  m². This geotextile is manufactured by Polyfelt America,
  Atlanta.
- Nonwoven Geotextile (GT5): polypropylene nonwoven
  staple filament needle punched calendered geotextile with
  a mass per unit area of 540 g/m². This geotextile is man-
  ufactured by Amoco.

It should be noted that the interface test results presented
herein are representative of the manufacturing lots tested. Geo-
synthetic products can vary from lot to lot with some products
varying significantly. Thus, the test results presented herein
can be used for design, but they must be confirmed through
construction phase quality control and/or assurance testing of
materials from manufacturing lots delivered to the project.

Geomembrane Specimen Preparation
Geomembranes are secured to a plastic ring using a thin
coat of epoxy cement. The epoxy cement is allowed to cure
for 24 h under a normal stress of approximately 25 kPa.
It should be noted that the curing normal stress does not exceed
the normal stress at which the test is conducted. The normal
stress also loading of the geomembrane and maintains ver-
tical displacements caused by the epoxy cement during testing.
The geomembrane and specimen container is matched to
ensure that the geomembrane does not slip during shear.

Geotextile and Drainage Geocomposite Specimen
Preparation
To aid in securing of the geotextiles to a plastic ring, the
geotextile is initially glued to a smooth geomembrane that is
cut to the actual specimen size. The smooth geomembrane
with the attached geotextile is then glued to a plastic ring that
is secured to the loading plate. The geotextile is cut in a circle
with a diameter of approximately 160 mm. It should be noted that
this diameter is larger than the outer diameter of the ring
shear specimen (100 mm). A small circular hole (roughly
10 mm) is cut in the center of the circular specimen so that the
geotextile does not interfere with the centering pin of the
ring shear apparatus. The geotextile is glued to the smooth
geomembrane ring using a thin coat of epoxy cement. A 2–3
kg mass is placed on the geotextile/smooth geomembrane to
aid adhesion. After 10–15 min of drying, the geotextile ex-
tending beyond the edge of the smooth geomembrane is cut
perpendicularly to the smooth geomembrane. This yields eight
wedges or flaps of geotextile extending beyond the outside
diameter of the smooth geomembrane. Adhesive is applied to
the back of the smooth geomembrane and four of the eight
wedges of geotextile are folded over and adhered to the re-
verse side of the smooth geomembrane. A 2–3 kg mass is
reapplied for roughly 20–25 min to aid adhesion. After curing,
the remaining four flaps are folded over and adhered to the
reverse side of the geomembrane in the same manner.
These four wedges are secured separately from the original
four since some additional trimming may be required to
ensure adequate space on the smooth geomembrane for se-
curing. This wrapping of the geotextile around the smooth
geomembrane prevents geotextile filaments from readily pull-
ning out during shear.

The smooth geomembrane/geotextile specimen is secured to a
plastic ring attached to the loading plate using a thin coat of
epoxy cement. The side with the eight wedges is glued to the
plastic ring. The ring is placed in the ring shear apparatus, and
then the textured geomembrane/geotextile interface is assembled. A sac-
crificial geotextile cushion is placed between the textured
geomembrane and geotextile to ensure there is no contact between
the geosynthetics before shearing. The loading plate and geotex-
tile are also matched to ensure that the geotextile does not slip
during shear.

After allowing the epoxy cement to cure for 24 h in the ring
shear apparatus, the geomembrane/geotextile interface is ready
for shearing. The sacrificial geotextile is removed and the two
interface components are placed in contact with each other,
such that no relative displacement occurs between the two sur-
faces prior to shearing.
A similar procedure is followed for securing the drainage geomembrane. The geocomposite, with a diameter of approximately 100 mm and a central circular hole of approximately 10 mm, is glued to the plastic ring attached to the loading plate. The cement is allowed to cure for 24 h under a normal stress (approximately 25–50 kPa) that does not exceed the normal stress at which the test will be conducted.

A shear displacement rate of 6 kPa/s/min is used for testing the geomembrane/geosynthetic interfaces. The specimens are placed in the desired normal stress and a shearing starts with minute intervals of normal stress application. For a typical textured geocomposite/geomembrane interface tested at a shear displacement rate of 0.27 mm/min, the peak stress will be usually mobilized within 10–20 min (4–8 s) and the residual resistance within 35–50 h (1000–1,150 mm).

**EFFECT OF TEXTURED GEOMEMBRANES ON INTERFACE SHEAR RESISTANCE**

Fig. 1 presents a comparison of failure envelopes for smooth and textured geocomposite/nonwoven geotextile interfaces. The geomembranes and geotextile are the tests in the tests are indicated by the GM, CO-GMX1, and GT2 as described previously. It can be seen that the peak and residual interface strengths are increased approximately 300% and 200%, respectively, by the use of textured geocomposites instead of smooth geomembranes. However, the peak stress resistance is substantially greater with a textured geomembrane. The mechanisms causing the large increase in peak stress resistance to textured geomembrane/nonwoven geotextile interfaces are discussed in a subsequent section of this paper.

**EFFECT OF SHEAR DISPLACEMENT RATE ON INTERFACE SHEAR RESISTANCE**

Fig. 2 presents peak and residual shear stresses for a textured geocomposite/nonwoven geotextile interface (CO-GMX1/GT1). The five interface test results shown were conducted at a normal stress of 6 kPa. It can be seen that the peak and residual shear stress relationships vary strongly as the displacement rate ranges from 0.029–36.7 mm/min. Therefore, it appears that the shear displacement rate does not significantly affect the measured peak and residual shear stress for a textured geocomposite/nonwoven geotextile interface. It should be noted that the American Society for Testing and Materials (ASTM) large-scale direct shear test procedure "Determining" (1993) recommends a shear displacement rate of 5.0 mm/min for geosynthetic/geosynthetic interfaces, which is encompassed in the range of displacement rates in Fig. 2. Fig. 2 also illustrates the postpeak stress loss for a typical textured geocomposite/nonwoven geotextile interface. It can be seen that the residual interface strength is 50–80% lower than the peak values for the displacement rates considered.

**TEXTURED GEOMEMBRANE/NONWOVEN GEOTEXTILE INTERFACE SHEAR RESISTANCE**

Fig. 3 presents typical shear stress-shear displacement relationships for a textured geocomposite/nonwoven geotextile (CO-GMX1/GT3) interface. It can be seen at a normal stress of 283 kPa that the interface exhibited a peak shear stress of approximately 70 kPa and a residual shear stress of about 65 kPa. The peak shear stress is usually mobilized at a shear displacement of 4–8 mm. It can also be seen in Fig. 3 that 500–750 mm of displacement is required to mobilize the residual interface shear resistance of this interface. This displacement may be larger than the displacement that can be achieved in large-scale direct shear tests. If so, direct shear apparatus may overestimate the residual strength of textured geocomposite/nonwoven geotextile interfaces.

**FIG. 1. Comparison of Failure Envelopes for Smooth and Textured Geomembrane/Geotextile Interfaces**

**FIG. 2. Effect of Shear Displacement Rate on Textured Geomembrane/Nonwoven Geotextile Interface**

**FIG. 3. Typical Ring Shear Test Results for Textured Geomembrane/Nonwoven Geotextile Interface**

**FIG. 4. Typical Failure Envelopes for Textured Geomembrane/Nonwoven Geotextile Interface**

Fig. 4 presents the peak and residual failure envelopes for the textured geocomposite/nonwoven geotextile (CO-GMX1/GT3) interface described in Fig. 3. It can be seen that the failure envelopes are approximately linear within the stress range tested. As a result, the peak and residual failure envelope.

lopes can be represented by a friction angle of 32° and 13°, respectively. Therefore, the postpeak strength loss corresponds to a reduction in friction angles of 19° or 60°. This is a typical postpeak strength loss for the textured geomembrane/nonwoven geotextile interfaces tested during this study. For comparison purposes, Fig. 4 presents the failure envelope corresponding to a shear displacement of 50 mm in the ring shear apparatus. The values of shear stress and displacement obtained from Fig. 3 at a shear displacement of 50 mm. A shear displacement of between 25 and 75 mm is usually achieved in a 30-c by 60-c direct shear box using the ASTM large-scale direct shear test procedure (1). Therefore, if a ring shear or direct shear test was terminated at a shear displacement of 50 mm, the resulting failure envelope would be significantly higher than the measured residual failure envelope. This would result in an overestimation of the residual or minimum interface shear strength.

Approximately 40 ring shear tests conducted on different textured geomembrane/nonwoven geotextile (GMI/GT) interfaces showed that some of the CM/GT interfaces exhibited nonlinear failure envelopes. In this case, the nonlinearities are attributed to the interface shear resistance along the failure surface. This can be accomplished by utilizing the entire nonlinear failure envelope or a fraction angle that corresponds to the average effective normal stress acting on the failure surface.

The postpeak strength loss exhibited by the textured geomembrane/nonwoven geotextile is mainly attributed to pulling out and/or tearing the filaments from the geotextile during shear. Additional shear displacement appears to comb or interlace detached fibers parallel to the direction of shear. As a result, the majority of the filaments in the failed specimens are oriented parallel to the direction of shear. This failure mechanism is illustrated in Figs. 5 and 6. Fig. 5 presents a scanning electron microscope photograph of nonwoven geotextile GT5 prior to testing. It can be seen that the filaments are randomly oriented and initially bonded together. Fig. 6 presents a scanning electron microscope photograph of nonwoven geotextile GT5 after shearing to the residual condition in a ring shear apparatus. It can be seen that the majority of the filaments are oriented parallel to the direction of shear. It should be noted that pulling of the textured surface of the geomembrane also contributes to the observed postpeak strength loss especially under high normal stresses.

This failure mechanism is in agreement with field observations that describe a large resistance to shear displacement when a nonwoven geomembrane is in contact with a textured geomembrane. This large resistance is sometimes referred to as a failure mechanism that results in a reduction of the interface shear resistance. However, after installing the nonwoven geotextile over the textured geomembrane for a small distance, the shearing or Velcro effect is usually reduced. This suggests that some of the filaments are broken or pulled out during movement, resulting in a smaller shear resistance. To facilitate placement of nonwoven geotextiles over textured geomembranes, a separation layer (e.g., Visqueen, a geonet, or other material) is usually placed on top of the geomembrane before the geotextile. After the geotextile is properly aligned, the separation layer is removed.

**EFFECT OF NONWOVEN GEOTEXTILE ON TEXTURED GEOMEMBRANE INTERFACE SHEAR RESISTANCE**

Effect of Geotextile Fiber Type and Fabric Style

Fig. 7 provides a comparison of failure envelopes for different nonwoven geotextiles incorporated into a textured geomembrane/nonwoven geotextile interface. In particular, a few nonwoven geotextiles are tested: (a) a coextruded textured geotextile (Co-GMX1) is shear tested against three 540-gm非 woven geotextiles (GT1, GT2, and GT4). Two of these geotextiles (GT1 and GT4) are composed of polypropylene fibers. The other nonwoven geotextile (GT2) is composed of polyester fibers and will be discussed in the following section. It can be seen that GT2 yields a higher peak failure envelope than the other polypropylene based-geotextile (GT1). Since the mass per unit area, polymer composition, and fabric style of these geotextiles are the same, it may be concluded that the fiber type can influence the peak tensile geo-
membrane/nonwoven geotextile interface shear resistance. GT1 utilizes staple fibers while GT4 is comprised of continuous large denier single fibers. As a result, the higher peak failure envelope may be attributed to the large denier (coarse) continuous single fibers used in the manufacturing of geotextile GT4.

It should also be noted that the residual failure envelope appears to be independent of the polypropylene geotextile fabric style and fiber type. This is mainly attributed to the effects of the fabric style being removed by detaching and orienting the filaments from the polypropylene geotextiles parallel to the direction of shear at the residual condition. In addition, any difference in fiber type is probably removed after 900–1,000 mm of shear displacement.

**Effect of Geotextile Polymer Composition**

Also shown in Fig. 7 is a comparison of textured geomembrane/nonwoven polyester geotextile (GT2) and nonwoven polypropylene geotextile (GT4) interfaces. Both geotextiles, GT2 and GT4, utilize the same fiber type (continuous single filament) and fabric style (nonwoven needle punched). Therefore, the main difference between these geotextiles is the fiber polymer. The polyester geotextile (GT2) yields a higher peak and residual failure envelope than the polypropylene geotextiles (GT4). Therefore, nonwoven geotextile polymer composition appears to influence the peak and residual interface strength.

The peak failure envelopes shown in Fig. 7 are nonlinear. For comparison purposes, if a secant failure envelope is assumed to pass through the origin and a normal stress of approximately 290 kPa, the interface friction angles for the GT2, GT4, and GT1 nonwoven geotextiles are 31°, 28°, and 26°, respectively. The secant residual friction angles at a normal stress of approximately 290 kPa are 16°, 12°, and 11° for the GT2, GT1, and GT4 nonwoven geotextiles, respectively. Therefore, the polymer composition, fiber type, and fabric style of 540 g/m² geotextiles appear to influence peak and residual textured geomembrane interface strengths. Site-specific testing of this interface should be conducted to assess the importance of the seaparators on interface shear strength.

Fig. 8 provides a similar comparison of failure envelopes for the three nonwoven geotextiles (GT1, GT2, and GT4) presented in Fig. 7 except that a laminated textured HDPE geomembrane (Lam-GMX) is utilized instead of a coextruded geomembrane (Co-GMX). The difference between the peak failure envelopes is not as pronounced with the laminated textured geomembrane as with the coextruded geomembrane (Co-GMX). It can be seen that the polyester nonwoven continuous single filament needle punched geotextile (GT2) again resulted in the highest residual failure envelope. Therefore, Figs. 7 and 8 indicate that the textured geombbrane also influences the peak interface failure envelope, and thus site-specific testing should be conducted.

**Effect of Geotextile Calendering**

Calendering of a geotextile results in the bonding of the filaments and/or frictioning of the fabric with rubber or plastic compounds. Calendering is usually accomplished by passing the fabric between two counterrotating heated rollers (Koerner 1994). The effect of calendering on the shear resistance of textured geomembrane/nonwoven geotextile (Lam-GMX/GT1 and Lam-GM/GT5) interfaces was also investigated. The same geotextile was used to test calendered (GT5) and noncalendered (GT1) nonwoven geotextiles with a mass per unit area of 540 g/m². The geotextiles are manufactured using the same polymer composition, fiber type, and fabric style, and thus the only difference between the two interfaces is calendering of the geotextile.

Fig. 9 presents typical peak and residual failure envelopes for the Lam-GMX/GT1 and Lam-GMX/GT5 interfaces. It can be seen that the calendered geotextile yielded a higher peak and residual interface strength than the noncalendered geotextile for the three normal stresses considered. The large postpeak strength loss observed in the noncalendered geotextile is primarily due to the tearing or pulling out of the geotextile filaments and/or the filaments parallel to the direction of shear. Figs. 5 and 6 illustrate the calendered geotextile (GT5) before and after shearing, respectively, at a normal stress of 285 kPa.

It can be seen at a normal stress of 480 kPa that the peak and residual shear stresses for both geotextiles deviate from the linear failure envelope defined at the lower normal stresses. This is attributed to the removal ofasperities from the surface of the laminated textured geomembrane, which results in the reduced shear resistance at a normal stress of 480 kPa and the bilinear failure envelopes. The calendered geotextile yields a peak friction angle of approximately 33° for normal stresses less than or equal to 285 kPa. However, the secant peak friction angle for the calendered geotextile at a normal stress of 480 kPa is only 28°. In addition, the calendered geotextile yields a residual friction angle of approximately 15° for normal stresses less than or equal to 285 kPa while the secant residual friction angle at a normal stress of 480 kPa is only 11°. A similar decrease in peak and residual friction angles is apparent for the noncalendered geotextile. This decrease in friction angle is also attributed primarily to the removal of texture from the surface of the geomembrane.

**Effect of Geotextile Mass per Unit Area**

Fig. 10 presents typical peak and residual failure envelopes for textured geomembrane/nonwoven geotextile (Co-GMX/GT1 and Co-GMX/GT5) interfaces. The mass per unit area of the nonwoven geotextiles was varied from 270 g/m² (GT3) to 543 g/m² (GT4) while the same textured geomembrane (Co-GMX) was used for both interfaces. The geotextiles are presented...
duced by the same manufacturer and utilize the same polymer composition, fibre type, and fabric style. Therefore, the only difference between these two geotextiles is the mass per unit area. It can be seen at normal stresses less than 100 kPa that there is a negligible difference between the peak failure envelopes. At normal stresses greater than 100 kPa, the 270 g/m² geotextile tends to yield a higher peak failure envelope than the 540 g/m² geotextile. This suggests that a 270 g/m² nonwoven geotextile may yield a higher interface shear resistance at normal stresses greater than 100 kPa for a textured geomembrane/nonwoven geotextile. It is anticipated that the larger mass per unit area or thickness results in some filament being more easily pulled out or torn from the 540 g/m² geotextile than the 270 g/m² geotextile at large shear stresses. This suggests that a lower mass per unit area may be more desirable for a liner system. At normal stresses less than 100 kPa, e.g., cover systems, the mass per unit area or thickness does not appear to significantly influence the interface strength.

From Fig. 10 it can be seen that the mass per unit area of the geotextile did not significantly affect the residual interface strength. This is probably caused by the geotextile filaments being pulled out or torn after the large shear displacement required to achieve a residual strength condition. At the residual condition, the majority of these filaments have been oriented or combed parallel to the direction of shear. As a result, the residual interface failure envelope appears to be independent of the mass per unit area of the nonwoven geotextile.

**EFFECT OF TEXTURED GEOMEMBRANE ON NONWOVEN GEOTEXTILE INTERFACE SHEAR RESISTANCE**

A comparison of Figs. 7 and 8 provides insight into the effect of the coextrusion and lamination manufacturing process on textured geomembrane/nonwoven geotextile interface strengths. For example, the peak shear friction angle at a normal stress of approximately 290 kPa for the Co-GMX/1/GT2 (Fig. 7) and Lam-GMX/GT2 (Fig. 8) interface is approximately 31°. Therefore, the coextrusion and lamination processes appear to yield similar peak interface strengths. However, if the induced shear stresses are large enough to delaminate the texture from the geomembrane, this conclusion probably will not be valid (Fig. 9). In addition, the coextrusion process appears to yield a higher residual interface strength than the lamination process. For example, the residual shear friction angles are approximately 290 kPa for the Co-GMX/1/GT2 (Fig. 7) and Lam-GMX/GT2 (Fig. 8) interfaces are approximately 16° and 12°, respectively. A similar trend was observed with the other nonwoven geotextiles.

**TEXTURED GEOMEMBRANE/DRAINAGE GEOCOMPOSITE INTERFACE SHEAR RESISTANCE**

Fig. 11 presents typical shear stress shear displacement relationshios for a textured geomembrane/drainage geocomposite (Co-GMX/1/GN) interface. The drainage geocomposite consists of two 270 g/m² polyester nonwoven continuous single filament needle punched geotextiles heat-bonded to a medium density polyethylene geom, It can be seen at a normal stress of 480 kPa that the interface exhibited a peak shear stress of approximately 250 kPa and a residual shear stress of about 105 kPa. The peak interface shear stress is usually mobilized at a shear displacement of 4–8 mm. It can also be seen in Fig. 11 that 500–800 mm of displacement is usually required to mobilize the residual interface shear strength. Fig. 12 presents the failure envelopes for the textured geomembrane/drainage geocomposite (Co-GMX/1/GN) interface test results shown in Fig. 11. It can be seen that the average peak and residual shear friction angles are 30° and 13°, respectively. These values of peak shear friction angle are similar to those measured for a similar textured geomembrane/nonwoven geotextile interfaces (e.g., Fig. 4). This implies that the presence of the geom, does not significantly alter the interface shear resistance with a coextruded textured geomembrane at normal stresses less than 480 kPa. Current research indicates that at normal stresses greater than 500 kPa, the geomembrane/drainage geocomposite can embed in the geomembrane. This was also observed by Sarr and Poeppel (1994) for a geomembrane/geotextile interface. The embedment occurred at a lower normal stress of 350–400 kPa because there was no geotextile between the geomembrane and drainage geocomposite. In summary, the failure mechanisms for the textured geomembrane/drainage geocomposite interface is similar to the textured geomembrane/nonwoven geotextile interface.
Effect of Textured Geomembrane on Drainage Geocomposite Interface Shear Resistance

Fig. 12 also illustrates the effect of the textured geomembrane manufacturing process on the interface shear resistance of the textured geomembrane/drainage geocomposite interface (Co-GMX/Co-GMX2/Co-GMX/Co-GMX2/Co-GMX2/GN). It can be seen that the Co-GMX2 textured geomembrane yielded the highest peak failure envelope, followed by the Co-GMX, Co-GMX2, and Co-GMX2/Co-GMX interfaces. This indicates that the Co-GMX2 textured geomembrane exhibited similar peak failure envelopes at normal stresses less than 285 kPa. The drainage geocomposite did not cause removal of or damage to the Co-GMX2 and Co-GMX geomembrane during shearing. However, the Co-GMX and Co-GMX2 geomembranes experienced delamination at normal stresses greater than 285 kPa with a drainage geocomposite. This resulted in the Co-GMX and Co-GMX2 geomembranes exhibiting a lower peak shear stress at a normal stress of 480 kPa than the Co-GMX1 and Co-GMX2 geomembranes. At normal stresses greater than 285 kPa, the geonet appeared to aid the damage or removal of the textured from the laminated and impingement products.

The Co-GMX2 textured geomembrane also exhibited the highest residual failure envelope. The Lam-GMX geomembrane exhibited the lowest residual failure envelope because some of the texturing was delaminated during shearing.

SUMMARY AND CONCLUSIONS

This paper describes torsional ring shear tests on HDPE geomembrane/nonwoven geotextile and drainage geocomposite interfaces. The following conclusions are based on the data and interpretation presented in this paper:

1. Textured HDPE geomembranes provide a substantial increase in interface shear strength over smooth HDPE geomembranes. Shear stresses imposed on the interface must be resisted in part by the texturing on the surface of the geomembrane. At high normal stresses, the applied shear stress can remove or damage some or all of the texturing. The removal or damage of the texturing appears mainly applicable to textured HDPE geomembranes created by the laminations and impingement products. The specific laboratory interface shear tests should accurately simulate field conditions to understand the performance of the materials involved. For example, the interface should be tested at the field normal stress with the delaminated geomembrane and geotextile to investigate field performance.

2. Textured HDPE geomembrane/nonwoven geotextile or drainage geocomposite interfaces exhibit a postpeak strength loss of 50–60%. The postpeak strength loss is primarily attributed to the pulling out and/or tearing of fibers from the nonwoven geotextile and orienting them parallel to shear. However, pulling of the geomembrane texturing also contributes to the strength loss.

3. Textured HDPE geomembrane/nonwoven geotextile interface failure envelopes can be nonlinear. It is recommended that the entire failure envelope or a friction angle that corresponds to the appropriate normal stress be used in stability analyses.

4. The mass per unit area, polymer composition, fiber type, and/or fabric style of the nonwoven geotextile can influence the peak textured geomembrane/nonwoven geotextile interface shear resistance. For example, continuous large denier fibers appear to result in a higher peak interface shear strength than staple fibers.

5. The residual textured geomembrane/nonwoven geotextile interface shear resistance appears to be independent of fiber type, fabric style, and mass per unit area. However, polyester geotextiles appear to yield a higher residual interface shear strength than comparable polypropylene geotextiles.

6. Calendering of a nonwoven geotextile can increase the textured geomembrane/nonwoven geotextile peak and residual interface strengths by 10–20% and 20–30%, respectively.

7. A nonwoven geotextile mass per unit area of 270 g/m² appears to result in higher residual interface strengths than a 540 g/m² geotextile at normal stresses greater than 100 kPa. This suggests that a lower mass per unit area or thickness may be more desirable for liner systems. At normal stresses less than 100 kPa, there appears to be negligible difference between the peak interface strengths.

8. Coextruded and laminated textured geomembranes exhibit similar peak nonwoven geotextile interface shear strength. The coextrusion process yields a higher residual interface strength than the laminated product. If the texturing is damaged or removed, the coextruded geomembrane exhibits a higher peak interface strength. The coextruded geomembrane appears to yield a higher residual interface shear strength than the laminated geomembrane.

9. The presence of a drainage net in a drainage geocomposite does not significantly increase the textured geomembrane/nonwoven geotextile interface shear resistance for normal stresses less than 500 kPa. However, the drainage net can facilitate damage or repair of the textured from a laminated or impingement geomembrane at normal stresses lower than 500 kPa. Therefore, the drainage net would be required for tissue damage or removal with only a nonwoven geotextile.

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APPENDIX. REFERENCES


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