HDPE GEOMEMBRANE/GEOTEXTILE INTERFACE SHEAR STRENGTH

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ABSTRACT: This paper describes torsional ring shear tests on interfaces comprised of high-density polyethylene (HDPE) geomembranes/nonwoven geotextiles and a drainage geocomposite. Four textured geomembranes 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, calendering, and mass per unit area on textured HDPE geomembrane interface strengths are investigated. The textured HDPE geomembrane/nonwoven geotextile and drainage geocomposite interfaces exhibited a large post-peak strength loss. This strength loss is attributed to pulling out or tearing of filaments from the nonwoven geotextile and orienting 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 combinations of low-permeability liners and liquid collection (drainage) layers. These systems usually contain compacted clay, granular soils, and geosynthetic materials. Geosynthetic components of these layered systems routinely include layers of geonet 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 Kettleman Hills Class I hazardous waste treatment and storage facility in Kettleman City, 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 the shear resistance developed along smooth geomembrane interfaces.

At present, there are three main techniques for manufacturing textured geomembranes (''Quality'' 1993): (1) coextrusion; (2) lamination; and (3) impingement. 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 laminates 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 impingement method also adheres texturing 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 Poeppel (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 shear; (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 a small specimen size and changing the direction of shear with respect to the manufacturing direction.

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 is manufactured by Wykeham-Farrance Ltd., Slough, U.K. As manufactured, the annular specimen has an inside diameter of 70 mm and outside diameter of 100 mm. The specimen is confined 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 also confined radially by an enlarged specimen container, which is 10 mm deep.

During shear the top/loading platen is in contact with the rotating specimen container. The normal stress is applied to the loading platen and a geotextile or drainage geocomposite is usually secured to the loading platen. The specimen container is used to secure 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

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securing the geosynthetics with an adhesive. The knurled porous stone attached to the loading platen is also replaced with a plastic ring for tests on geosynthetic/geosynthetic interfaces. The plastic rings are secured to the loading platen 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 displacement 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 measured using two proving rings or load cells attached to the stationary loading platen. The specimen container rotates past the stationary loading platen 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-Flex, Inc., Grand Praire, Tex. (Co-GMX2).
- Laminated Textured Geomembrane (Lam-GMX): 1.5-mm-thick HDPE textured geomembrane manufactured by National Seal Co., Aurora, Ill.
- Impingement 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 (GN): 5.6-mm-thick HDPE geonet is heat bonded to two polyester nonwoven continuous single filament needle punched geotextiles each with a mass per unit area of 270 g/m^2. 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/m^2. This geotextile is manufactured by Amoco, Atlanta.
- Nonwoven Geotextile (GT2): polyester nonwoven continuous single filament needle punched geotextile with a mass per unit area of 540 g/m^2. This geotextile is manufactured by Hoechst-Celanese, Spartanburg, S.C.
- Nonwoven Geotextile (GT3): polypropylene nonwoven continuous single filament needle punched geotextile with large denier filaments and a mass per unit area of 270 g/m^2. 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 540 g/m^2. This geotextile is manufactured by Polyfelt America.
- Nonwoven Geotextile (GT5): polypropylene nonwoven staple filament needle punched calendered geotextile with a mass per unit area of 540 g/m^2. This geotextile is manufactured by Amoco.

It should be noted that the interface test results presented herein are representative of the manufacturing lots tested. Geosynthetic 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 aids bonding of the geomembrane and minimizes vertical displacements caused by the epoxy cement during testing. The geomembrane and specimen container are marked 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 platen. 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 outside 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 extending beyond the edge of the smooth geomembrane is cut perpendicular 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 reverse 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 wedges of geotextile 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 securing. This wrapping of the geotextile around the smooth geomembrane prevents geotextile filaments from readily pulling out during shear.

The smooth geomembrane/geotextile system is secured to a plastic ring attached to the loading platen using a thin coat of epoxy cement. The side with the eight wedges is glued to the plastic ring. The cement is allowed to cure for 24 h under a normal stress (approximately 25 kPa) that does not exceed the normal stress at which the test will be conducted. The normal stress is applied in the ring shear apparatus, and thus the textured geomembrane/geotextile interface is assembled. A sacrificial geotextile cushion is placed between the textured geomembrane and geotextile so there is no contact between the geosynthetics before shearing. The loading platen and geotextile are also marked 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 surfaces prior to shearing.

A similar procedure is followed for securing the drainage geocomposite. The geocomposite, with a diameter of approximately 100 mm and a center circular hole of approximately 10 mm, is glued to the plastic ring attached to the loading platen. 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 0.37 mm/min is used for testing the geomembrane/geosynthetic interfaces. The sample is loaded to the desired normal stress and shearing starts within minutes of normal stress application. For a typical textured geomembrane/geotextile interface tested at a shear displacement rate of 0.37 mm/min, the peak shear resistance is usually mobilized within 10–20 min (4–8 mm) and the residual resistance within 35–50 h (800–1,150 mm).

EFFECT OF TEXTURED GEOMEMBRANES ON INTERFACE SHEAR RESISTANCE

Fig. 1 presents a comparison of failure envelopes for smooth and textured geomembrane/nonwoven geotextile interfaces. The geomembranes and geotextile used in the tests are indicated by 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 geomembranes instead of smooth geomembranes. However, the post peak strength loss is substantially greater with a textured geomembrane. The mechanisms causing the large post peak strength loss in 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 geomembrane/nonwoven geotextile interface (Co-GMX1/GT1). The five interface test results shown were conducted at a normal stress of 96 kPa. It can be seen that the peak and residual shear stress relationships vary slightly 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 geomembrane/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 strength loss for a typical textured geomembrane/nonwoven geotextile interface. It can be seen that the residual interface strength is 50–60% 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 geomembrane/nonwoven geotextile (Co-GMX1/GT3) interface. It can be seen at a normal stress of 285 kPa that the interface exhibited a peak shear stress of approximately 170 kPa and a residual shear stress of about 65 kPa. The peak interface 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 apparatuses may overestimate the residual strength of textured geomembrane/nonwoven geotextile interfaces.

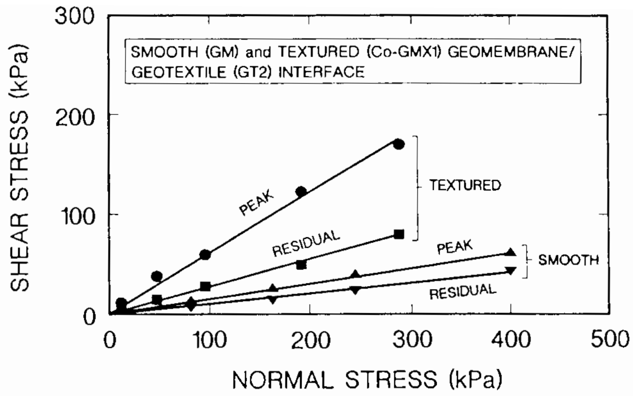

FIG. 1. Comparison of Failure Envelopes for Smooth and Textured Geomembrane/Geotextile Interfaces

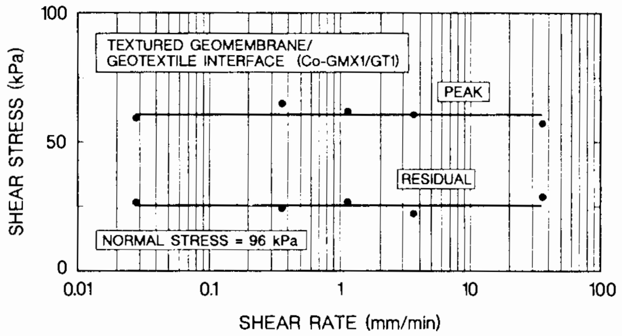

FIG. 2. Effect of Shear Displacement Rate on Textured Geomembrane/Nonwoven Geotextile Interface

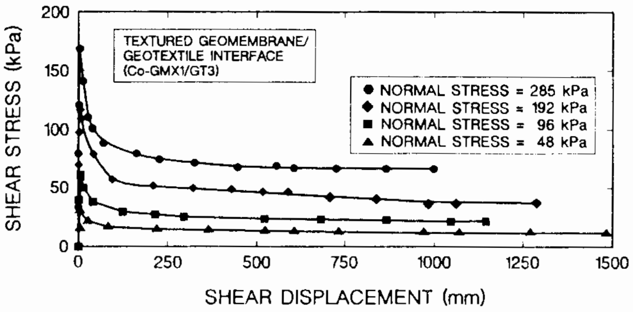

FIG. 3. Typical Ring Shear Test Results for Textured Geomembrane/Nonwoven Geotextile Interface

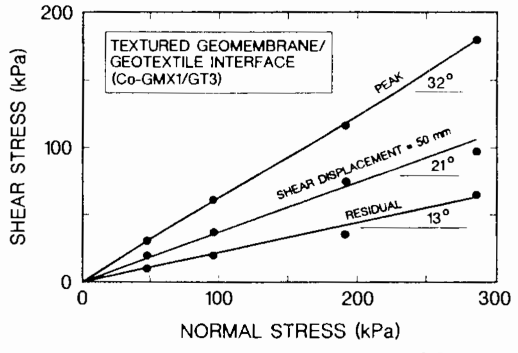

FIG. 4. Typical Failure Envelopes for Textured Geomembrane/Nonwoven Geotextile Interface

Fig. 4 presents the peak and residual failure envelopes for the textured geomembrane/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 envelopes can be represented by a friction angle of 32° and 13°, respectively. Therefore, the postpeak strength loss corresponds to a reduction in friction angle 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 shown were 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-cm-by-30-cm direct shear box using the ASTM large-scale direct shear test procedure ("Determining" 1993). 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 80 ring shear tests conducted on different textured geomembrane/nonwoven geotextile (GMX/GT) interfaces showed that some of the GMX/GT interfaces exhibited nonlinear failure envelopes. In this case, the nonlinearity should be modeled in stability analyses to accurately represent the interface shear resistance along the failure surface. This can be accomplished by utilizing the entire nonlinear failure envelope or a friction 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 orient these 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 shearing. 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 polishing 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 geotextile is placed in contact with a textured geomembrane. This large resistance is sometimes referred to as a Velcro-type attachment or resistance. However, after installers drag the nonwoven geotextile over the textured geomembrane for a small distance, the shear resistance 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 coextruded textured geomembrane (Co-GMX1) is sheared against three 540 g/m^2 nonwoven 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 GT4 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 textured geo-

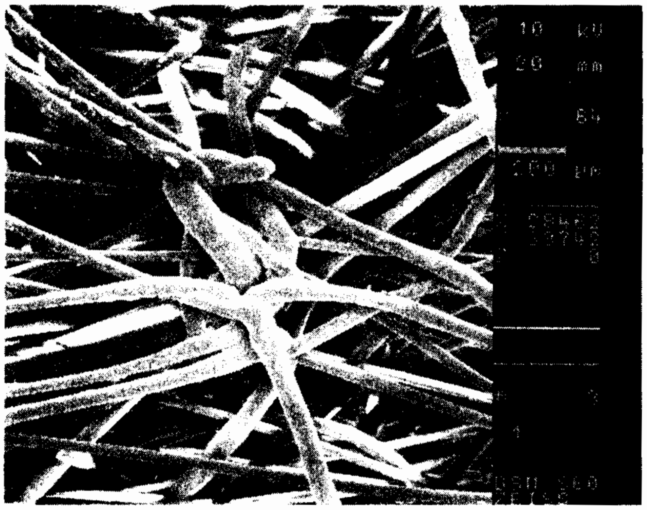

FIG. 5. Filaments of GT5 Geotextile Prior to Shear

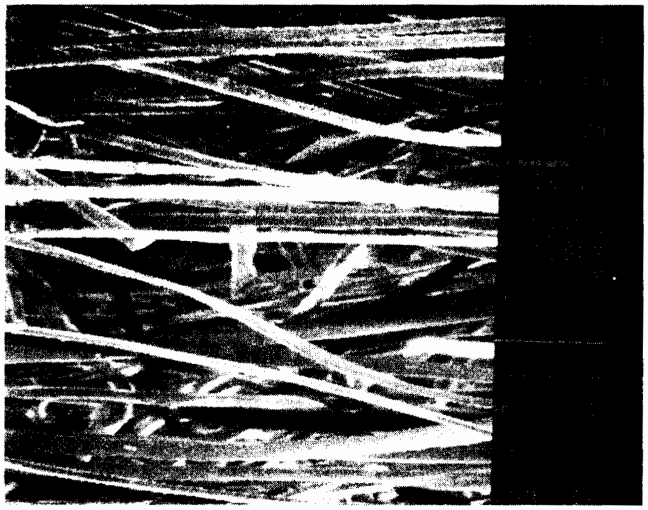

FIG. 6. Filaments of GT5 Geotextile Oriented Parallel to the Direction of Shear after 1,000 mm of Shear Displacement in a Ring Shear Test

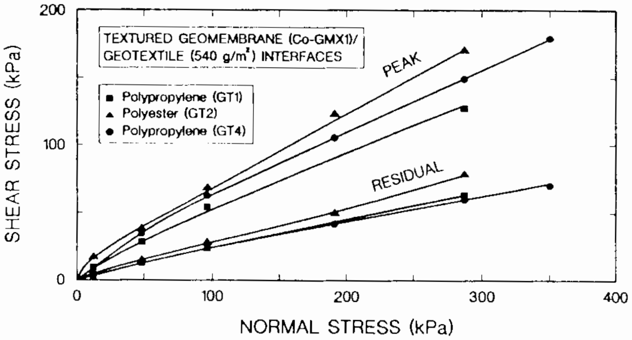

FIG. 7. Effect of Nonwoven Geotextile Manufacturing and Polymer Composition on Interface Shear Resistance

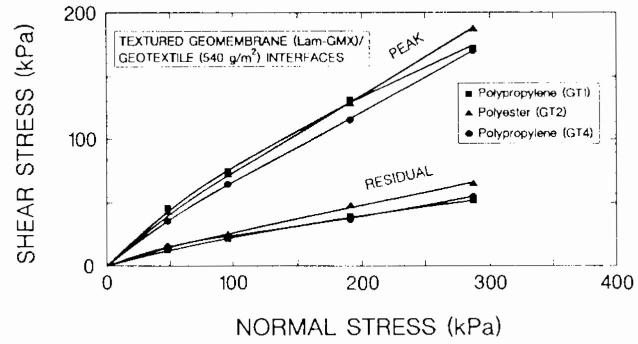

FIG. 8. Effect of Textured Geomembrane Manufacturing and Geotextile Polymer Composition on Interface Shear Resistance

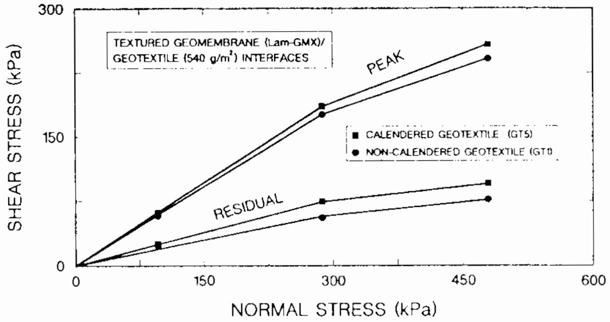

FIG. 9. Effect of Nonwoven Geotextile Calendering on Interface Shear Resistance

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 separameters 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-GMX1). The difference between the peak failure envelopes is not as pronounced with the laminated textured geomembrane as with the coextruded geomembrane (Co-GMX1). 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 geomembrane 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-GMX/GT5) interfaces was also investigated. The same geomembrane 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 post-peak strength loss observed is primarily caused by the tearing or pulling out of the geotextile filaments and orienting the filaments parallel to the direction of shear. Figs. 5 and 6 illustrate the calendered geotextile (GT5) before and after shear, 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 of asperities 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 angle is apparent for the noncalendered geotextile. This decrease in friction angle is also attributed primarily to the removal of texturing 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-GMX1/GT3 and Co-GMX1/GT4) interfaces. The mass per unit area of the nonwoven geotextiles was varied from 270 g/m² (GT3) to 540 g/m² (GT4) while the same textured geomembrane (Co-GMX1) was used for both interfaces. The geotextiles are produced by the same manufacturer and utilize the same polymer composition, fiber 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/m^2 geotextile tends to yield a higher peak failure envelope than the 540 g/m^2 geotextile. This suggests that a 270 g/m^2 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 filaments being more easily pulled out or torn from the 540 g/m^2 geotextile than the 270 g/m^2 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 and/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 processes on textured geomembrane/nonwoven geotextile interface strengths. For example, the peak secant friction angle at a normal stress of approximately 290 kPa for the Co-GMX1/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 texturing 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 secant friction angle at a normal stress of approximately 290 kPa for the Co-GMX1/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 relationships for a textured geomembrane/drainage geocomposite (Co-GMX1/GN) interface. The drainage geocomposite consists of two 270 g/m^2 polyester nonwoven continuous single filament needle punched geotextiles heat-bonded to a medium density polyethylene geonet. 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 resistance.

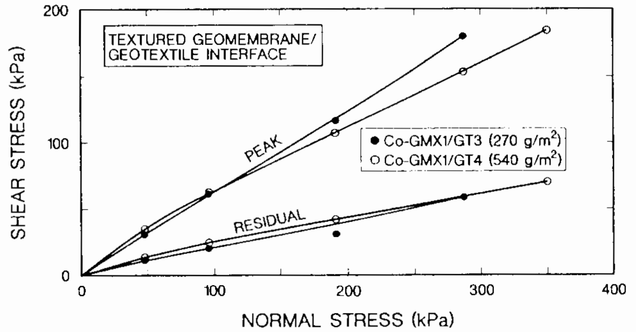

FIG. 10. Effect of Nonwoven Geotextile Mass Per Unit Area on Interface Shear Resistance

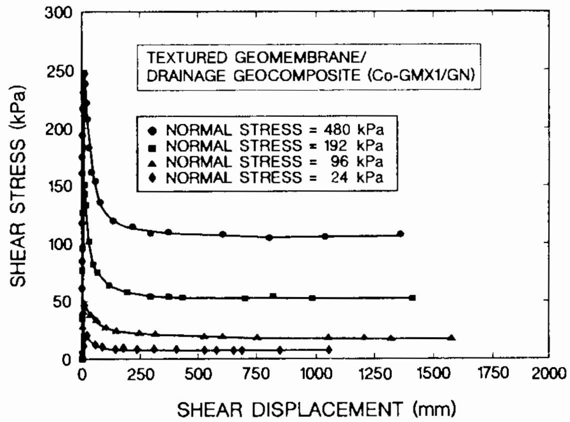

FIG. 11. Typical Ring Shear Test Results for Textured Geomembrane/Drainage Geocomposite Interface

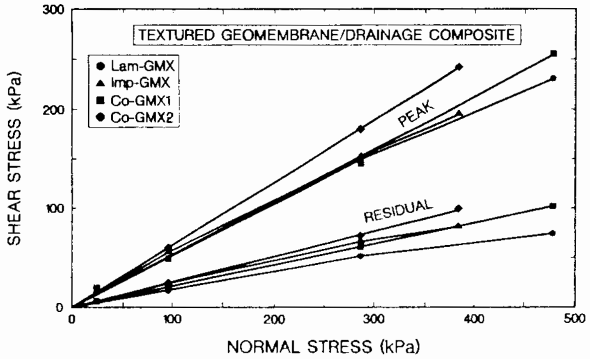

FIG. 12. Failure Envelopes for Textured Geomembrane/Drainage Geocomposite Interface

Fig. 12 presents the failure envelopes for the textured geomembrane/drainage geocomposite (Co-GMX1/GN) interface test results shown in Fig. 11. It can be seen that the average peak and residual secant friction angles are 30° and 13°, respectively. These values of secant friction angle are similar to those measured for similar textured geomembrane/nonwoven geotextile interfaces (e.g., Fig. 4). This implies that the presence of the geonet 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 geonet in the drainage geocomposite can embed in the geomembrane. This was also observed by Stark and Poeppel (1994) for a geomembrane/geonet interface. The embedment occurred at a lower normal stress of 350–400 kPa because there was no geotextile between the geonet and geomembrane.

It should also be noted that failure occurred through the geotextile in all of the tests on the textured geomembrane/drainage geocomposite. In summary, the failure mechanism 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-GMX1/GN, Co-GMX2/GN, Lam-GMX/GN, and Imp-GMX/GN). It can be seen that the Co-GMX2 textured geomembrane yielded the highest peak failure envelope. The Co-GMX1, Lam-GMX, and Imp-GMX textured geomembranes 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-GMX1 and Co-GMX2 geomembrane texturing during shearing. However, the Lam-GMX and Imp-GMX geomembranes experienced delamination at normal stresses greater than 285 kPa with a drainage geocomposite. This resulted in the Lam-GMX and Imp-GMX 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 texturing 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 shear.

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 lamination and impingement techniques. Therefore, site-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 delivered geomembraneand 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, polishing 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/m^2 appears to result in higher peak interface strengths than a 540 g/m^2 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 strengths if the texturing is not damaged or removed from 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 to or removal of the texturing from a laminated or impingement geomembrane at normal stresses lower than would be required for texture damage or removal with only a nonwoven geotextile.

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APPENDIX. REFERENCES

Bromhead, E. N. (1979). "A simple ring shear apparatus." *Ground Engrg.*, 12(5), 40–44.

Byrne, R. J., Kendall, J., and Brown, S. (1992). "Cause and mechanism of failure, Kettleman Hills Landfill B-19, unit IA." *Proc., ASCE Spec. Conf. on Perf. and Stability of Slopes and Embankments—II*, 2, ASCE, New York, N.Y., 1188–1215.

"Determining the coefficient of soil and geosynthetic or geosynthetic and geosynthetic friction by the direct shear method." (1993). *ASTM standards on geosynthetics*, D5321, ASTM, Philadelphia, Pa., 110–114.

Koerner, R. M. (1994). *Designing with geosynthetics*, 3rd Ed., Prentice-Hall, Englewood Cliffs, N.J.

"Quality assurance and quality control for waste containment facilities." (1993). *Tech. Guidance Document, EPA/600/R-93/182*, U.S. Environmental Protection Agency, Washington, D.C.

Stark, T. D., and Poeppel, A. R. (1994). "Landfill liner interface strengths from torsional-ring-shear tests." *J. Geotech. Engrg.*, ASCE, 120(3), 597–615.