THE DESIGN OF A REDUCED STRENGTH LINER INTERFACE FOR SEISMIC LOADING CONDITIONS

The potential cost for damage to a landfill liner system subjected to large deformations from earthquakes is significant. The design of an engineered low-strength interface above the composite-geosynthetic landfill liner can minimize the potential for damage from seismically-induced deformations. This paper reports results of laboratory investigations to develop an engineered reduced peak strength interface for design of a solid waste landfill liner containment system. The composite liner system to be protected consisted of a double-nonwoven, needlepunch reinforced GCL placed on a native subgrade and overlain by a 1.5 mm HDPE geomembrane.

A reduced peak strength interface forces any potential seismically-induced deformation to occur above, rather than within, the liner system. Residual strength of this interface must also be great enough to limit deformation of slopes. The design approach consisted of testing combinations of materials to achieve an optimum combination of relatively low peak and residual shear strengths. Results show that: 1) sand/smooth geomembrane and textured geomembrane/woven geotextile interfaces represent suitable material combinations for a reduced peak strength interface; 2) sand particle shape greatly influences strength behavior; and 3) contact conditions control shear behavior of sand/geomembrane interfaces.

Reference

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THE DESIGN OF A REDUCED STRENGTH LANDFILL LINER INTERFACE FOR SEISMIC LOADING CONDITIONS

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ABSTRACT

The design of Subtitle D containment systems for landfills located in seismically active areas can be complicated by factors such as potential earthquake-induced deformations and the inherent strength limitations of many liner system types. This paper reports results of laboratory investigations to develop an engineered reduced peak strength interface for design of a solid waste landfill containment liner system. A reduced peak strength interface forces any potential seismically-induced deformation to occur above, rather than within, the liner system. Residual strength of this interface must also be great enough to limit deformation of slopes. The design approach consisted of testing combinations of materials to achieve an optimum combination of relatively low peak and high residual shear strengths. Results show that: 1) sand/smooth geomembrane and textured geomembrane/woven geotextile interfaces represent suitable material combinations for a reduced peak strength interface; 2) sand particle shape greatly influences strength behavior; and, 3) contact conditions control shear behavior of sand/geomembrane interfaces.

INTRODUCTION

The potential for damage to a landfill liner system subjected to large deformations by earthquake shaking is significant. Tensile stresses imposed on components of the liner could cause tearing or severe straining of the geosynthetics. Post-earthquake repair of a damaged liner is expensive and disrupts filling operations. As described by Richardson et al. (1998), design of an engineered low strength interface above the composite-geosynthetic landfill liner can minimize the potential for damage from seismically-induced displacements. A reduced peak strength (RPS) interface is placed above the composite liner system to be protected. This "sacrificial" interface has lower peak strength than other interfaces and fails first as deformation-induced shear stresses increase. This interface must also have a relatively small degree of post-peak strain softening to prevent excessive deformation of refuse slopes.

This paper reports results of laboratory investigations to design the RPS interface for a landfill cell in California that will protect the composite liner system from forces induced by horizontal acceleration of an interim unbuttressed fill slope of up to 0.46g from a magnitude 7.2 earthquake. The fill slope will be unbuttressed for a period of four to five years. At the critical design section the cell has 3H:1V slopes, and a 35 m long by 67 m wide floor. The final refuse-fill height over the lined cell will be approximately 27 m.

DESIGN CRITERIA/INTERFACE ALTERNATIVES

The design concept developed for this landfill containment system is based on incorporating a RPS interface above the composite geosynthetic liner system. The composite liner system to be protected consisted of a double nonwoven, needle-punch reinforced GCL placed on prepared native subgrade, overlain by a 1.5 mm high density polyethylene (HDPE) geomembrane. The internal and interfacial shear strengths of the composite liner are designed sufficiently strong to withstand expected shear forces, as discussed below.

To provide for adequate internal shear strength of the GCL, it was required that the GCL exhibit a minimum peel strength of 111 N (25 pounds). The peak internal shear strength GCL used was 30 degrees. Fox et al. (1998) showed that needle-punched GCLs with high peel strengths also possess high peak internal shear strengths. Gilbert et al. (1996) and Fox et al. (1998) demonstrated that GCL peak shear strength failure envelopes are non-linear. However, Richardson (1997) found peak internal shear strength failure envelopes for a needle-punched, reinforced GCL can remain approximately linear over stress ranges up to and exceeding about 478 kPa (10,000 psf).

The GCL was also selected to optimize the value of peak interface shear strength between the GCL and the overlying geomembrane. Project specifications required that the bottom side of the overlying HDPE geomembrane be textured. Studies by Hewitt et al. (1997), Daniel et al. (1998) and Eid and Stark (1997) suggest that peak interface friction angles of non-woven needle punched reinforced GCLs are higher than woven needle punch reinforced or a stitch-bonded woven/nonwoven GCLs when tested against a textured geomembrane

Preliminary static stability analyses of the new cell configuration indicated that a peak shear strength of at least 18 degrees would be required for the RPS interface within the containment system. This analysis was based on use of the GCL and assumed geomembrane texturing characteristics. In order to limit potential seismically-induced displacements of an unbuttressed refuse slope, a post-peak interface friction angle of greater than 14 degrees was required for the RPS interface. This post-peak friction angle is higher than the range of residual interface friction angles typically reported for more conventional geosynthetic interfaces used as "sacrificial" interfaces above liners.

Two interface systems were evaluated for their suitability as the RPS interface. Each system incorporates a layer of sand as the leachate collection/drainage layer beneath the waste. The leachate collection layer is located either as part of, or immediately above interface. The trial interface systems consisted of:

- A 0.3 m thick drainage layer composed of subrounded to rounded sand placed directly on a HDPE geomembrane (smooth upper surface); and,

- A woven geotextile placed above the HDPE geomembrane (textured upper surface). The sand-drainage layer to be placed on top of the geotextile had no roundness requirements for the individual sand grains.

MATERIAL INTERACTIONS

Sand/Smooth-HDPE Geomembrane Interfaces. Recent studies of interface friction mechanisms for a sand/smooth geomembrane interface provide rational basis for evaluating laboratory test data. Figure 1a shows the variation in peak secant friction coefficient resulting from tests on Ottawa 20/30 sand and smooth geomembrane (Dove and Frost, 1999). It may be inferred that the failure envelope for this material combination is non-linear. At normal stresses below 50 kPa, the peak secant friction coefficient decreases with increasing normal stress. The shear mechanism up to about 50 kPa is grain sliding with contact conditions between fully elastic and fully plastic. The decrease in friction coefficient is caused by the small rate of increase in real contact with increasing applied normal stress. The real contact area governs the interface shear force, therefore by definition, the friction coefficient must decrease and the failure envelope is concave downward.

Above a normal stress of about 50 kPa for Ottawa 20/30 sand, the plowing mechanism becomes important. Plowing has been referred to as "scouring" or "polishing" in previous studies. Plowing results when the normal stress reaches a level where the sand grains plastically indent the geomembrane surface. The grains remove the polymer as shear stress is applied thus requiring greater shear force to reach peak state. This increase in shear strength is proportional to normal stress resulting in a concave up failure envelope. The consequence of plowing is that the friction coefficient increases over sliding alone and the geomembrane is permanently scratched or grooved, depending on the shape of the soil particle. The increase in smooth geomembrane surface roughness after shear can be related to the degree of plowing.

Dove and Frost (1999) indicate that particle shape has an important influence on the peak and residual interface friction angles and on which mechanism controls friction behavior. Figure 1b shows that highly angular blasting sand exhibits plowing at all normal stresses with peak interface friction values of up to 28 degrees. However, spherical glass beads exhibited peak friction values of 11 degrees in a sliding shear mode. Subrounded sands exhibited intermediate friction angles of about 21 degrees. Based on the information obtained from these tests, it was inferred that natural sands with subrounded to rounded grains might exhibit favorable peak and residual interface friction behavior for designing the weak interface layer.

Woven Geotextile vs. Textured HDPE Geomembrane Interfaces. Little data could be found by the authors regarding either the peak or residual interface behavior between a woven geotextile and the textured surface of an HDPE geomembrane. However, GRI (1998) data included test results from a single interface direct shear test between a woven geotextile and a smooth HDPE geomembrane. This combination produced a peak interface friction angle of 10 degrees. The interface between a woven geotextile and a textured HDPE geomembrane was selected for further testing for the following reasons:

- A preliminary review of test results from similar projects indicated that the range of peak friction angles expected for the interface between a typical nonwoven geotextile and a textured HDPE geomembrane (25 to 30 degrees) would be too high to permit a nonwoven geotextile to be used as a RPS interface above the liner system;

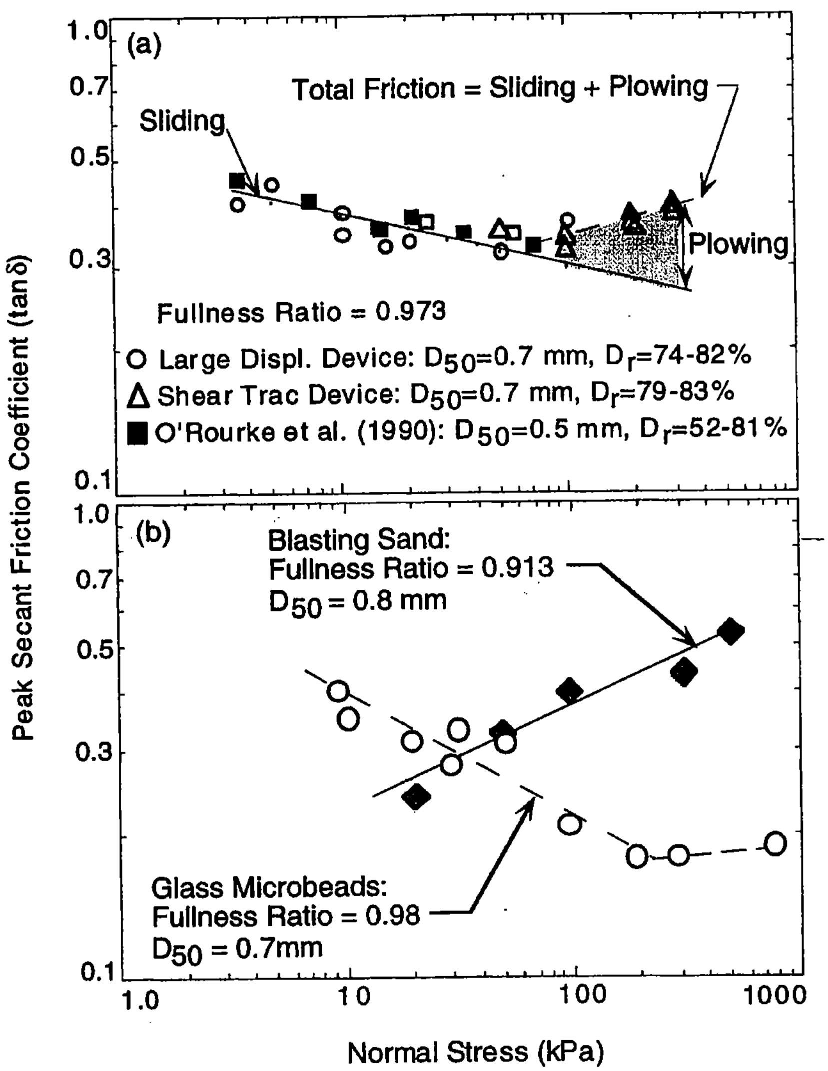

Figure 1. Behavior of Sand/Smooth Geomembrane Interfaces: (a) Ottawa 20/30 Sand; (b) Glass Microbeads and Blasting Sand (after Dove and Frost, 1999)

- A similar review of other test data indicated that the expected peak and residual friction angles for the interface between a typical nonwoven geotextile and a smooth-HDPE geomembrane (typically 9-13 degrees) would be too low to satisfy the project's minimum stability needs; and

- No other combination of geosynthetic interfaces previously known to have been tested (such as a geonet vs. nonwoven geotextile or nonwoven geotextile vs. double-sided geocomposite) appeared to exhibit the appropriate combination of moderately high peak- and relatively high residual-friction angles for this project.

EXPERIMENTAL STUDIES

Sand/Smooth HDPE Geomembrane Interface. A series of three point interface direct shear tests were conducted to evaluate the peak and residual interface behavior of four candidate sands when placed in contact with the smooth HDPE geomembrane surface. Interface tests were initially performed at a testing laboratory in California using a commercially available 300 mm square shear box at normal loads of 47.9 kPa (1,000 psf), 143.7 kPa (3,000 psf), and 287.4 kPa (6,000 psf). Index data for the sands are given in Table 1. The Fullness Ratio (FR) is a measure of grain shape that was determined using a microscope coupled to an image analyzer (D'Andria 1996). For comparison, a FR value of 1.0 is a perfectly round sphere; FR decreases with increasing angularity. One drawback to FR is that it is somewhat dependent on the particle D_{50} and grain size distribution. For two equally angular particles of different size the smaller particle would have the larger FR since the magnification would effectively be lower and would appear more spherical. The sands used herein have relatively small variation in D_{50} thus FR gives a general index of grain shape. The differences in FR would be greatest for angular particles of different sizes with differences decreasing with increasing roundness.

Table 1. Soil Index Data

Sand	D_{50} (mm)	$\gamma_{d\,max}$, kN/m^3 (pcf)	Opt. Moisture (%)	Cu	Fullness Ratio
Arroyo Seco	0.70	16.9 (108.1)	5.3	4.3	0.889
Kaiser-Felton Plant	0.62	18.0 (114.7)	5.7	4.4	0.871
Granite Rock-Quail Hollow	0.64	16.9 (108.1)	5.3	4.4	0.912
RMC-Lapis Plant	0.50	16.0 (102.1)	5.4	2.1	0.953

The sands were placed in the shear box at 90 percent of maximum dry density at optimum moisture content using ASTM Method D 698. The geomembrane was stapled to the back of the shear box in order to constrain the geomembrane and force the failure to occur along a uniform, smooth geomembrane surface. The shearing rate used in each test was 1 mm per minute (0.04 inches per minute). From top to bottom, the test section consisted of: a layer of the selected sand; 60 mil smooth/textured HDPE geomembrane (smooth side against the sand); and a concrete board used as the substrate.

A system performance test using RMC Lonestar-fill sand was conducted at a second laboratory at the same normal loads using a 300 mm square shear box. In this test series, the sand was compacted to 75% percent of maximum dry density at optimum moisture content (ASTM Method D 698). The entire liner system consisting of, a pre-hydrated specimen of double-nonwoven, needle punched GCL, an overlying 60-mil smooth/textured HDPE geomembrane, and an overlying layer of the test sand were included in the shear box test specimen assemblage. The geomembrane was left in a free condition (i.e., the geomembrane was not attached to the shear box in any way). The sand was first soaked for about 30 minutes under no load. Then the entire section was consolidated for 24 hours under each pressure and the entire section was sheared immediately thereafter at 1 mm per minute (0.04 inches per minute).

Woven Geotextile/Textured HDPE Geomembrane Interface. Two woven geotextiles were chosen for laboratory testing: Geotex 315 ST, a polypropylene slit-tape-woven geotextile manufactured by Synthetic Industries, Chattanooga, Tennessee; and SRW 300, an orthogonal weave, polyester/polypropylene woven geotextile manufactured by TC Mirafi, Pendergrass, Georgia. Each geotextile had a fabric weight of approximately 200 g/m^2. A 300 mm square shear box designed and constructed by one of the authors was used. Tests were performed at a shearing rate of 1 mm per minute.

A series of three point direct shear tests were performed using the 315 ST and the SRW 300 geotextiles against the textured side of a double-sided textured HDPE geomembrane (Geomembrane No. 1). The roughness of the geomembrane was not assessed, however similar specimens of Geomembrane No. 1 have a typical average roughness, R_a, of 0.055 mm (Dove and Harpring, 1999).

To subjectively assess the influence of texturing on interface strength, additional single-point tests were conducted on both woven geotextiles using a HDPE geomembrane (Geomembrane No. 2) at a normal stress of 287.4 kPa (6,000 psf). Similar specimens of Geomembrane No. 2 have a typical average roughness, R_a, of 0.087 mm (Dove and Harpring, 1999).

A system performance test was conducted on the entire liner system to examine shear behavior of the composite section. The base layer consisted of a pre-hydrated specimen of double nonwoven, needle-punched GCL overlain by a 1.5 mm thick smooth/textured HDPE geomembrane.

In all of these woven geotextile/textured geomembrane interface test assemblages, a 50 mm thick layer of poorly graded fine-to-medium grained, angular to subangular sand was included as a superstrate layer over the geotextile. This material was used to simulate expected as-built field conditions, which would include a minimum 0.3 m thick sand drainage layer placed directly over the HDPE geomembrane. During each test, the geomembrane was attached to the back of the lower shear box, and the geotextile was left in a free condition (unattached to the shear box).

RESULTS

Sand/Smooth HDPE Geomembrane Interface Shear Strengths. Strength envelopes from the sand/smooth HDPE geomembrane interface testing are shown on Figure 2. Table 2 provides values of friction and adhesion determined by a conventional linear regression analysis of the data. This interpretation yields friction and "adhesion" values as the slope and intercept, respectively.

The RMC Lonestar fill sand exhibited the lowest peak friction coefficient of the candidate sand materials tested in the higher normal stress ranges. Therefore, this type of sand was found to be favorable for providing moderately low peak friction angles.

An interpretation of the test data using secant friction coefficients is shown on Figures 3 and 4. The secant friction coefficient is determined as the slope of a line connecting the origin of the strength diagram and each stress point. This interpretation permits evaluation of the changes in friction angle and shear mechanism with increasing normal stress. Figure 3 shows the logarithmic plot of peak secant friction coefficient versus normal stress of Figure 1a along with the data collected from the four sands tested in this study. For comparison, the angular blasting sand used by Dove and Frost (1999) from Figure 1b is included.

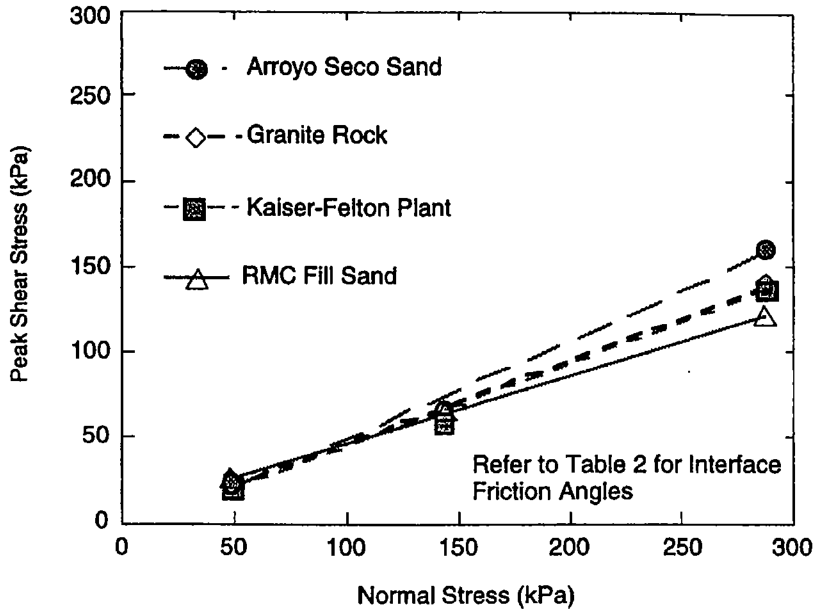

Figure 2. Peak Strength Envelopes from Sand/Smooth Geomembrane Tests

Table 2. - Interface Testing Results For Four Sands Vs. Smooth HDPE Geomembrane Interface (Conventional Interpretation)

Sand/Smooth Geomembrane	Peak Friction Angle (degrees)	Peak "Adhesion" (kPa)	Residual Friction Angle (degrees)
Arroyo Seco	28	0	25
Kaiser-Felton Plant	25	0	19
Granite Rock (Quail Hollow)	26	0	18
RMC Lonestar Fill Sand	22	6.7	14
RMC Lonestar Fill Sand (System test)	21	4.5	20

The candidate sands have FR values ranging from approximately 0.871 to 0.953. Even though the angular blasting sand had FR of 0.913, it is visually more angular than the candidate materials. This discrepancy is probably due to differences in effective magnification with varying D_{50}, as discussed earlier. The FR and the D_{50} of each sand given in Table 1 are also shown on Figure 3.

The friction coefficient of the materials tested in this study exhibit behavior similar to the Ottawa 20/30 sand, as shown in Figure 1a. The decreasing friction coefficient is due to unequal changes in contact area with increasing normal stress as discussed earlier. The slope of a line

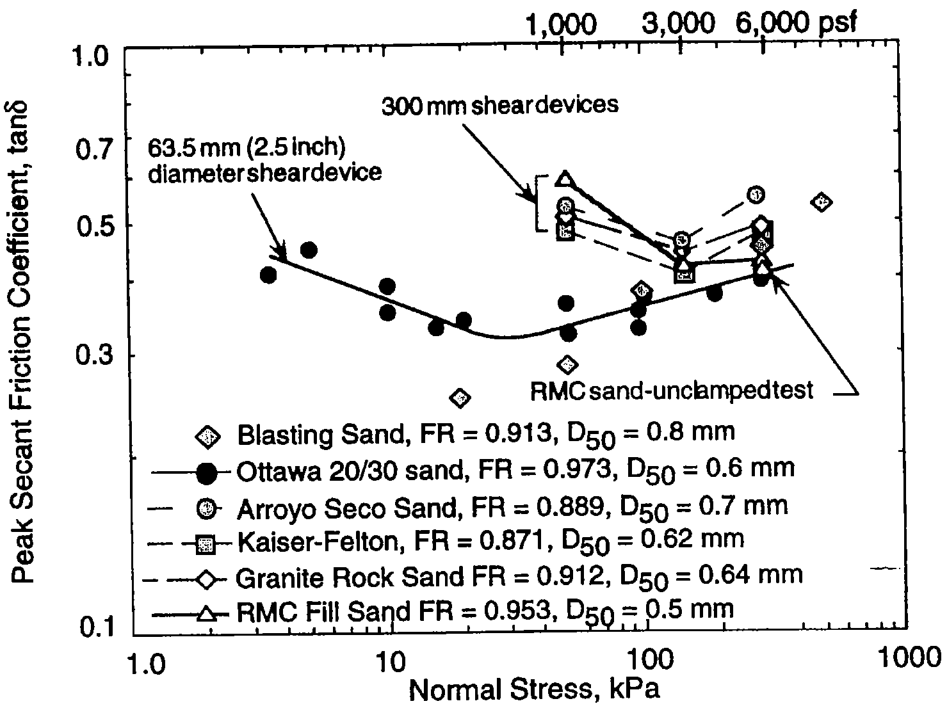

Figure 3. Behavior of Sand/Smooth HDPE Geomembrane Interfaces

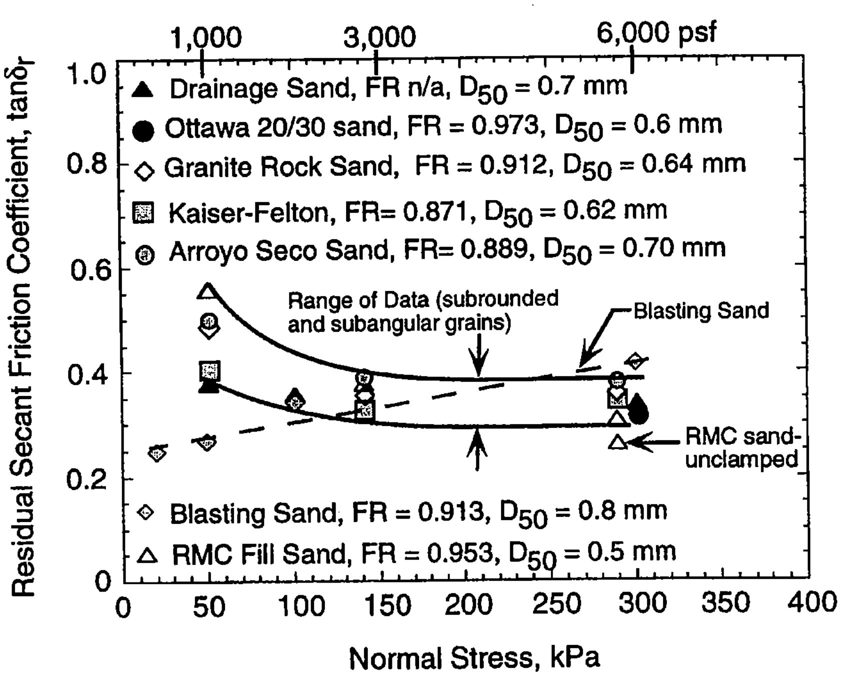

Figure 4. Secant Residual Friction Coefficients

through the data plotted on a logarithmic failure envelope is referred to as the "load index", n. (Dove and Frost, 1999).

The slopes of the sliding portions of the curves shown on Figure 3 is n-1 and ranges from -0.16 to-0.13 for Arroyo Seco, Kaiser, and Granite Rock sands, respectively. The curve for Ottawa 20/30 sand has a slope of -0.12. These slopes indicate that contact conditions are between fully elastic and fully plastic. In contrast, the sliding portion of the RMC fill sand curve of Figure 3 has a slope of -0.32. This means the load index equals 0.68 which corresponds to Hertz theory for elastic spheres. Thus the RMC sand contact conditions below 143.7 kPa are fully elastic, which would be expected with a more spherical particle. Except for the RMC Lonestar fill sand, the materials tested in this study exhibit plowing at higher normal stresses as shown on Figure 3.

Plowing requires additional energy input over that needed for adhesive sliding and results in a higher friction coefficient. Factors controlling the location of the sliding to plowing inflection point are being investigated but are likely related to polymer surficial shear strength and grain contact area. Plowing is discussed in more detail later in this paper.

The RMC fill sand does not exhibit plowing. The nearly constant friction coefficient between 143.7 kPa (3,000 psf) and 287.4 kPa (6,000 psf) is likely due to insufficient particle roughness to tear the polymer. The constant friction coefficient is typical of "plastic" contact conditions where the increase in contact area is directly proportional to normal load. The coefficient of friction in plastic contact will remain constant as long as plowing does not occur.

Figure 4 shows an arithmetic plot of the residual secant friction coefficient vs. normal stress for the sand/smooth HDPE geomembrane interfaces. It shows that grain shape has significant influence on residual friction. For subangular to subrounded sands, residual strengths decrease with increasing normal stress to a fairly narrow range of values at approximately 287.3 kPa. Greater residual strengths are observed at lower normal stresses analogous to peak-state behavior. Behavior of angular-blasting sand is shown for contrast. As normal stress increases, the residual-friction coefficient increases.

The value in examining the system behavior in plots such as Figures 3 and 4 is that the shear mechanism operating for a given particle, geomembrane and normal stress can be determined. Knowledge of the shear mechanism allows the engineer to better anticipate and model expected behavior of the interfaces. Greater benefit is achieved from being able to engineer the materials that produce a desired behavior.

The test results of Figures 3 and 4 indicate that a sand/smooth HDPE geomembrane reduced peak strength interface will likely be limited to sand particles that exhibit a relatively high FR and low angularity. The acceptability of a specific sand/smooth geomembrane interface also may depend on other factors such as geomembrane surface hardness, geomembrane polymer characteristics, field durability of sand grains, and/or the grain-size distribution of the sand particles used. This possibility requires additional interface testing of subrounded to rounded granular materials with different sizes (e.g., gravel). Because of variability in geosynthetic materials and the interface's sensitivity to material surfaces, specific testing should be performed when construction materials are selected. With the ability to quantify and control geomembrane roughness (see Dove and Harpring, 1999), the choice of geomembrane could be made rationally.

Woven-Geotextile/Textured-HDPE-Geomembrane Interface Shear Strengths. Interface-testing results for each geotextile with two differently textured HDPE geomembranes are summarized in Table 3. Friction angles for three-point tests were determined by regression analysis. Friction angles for the single-point tests were obtained by connecting a line from the stress point at 287.3 kPa (6,000 psf) to the plot origin.

Three-point tests on the 315 ST woven slit tape geotextile and Geomembrane No. 1 (less textured) interface resulted in peak and residual friction angle values of 19 and 17 degrees, respectively. When used with the overlying sand drainage layer, these data indicate this geotextile meets the range of friction angles for the engineered weak interface above the GCL-based composite liner system. This material combination could also be used for similar design applications under similar loading conditions.

Table 3 – Test Results-Woven Geotextile/Textured HDPE Geomembrane Interfaces

Woven Geotextile/Textured HDPE Geomembrane	Peak Friction Angle (degrees)	Peak "Adhesion" (kPa)	Residual Friction Angle (degrees)
315 ST slit-tape (3-point test-Gm. No. 1)	19	0	17
315 ST slit-tape (1-point test-Gm. No. 2)	21	0	18
SRW 300 (3-point test- Gm. No. 1)	21	10.8	19
SRW 300 (1-point test- Gm No. 2)	27	0	24

Results of the single-point interface testing conducted using the 315 ST slit-tape geotextile on the highly textured Geomembrane No. 2 gave 21 degree peak and 18 degree residual friction angles, respectively. This suggests this geotextile might be suitable for use with a variety of textured HDPE geomembranes exhibiting widely different degrees of texturing. Additional testing appears to be warranted to determine the peak and residual interface friction behavior of this type of woven geotextile when placed in contact with different textured HDPE geomembranes and using a variety of granular materials having varying grain shapes and sizes and loads as the superstrate layer.

The peak interface friction angle 21 degrees for the three-point system testing on the SRW 300 polyester/polypropylene woven geotextile and Geomembrane No. 1 interface is sufficiently high to meet stability requirements. It is also sufficiently low to permit underlying liner system components to be designed with stronger interface or internal shear strengths. The 19 degree residual friction angle determined for this interface also provides additional resistance to potential seismically induced deformation that might occur along this interface.

The 27 degree peak friction angle and 24 degree residual friction angle of the single point interface test using SRW 300 polyester/polypropylene woven geotextile and Geomembrane No. 2 suggest that this geotextile is not suitable for use with more aggressively textured HDPE geomembranes for the range of normal stresses studied in this investigation. This is because it may be difficult to design all elements of the liner system to be stronger than this interface. To assess peak and residual interface friction behavior, additional interface testing of this type of woven geotextile in contact with different lightly to moderately textured HDPE geomembranes, is warranted for this application.

It was observed after testing that the finer-grained sand particles penetrated the more loosely woven polyester/polypropylene geotextile material to a greater degree when Geomembrane No. 1 (less textured) was tested than when Geomembrane No 2 (more textured) was used instead. It is possible that the greater abundance of granular particles along the surface of the more textured geomembrane could, to some extent, have affected the resulting interface friction angle values. Additional interface testing of this geotextile using different geomembrane textures and coarser and/or finer grained granular materials is an area for additional study.

System Performance Test. Results of system interface direct shear tests performed using the RMC Lonestar Fill sand/smooth HDPE geomembrane interface are shown on Figure 5. The values of peak interface friction angle obtained for the sand/smooth geomembrane interface fell within the range of values sought for the design. Specifically, the peak interface friction value was sufficiently high to meet stability requirements but also sufficiently low to permit all underlying liner-system components to be designed with stronger interface or internal shear strength properties. Therefore, this value was compatible with a design that forces any potential seismically-induced deformation to occur above, rather than within, the liner system. The relatively high residual interface friction value of 20 degrees helps limit the magnitude of any seismically induced deflections.

DISCUSSION

Evaluation of Plowing. An investigation was made to examine the plowing component of shear resistance. An index of surface roughness was determined perpendicular to the scratches remaining in the geomembrane samples after shear. The scratches begin forming at peak state and can be related to shear strength. Sets of smooth geomembranes used for the sand/geomembrane interface tests were profiled using a Taylor-Hobson Talysurf stylus profilometer. The profiles were 40 mm in length and were filtered to eliminate waviness. The Average Roughness parameter, R_a, was used as the roughness index since it is a standard measure of average profile height. Average spatial and geometric parameters for characterizing geomembranes are more fully discussed in Dove and Harpring (1999).

The average value of R_a for virgin geomembrane surface is 1.7 μm (microns). Increasing normal stress increases the depth and number of surface scratches thereby increasing the value of average roughness, R_a. It may be seen on Figure 6a that angular sands produce the greatest surface roughness. The less angular RMC Lonestar sand causes smaller increase in surface roughness. The data shown on Figure 6b are changes in R_a from the virgin state. From a normal stress of 47.9 kPa (1,000 psf) to 147.3 kPa (3,000 psf) the increase in R_a for the angular sands ranges from 0.3 μm to 0.8 μm. However, from 147.3 kPa (3,000 psf) to 287.3kPa (6,000 psf) the increase for these sands ranges from 1 μm to about 1.5 μm. In contrast, the RMC sand produces only about 0.6 μm total change in R_a, illustrating the influence of grain shape.

By referring to Figures 3 and 4, it may be seen that the degree of increase in surface roughness is related to the secant friction coefficients. Peak friction in sliding was discussed earlier. Peak friction in plowing is due to initiation of grooves in the geomembrane with higher normal stresses causing deeper penetration and higher initial resistance to displacement.

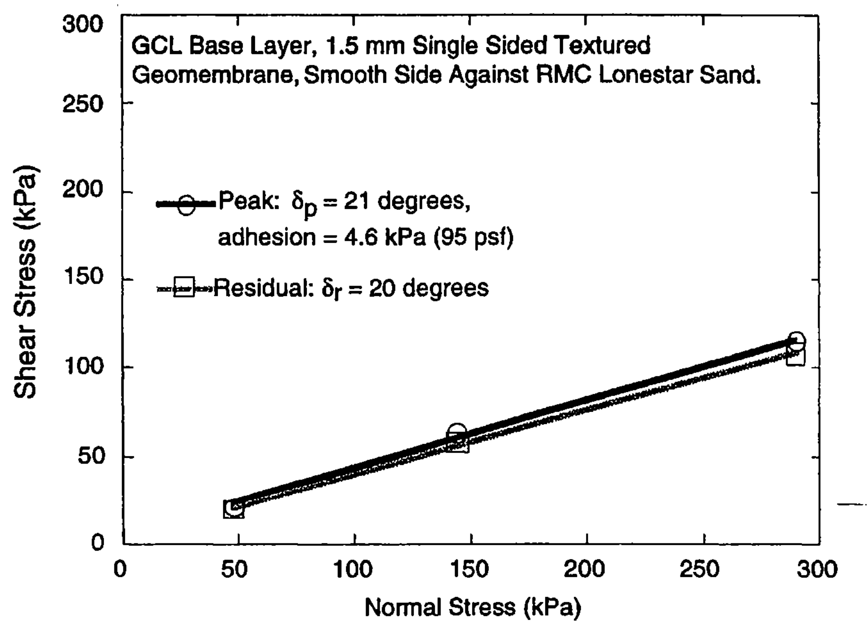

Figure 5. System Performance Test Results

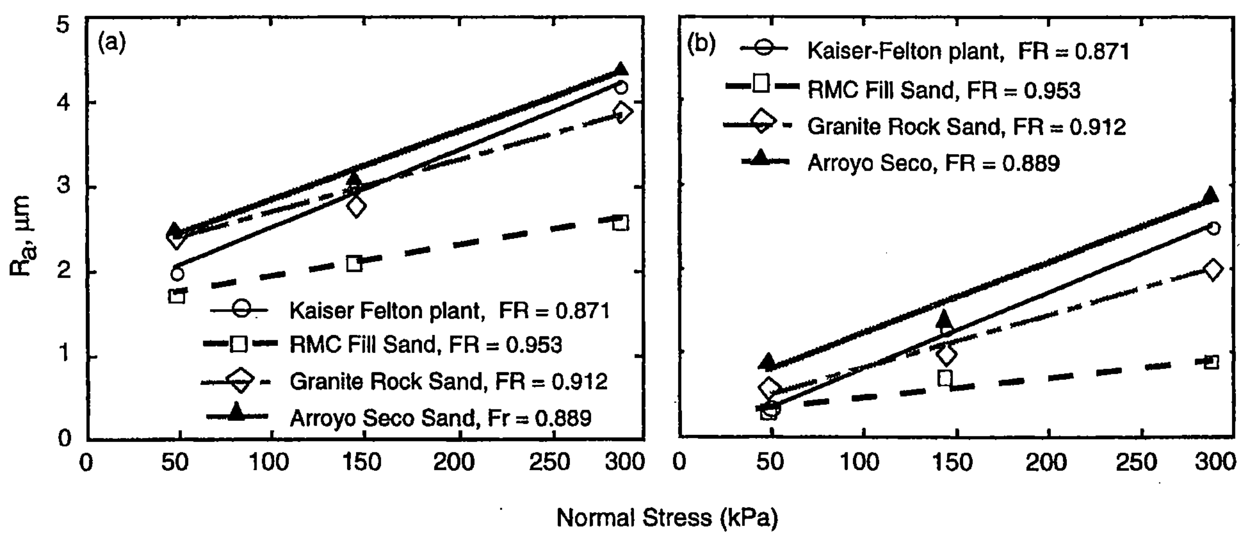

Figure 6. Large Displacement Roughness: (a) After Shear; (b) Change from Initial State

The residual friction coefficient may be controlled by attainment of equilibrium scratch geometry at relatively small shear displacements, contact area changes, and filling of scratches with finer particles. Equilibrium scratch geometry is reached as the vertical contact stresses from the particles are balanced by elastic resistance of the polymer. Once equilibrium scratches are initiated at peak state by leading sand grains, trailing sand grains in the same path do not shear through the polymer but travel in or closely adjacent to the pre-formed path. Thus post-peak strain softening is pronounced when shear resistance rapidly decreases to a steady value when grooves meet and overlap as displacement increases. The steady state value is determined by the shear strength of the geomembrane within the upper few microns of the surface. This indicates that the most important variable determining system shear strength in the plowing mode is the shear strength of the softer material itself. The cause of the decreasing residual friction with increasing normal stress shown on Figure 4 is not known but is possibly related to variable contact area or test procedures. The plowing process is not fully understood and is the subject of current research.

Inter-laboratory Variations. Differences in peak interface friction and residual interface friction angles of 1 degree and 6 degrees, respectively were observed for the RMC Lonestar fill sand/smooth geomembrane interface between the two testing laboratories. The minor difference in reported peak values is considered to be within the expected range of inter-laboratory variability. The reported difference in residual interface shear strength appeared to be large compared to the typical range of inter-laboratory differences.

Possible reasons include: differences in the height of the gap maintained within the shear box during the interface testing, differences in the type of loading devices used or other apparatus-related factors, and/or differences in testing approaches used by the two laboratories. A larger gap permits a larger amount of sand to extrude from the shear box, which could influence the magnitude and distribution of applied normal load during at large displacements. The first laboratory used a simplified three-layer test specimen test approach whereas the second laboratory used a system performance test approach with all containment system components incorporated. Additional comparative tests by different laboratories using the same test approach would help resolve the importance of the reported differences in peak and residual interface shear strength.

CONCLUSIONS

The following systems were found to be appropriate for a reduced peak strength interface above a composite liner incorporating a GCL at the range of normal loads used herein: (1) woven slit-tape polypropylene geotextile with textured HDPE geomembrane; (2) polyester/polypropylene woven geotextile with textured geomembrane; and, (3) subrounded to rounded sands placed in direct contact with smooth HDPE geomembranes.

An ability to characterize the earth and manufactured materials, and rationally evaluate laboratory data are critical for designing optimum interface strengths for landfill applications. Values of peak and residual interface friction angle for each of the two interfaces of this study allows for: (1) design of a deeper disposal cell cut than originally conceived in preliminary design; (2) a higher interim refuse fill height than previously contemplated; and, (3) the possibility for greater utilization of interim landfill airspace. When properly evaluated, use of either of these interfaces could be used for other waste disposal facilities.

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