UNSATURATED INTERFACE SHEAR STRENGTH PROPERTIES FOR NONWOVEN GEOTEXTILES

JOSHUA L. HANSON, UNIVERSITY OF TEXAS, AUSTIN
UNITED STATES OF AMERICA
ROBERT B. GILBERT, ASSOCIATE PROFESSOR, UNIVERSITY OF TEXAS, AUSTIN
UNITED STATES OF AMERICA
STEPHEN G. WRIGHT, BRUNSWICK-ABERNATHY REGENTS PROFESSOR, UNIVERSITY OF TEXAS, AUSTIN
UNITED STATES OF AMERICA
RICK S. THIEL, PRINCIPAL, THIEL ENGINEERING
UNITED STATES OF AMERICA

ABSTRACT

Nonwoven geotextiles are subjected predominantly to unsaturated conditions in typical field applications. However, nearly all of the work to date in researching and measuring engineering properties for nonwoven geotextiles has focused on water-saturated (wet) or air-saturated (dry) conditions. This paper focuses on the design and development of an apparatus to measure the interface shear strength for interfaces containing nonwoven geotextiles under unsaturated conditions. The major conclusions are that the new apparatus is capable of producing repeatable and valid test results, that conventional principles about the shear-strength behavior for unsaturated soils are applicable to the interface shear strength for unsaturated geosynthetics, and that a better understanding of unsaturated properties would benefit design, construction, and operation.

INTRODUCTION

Nonwoven geotextiles are used in many different applications to serve as filter layers, liquid transmission layers, and gas transmission layers. The geotextiles are subjected predominantly to unsaturated conditions in all of these applications, which range from pavement foundations to earth dams to landfill covers. Accordingly, it is important to understand the engineering properties of nonwoven geotextiles under unsaturated conditions. Specific engineering properties of interest include:

- Liquid transmissivity where the geotextile is serving as a drainage layer;
- Liquid permittivity where the geotextile is serving as a filter layer;
- Gas transmissivity the geotextile is serving as a gas transmission layer; and
- Interface shear strength where the geotextile could provide the critical slip surface in a slope.

As an example of the importance of engineering properties for a nonwoven geotextile under unsaturated conditions, consider the landfill cover slope application shown on Figure 1. In this application, the nonwoven geotextile is serving as a gas transmission layer to control gas migration. The properties of interest for this geotextile are gas transmissivity and the shear strength of the interface between the geotextile and the overlying geomembrane (e.g., Liu et al. 1997, Thiel 1998 and Thiel 1999). Under typical conditions, this geotextile will be unsaturated and contain liquid from both the underlying waste cover and from gas condensate as well as gas from the underlying waste. The presence of liquid in the geotextile will affect its ability to transmit gas. The presence of liquid and gas pressures in the geotextile will affect the shear strength of the interface with the geomembrane.

Nearly all of the work to date in researching and measuring engineering properties for nonwoven geotextiles has focused on water-saturated (wet) or air-saturated (dry) conditions. Because there is a lack of data on the transmissivity and shear strength for unsaturated nonwoven geotextiles, we are designing two devices to measure unsaturated properties. The first device is an air permeameter for measuring transmissivity of a nonwoven geotextile at different degrees of saturation, while the second device is designed to measure interface shear strength for interfaces with unsaturated geotextiles. This paper focuses on the interface shear device. It describes the design and development of the laboratory equipment and provides preliminary test results.

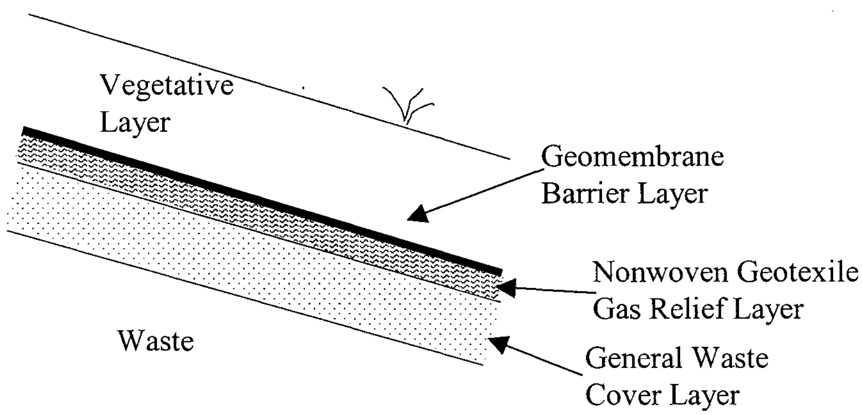

Figure 1. Example Landfill Cover Slope with Nonwoven Geotextile

THEORY

As a starting point, the current theories for the behavior of unsaturated soils will be adopted for nonwoven geotextiles. Fredlund and Rahardjo (1993) provide a comprehensive reference for the current theories in unsaturated soil mechanics. For the purposes of this paper, the relevant theories are summarized briefly.

Moisture Retention Functions

Moisture (or water) retention functions for a porous media describe the relationship between the degree of saturation or water content and the liquid and gas pressures. For soils these functions are also referred to as soil-water characteristic curves. Example functions for soils (Fredlund and Rahardjo 1993) are shown on Figure 2. Also shown on Figure 2 is a function for a nonwoven geotextile (Stormont et al. 1996), one of the few publications with data for the properties of unsaturated nonwoven geotextiles. The important features of these moisture retention functions are the following:

- The degrees of liquid or gas saturation are related to the difference between the liquid pressure (u_w) and the gas pressure (u_a), which is known as the matric potential (Ψ):

$$\Psi = u_w - u_a \tag{1}$$

In this equation we are defining the matric potential such that the potential is negative when there is suction in the soil. This is the convention used in soil physics (e.g. Fetter, 1993) and is consistent with the convention used in saturated soil mechanics where pressures in excess of atmospheric pressure are considered positive pore water pressures. However, the negative of Equation 1 ($-\Psi$) is commonly termed the "Matric suction" and used in the geotechnical literature (e.g. Fredlund and Rahardjo 1993). Positive matric suctions correspond to negative matric potentials and vice versa. The authors prefer the notation used in Equation 1 because of its consistency with what is used in soil mechanics for saturated soils.

- The moisture retention functions are hystertic with different curves resulting for the same porous material depending on whether it is being wetted (the matric potential is increasing and becoming less negative) or dried (the matric potential is decreasing and becoming more negative). Figure 2 illustrates this behavior for a nonwoven geotextile.
- The moisture retention functions depend on the size and shapes of pores, as shown for different soil types on Figure 2. Also, compression of a porous material will change the size and shape of pores and consequently change the moisture retention function. This feature is particularly important for nonwoven geotextiles due to their large compressibilities compared to typical soils. The moisture retention functions measured for nonwoven geotextiles by Stormont et al. (1996) correspond to negligible compressive stress, which is not the typical condition for most field applications.
- Moisture retention functions are affected by the interactions between the liquid and the porous media and the gas and the porous media. Since geotextile fibers are generally hydrophobic while soil particles are generally hydrophylic, the unsaturated behavior of geotextiles cannot directly be extrapolated from that for soils.

Fluid Transmission

The hydraulic conductivity of a porous media for a particular fluid depends on the degree of saturation with respect to that fluid. As the degree of saturation decreases, the hydraulic conductivity also decreases, e.g. Benson and Gribb 1997. The transmissivity and permittivity to either a liquid or a gas for a nonwoven geotextile is also expected to depend on the degree of saturation with respect to that permeant. Thiel (1998) presents test results for the gas transmissivity of a nonwoven geotextile under "dry" and "wet" conditions. The gas transmissivity is lower for the "wet" conditions, illustrating that the gas transmissivity decreases with decreasing gas saturation. However, the degree of gas saturation was not measured for either the "dry" or the "wet" conditions, so these tests provide only qualitative information about the relationship between transmissivity and saturation for nonwoven geotextiles.

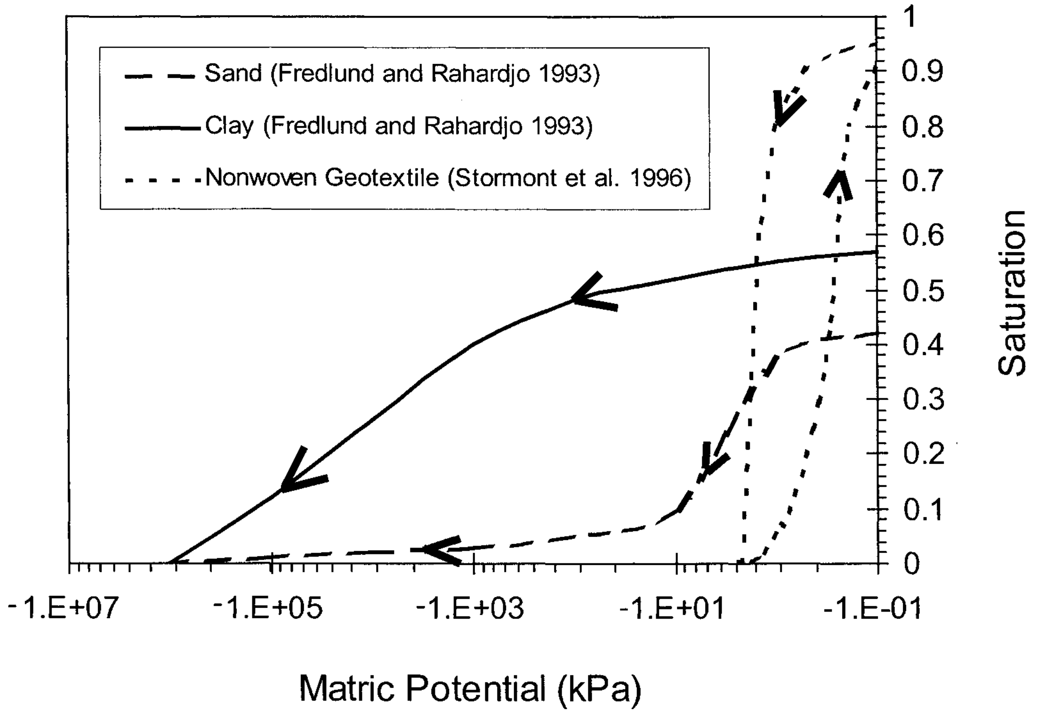

Figure 2. Example Moisture Retention Functions for Soils and Nonwoven Geotextiles

<u>Shear Strength</u>

The shear strength of an unsaturated soil depends on the total compressive stress acting on the shear plane (σ), the liquid pressure acting on that plane (u_w), and the gas pressure acting on that plane (u_a). Based on the work of Fredlund and Rahardjo (1993), a relationship such as the following can be used to model the shear strength of an unsaturated soil

$$s = c' + \sigma' \tan \phi' + \Psi \tan \phi_\psi \qquad (2)$$

where s is the shear strength, σ' is equal to $\sigma - u_w$ and equivalent to the effective stress in a saturated soil, and c', ϕ' and ϕ_Ψ are shear strength parameters. This equation differs in form from the ones proposed by Fredlund and Rahardjo (1993) in that the matric potential defined by

Equation (1) is negative when there is soil suction. Consequently, the sign of ϕ_Ψ is positive in Equation (2). The parameter equivalent to ϕ_Ψ used by Fredlund and Rahardjo (1993) is termed ϕ'' and relates strength to matric suction. The parameter ϕ'' is equal in magnitude, but opposite in sign to ϕ_Ψ ; ϕ_Ψ is normally positive while ϕ'' is normally negative. The important features of the model in Equation (2) are the following:

- Positive water and gas pressures reduce the shear strength, however the effect of gas pressure is not the same as the effect of water pressure. If the gas pressure is equal to the water pressure, then the matric potential (Ψ) is zero and the reduction in shear strength due to a postive water pressure is proportional to $\tan\phi'$. However, if the water pressure is zero but the gas pressure is positive (such as the condition for the nonwoven geotextile in Figure 1), then the shear strength reduction due to a positive gas pressure is proportional to $\tan\phi_\Psi$. The parameter ϕ_Ψ is less than ϕ', possibly because the gas pressure acts over a smaller effective area due to the presence of water in the pores. As an example for a silt, ϕ' is 35° and ϕ_Ψ is 22° (Fredlund and Rahardjo 1993).
- The relationship between shear strength and effective stress (σ - u_w) for most soils and geosynthetic interfaces is nonlinear (e.g., Liu et al. 1997), with ϕ' generally decreasing with increasing effective stress. In addition, the relationship between shear strength and matric potential for most soils is also nonlinear (e.g., Fredlund and Rahardjo 1993), with ϕ_Ψ generally approaching ϕ' as the magnitude of the matric potential increases (that is, as Ψ becomes more negative). Therefore, the linear model in Equation (2) is expected to only be applicable over narrow ranges in effective stress and matric potential for nonwoven geotextiles (that is c', ϕ' and ϕ_Ψ will likely depend on the effective normal stress and the matric potential).
- The shear strength for most geotextile interfaces is very dependent on shear displacement, with potentially significant strain-softening behavior (e.g., Li and Gilbert 1999). Therefore, the model parameters in Equation (2) (that is c', ϕ' and ϕ_Ψ) are expected to depend strongly on whether peak or residual (ultimate) values are used.

DESIGN OF TEST EQUIPMENT

Because there is a lack of data on the permittivity and shear strength of unsaturated nonwoven geotextiles, we are designing two devices to measure the properties of unsaturated materials. The first device is an air permeameter for measuring transmissivity of a nonwoven geotextile at different degrees of saturation. The design of the device is patterned after an air permeameter for soil described by Brooks and Corey (1964). The second device is designed to measure interface shear strength for interfaces with unsaturated geotextiles. The device mounts inside a triaxial cell and uses triaxial load systems to pressurize and shear the specimen. The design that we have developed for the interface shear device is described in this section.

Interface Shear Device

The interface shear device is designed to allow interface conditions ranging from air to water saturated and provide independent control of air and water pressures. This is accomplished using a triaxial cell with a special, three-piece acrylic "shear pedestal". A sketch of the shear pedestal is shown in Figure 3. All three pieces have a diameter of 89 mm. The lower two pieces are made from a cylinder that is approximately 140 mm high, and split into 2 halves along a plane oriented at 45°.

The geosynthetic materials are placed between the central portion and bottom half of the shear pedestal. The specimens are elliptical in shape with a surface area of 8,800 mm^2. The upper component in the interface to be tested is fixed to the upper portion of the pedestal and the nonwoven geotextile sits on the lower portion of the pedestal, which is bolted to the bottom of a triaxial cell. The bottom pedestal contains a porous ceramic disk for controlling water pressures and drainage. The bottom pedestal also contains a small hole for controlling the air pressure in the specimen. The geosynthetic specimens are isolated from the cell pressure using a rubber membrane. The rubber membrane is attached to the lower and central portions of the pedestal and does not touch the top cap. The top cap primarily serves to transfer load from the piston of the triaxial cell to the lower portions of the shear pedestal.

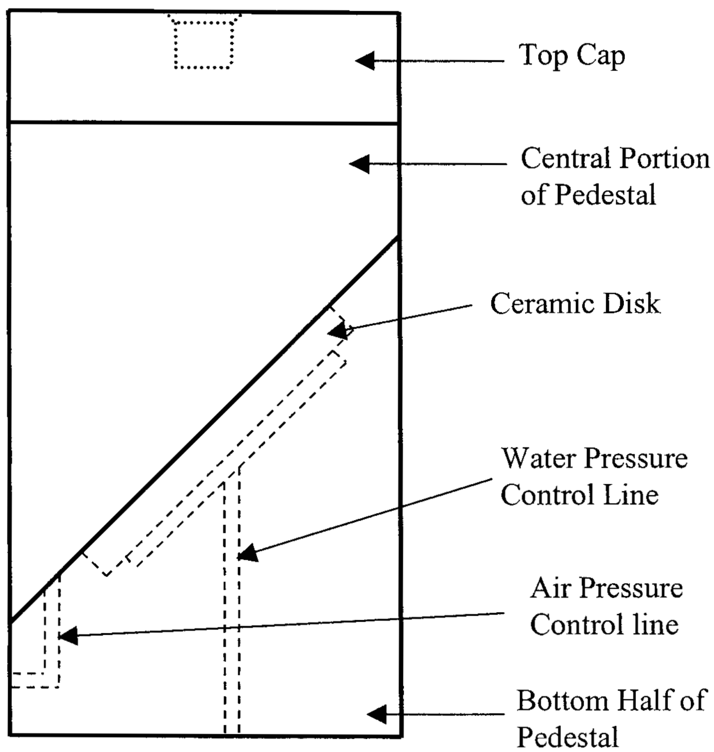

Figure 3. "Shear Pedestal" for Interface Shear

The porous ceramic disk has a high air-entry (or bubbling) pressure that allows for independent control of air and water pressures. The ceramic disk is mounted in the bottom half of the pedestal with epoxy and is supported over its area by a groove pattern cut in the acrylic. The grooves aid in the removal of air from behind the ceramic disk during set-up (see Figure 4). A ceramic disk with a minimum bubbling pressure in the range of 131 to 193 kPa was selected. This ceramic disk allows the device to function over a wide range of air and water pressures and allows relatively fast drainage of water during testing.

The bottom half of the shear pedestal is bolted to the bottom plate of the triaxial cell. Two water connections and one air connection are made between the base of the shear pedestal and the outside of the triaxial cell. One of the water connections passes directly through the base of the triaxial cell from the shear pedestal, while the other is made via a tube running from the side of the shear pedestal and then through the base of the triaxial cell. The air connection is also via a tube connected to the side of the shear pedestal and then running through the base of the triaxial cell. The two water connections permit air to be flushed from the area behind the ceramic plate by circulating water in one line and out the other.

In addition to measuring the shear strength of interfaces with unsaturated nonwoven geotextiles and other geosynthetic components, the shear device can also be adapted for interfaces containing soils or other geosynthetic materials. For example, we plan to conduct undrained tests with pore water pressure measurements on a geosynthetic clay liner. This device can also be used to measure the water retention curve of nonwoven geotextiles.

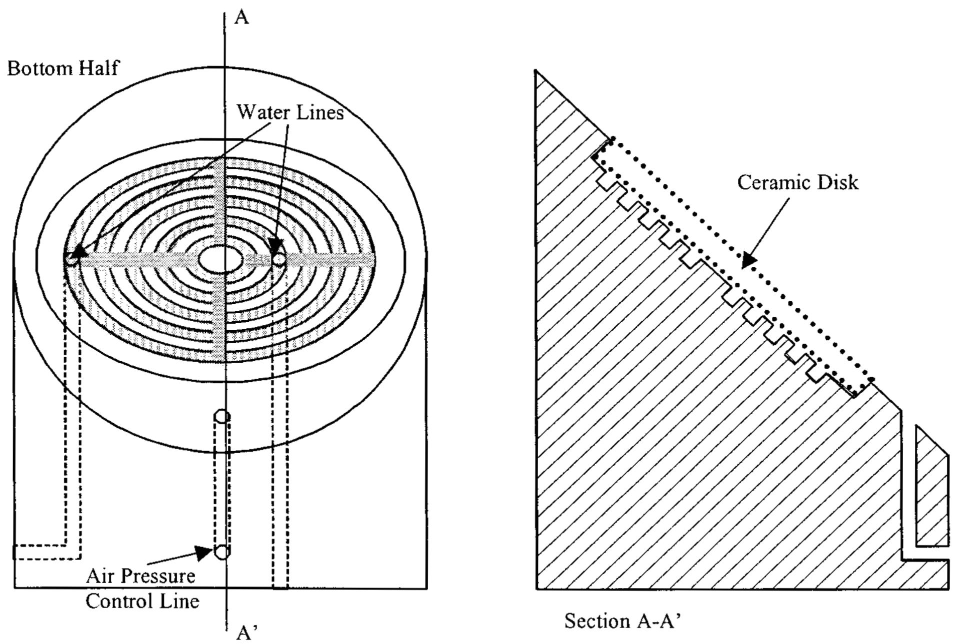

Figure 4. Groove Pattern for Shear Pedestal

DEVELOPMENT OF PROTOTYPE TEST EQUIPMENT

A prototype for the interface shear device has been built and used. The problems that have arisen in using this prototype and our design modifications are described here.

Friction between the top cap and central portion of the shear pedestal (Figure 3) was found to have a significant effect on the test results, especially at low confining stresses. In order to reduce the friction, two sets of flat-cage roller bearings are placed on the interface between the top and central portion of the shear pedestal. Lubricants, ranging in viscosity from mineral oil to vacuum grease, were tried for reducing the friction and found to be unsuitable because of the tendency of the lubricant to flow from the interface.

There are two major effects associated with the thin rubber membrane that seals the specimen from the surrounding cell pressure. One effect is an increase in confinement, and the other effect is the additional amount of interface resistance associated with shearing the membrane along the 45-degree shear plane. An oversized rubber membrane, consisting of a membrane intended for 100-mm diameter specimens on the smaller 89-mm diameter acrylic shear pedestal, was used to reduce these effects. Using this oversized membrane, however, created an additional problem. The oversized membrane wrinkled and, when held in place by o-rings, the cell pressure leaked through the wrinkles. To obtain a seal, the diameter of the two halves of the shear pedestal was increased at the location of the o-ring. In addition to using an oversized membrane, tests were run with two and three membranes on the shear pedestal. From the tests with two and three membranes, a correction for the membrane effects was developed.

The maximum shear displacement that can be obtained with this device is limited by three factors: the diameter of the surrounding triaxial cell because the upper shear pedestal moves laterally with shear displacement at the interface and will eventually contact the surrounding cell (Figure 3), the reduction in the contact area between the interface materials due to shear displacement, and the eccentricity of the piston load causing a non-uniform distribution of normal and shear stress along the interface as the central portion of the pedestal moves laterally. At this point, the maximum possible shear displacement is about 20 mm. In order to simulate the effect of large shear displacements, the interface specimens could be sheared repeatedly in the device or specimens could be subjected to large displacements in another device, such as a direct shear box, and then tested in the triaxial device.

As the load is increased on the triaxial load piston during shear, both the shear and normal load acting on the interface increase and the contact area of the interface decreases. To account for these effects, the contact area at any given shear displacement is used to calculate shear and normal stresses at that displacement. A constant normal stress was maintained on the interface throughout the tests by calculating the increase every 0.1 to 0.2 mm of displacement and reducing the cell pressure by that amount.

SAMPLE TEST RESULTS

An initial series of tests has been completed in the shear device described above. The materials and test results are described below.

Geosynthetic Materials

Tests were performed on the interface between a nonwoven geotextile and a geomembrane. The geomembrane was high-density polyethylene (HDPE) 1.5 mm thick, and finished with two smooth surfaces. The nonwoven geotextile is described by Thiel (1998), and was composed of two layers of nonwoven geotextile needle punched together. The first layer was a six-denier needle punched nonwoven geotextile with a mass per area of 200 grams per square meter. The second layer was a 45-denier nonwoven geotextile with a mass per area in the range of 740-810 grams per square meter. Both geotextile layers were made from recycled polyethylene terephthalate (PET).

Testing Procedure

Setup of a test began by placing the oversized membrane on the bottom half of the shear pedestal, which was attached to the bottom plate of the triaxial cell. The geotextile was placed on the bottom half of the shear pedestal. Deaired water was introduced through the air line to partially fill the membrane and begin to water saturate the geotextile. The central portion of the shear pedestal, with the geomembrane fixed to the inclined plane, was then placed on the bottom half of the shear pedestal. Care was taken at this point to remove air bubbles from the inside of the membrane. The oversized-rubber membrane was then sealed to the central portion of the shear pedestal. Next the top cap and triaxial cell wall were put in place. The top plate of the triaxial cell was fixed in place and the entire triaxial cell and apparatus were tilted to an inclination of approximately 45 degrees so that the interface was horizontal. Tilting the entire setup was done to facilitate the alignment of the central portion of the pedestal under the top cap and over the bottom half. At this point the air line was water saturated. Next equal cell and water pressure were applied in order to "backpressure" saturate the specimen. Once water saturated (B value = 1), the air line was drained of water for a test on an unsaturated specimen, the water pressure was reduced to test level, and air pressure for the test was applied. Excess water drained from inside the rubber membrane through the porous ceramic disk during this stage. After drainage stopped, the air and water lines were closed, the cell pressure was removed and the cell was turned upright. The cell remained tilted until this point to prevent the central portion from sliding down the interface. The top plate of the cell was removed, the flat cage roller bearings put in place between the top cap and central portion of the pedestal, and the relative positions of all portions of the shear pedestal and geosynthetics were checked for alignment and adjusted if necessary. The cell was reassembled and then positioned onto the load frame. The cell, water, and air pressures were reapplied and finally the specimen was sheared.

A set of 3 triaxial shear tests was performed to determine c', ϕ', and ϕ_Ψ (Equation 2) at normal stresses, water pressures and air pressures that are typical for a landfill cover. All tests were performed using a confining pressure of 15.2 kPa. Loading was accomplished with an automatic (motorized) load frame, at an axial displacement rate of approximately 0.15 mm/min (0.21 mm/min along the interface). Loads were measured using a calibrated proving ring. Pore pressures were measured and set using slack tube manometers. New specimens of geosynthetics were used for each test.

For comparison, a direct shear test was also performed on the geomembrane-geotextile interface. This test was conducted with water-saturated geotextiles. The test specimen was submerged and subjected to a normal stress of 14.2 kPa. The direct shear test specimens were 64 mm in diameter.

Test Results

The test results are summarized in Table 1 and shear stress-displacement curves from all the tests are presented in Figures 5, 6, and 7. The test results from the new shear device beyond a shear displacement of about 18 mm are suspect because of eccentricity of the loading piston and shearing and confinement by the surrounding rubber membrane (the membrane correction was developed and applied for displacements up to 18 mm).

Table 1. Summary of Triaxial Shear Test Results

Test Designation	Cell Pressure (kPa)	u_w (kPa)	u_a (kPa)	Mobilized[1] s (kPa)
Saturated – High σ'	15.2	0.0	0.0	4.6
Saturated – Low σ'	15.2	4.8	4.8[2]	3.0
Unsaturated	15.2	0.0	4.8	3.5

[1]Mobilized stresses correspond to the maximum (or peak) shear strength.
[2]Specimen is saturated with water so $u_a = u_w$.

The first set of tests (Figure 5) corresponds to a water-saturated geotextile with no water pressure. Raw tests results and results corrected for membrane effects are shown to illustrate the impact of the membrane on the results. The effect of the membrane, which has been corrected using test results with one, two and three membranes, is especially noticeable due to the very low normal stresses being used in these tests. Results from the direct shear test at a similar normal stress are also shown on Figure 5. Note that the corrected shear stress versus displacement curve for the triaxial device is comparable to the direct shear test result (Figure 5).

The second test (Figure 6) corresponds to a water-saturated geotextile with a water pressure of 4.8 kPa in the triaxial device. The results on Figures 5 and 6, which give a peak shear strength to effective normal stress ratio of about 0.3, are consistent with published data for similar interfaces (e.g., Liu et al. 1997).

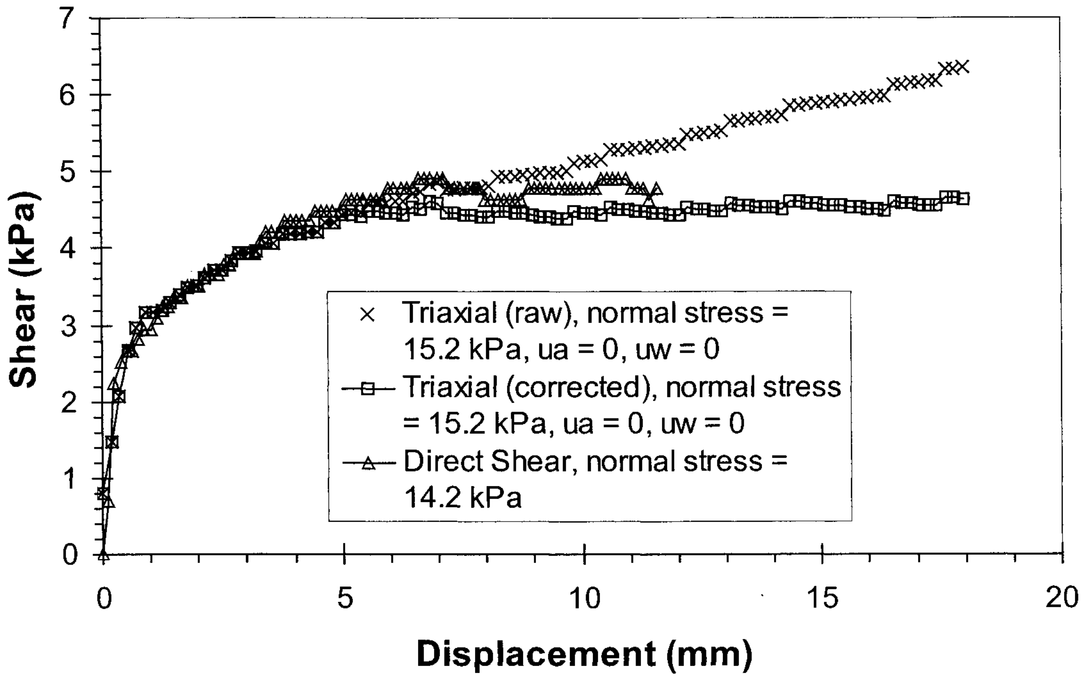

Figure 5. Interface Shear Test Results for Water-Saturated Geotextile

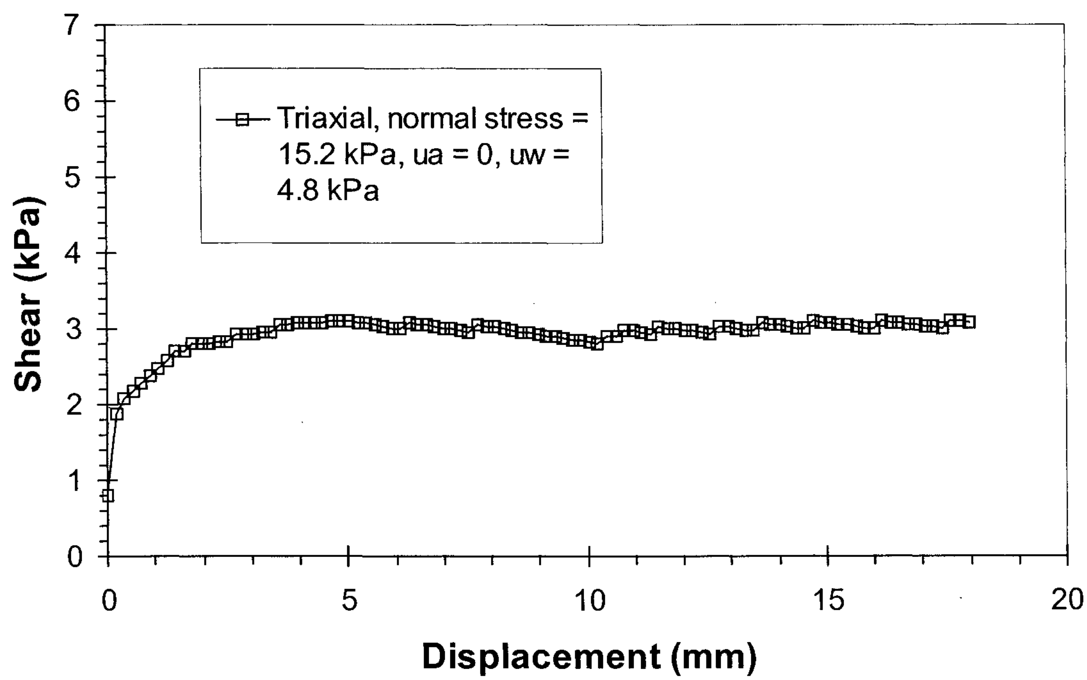

Figure 6. Interface Shear Test Results for Water-Saturated Geotextile with Water Pressure

The third tests (Figure 7) correspond to an unsaturated geotextile with a water pressure of 0.0 kPa and an air pressure of 4.8 kPa. These tests and results illustrate the value of the device; it is not possible to test a geotextile under these conditions with conventional test equipment. Two tests were conducted with similar conditions to evaluate the repeatability of the test procedure. These tests indicate that repeatable results can be obtained with this device (Figure 7).

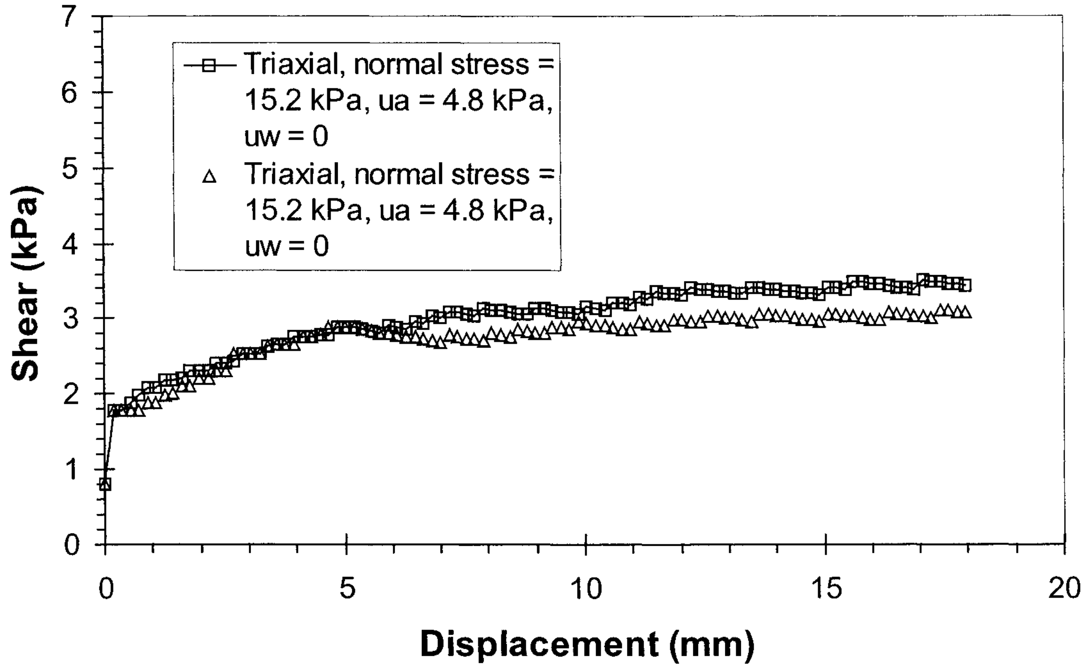

Figure 7. Interface Shear Test Results for Unsaturated Geotextile with Gas Pressure

Analysis of Test Results

Normalized values for the parameters in the shear strength model (Equation 2) were calculated from the test results summarized in Table 1. First, the values of c' and ϕ' are obtained from Equation (2) with the first two sets of results on the saturated specimen:

$$4.6\ kPa = c' + (15.2 - 0.0\ kPa)\tan\phi' + (0.0 - 0.0\ kPa)\tan\phi_\psi \quad (3)$$

$$3.0\ kPa = c' + (15.2 - 4.8\ kPa)\tan\phi' + (4.8 - 4.8\ kPa)\tan\phi_\psi \quad (4)$$

Solving for c' and ϕ' from Equations (3) and (4) gives c' = -0.5 and ϕ' = 18.4°. Next, ϕ_Ψ is obtained from the set of results on the unsaturated specimen:

$$3.5\ kPa = -0.5 + (15.2 - 0.0\ kPa)\tan(18.4°) + (0.0 - 4.8\ kPa)\tan\phi_\psi \quad (5)$$

Solving for ϕ_Ψ from Equation (5) gives ϕ_Ψ = 12.4°.

The measured value for ϕ_{Ψ} is smaller than ϕ', which is consistent with test results for unsaturated soils. This conclusion is significant because it indicates that our understanding about the shear strength of unsaturated soils can at least generally be applied to the interface shear strength for unsaturated geosynthetics. This is also a significant conclusion because it indicates that the effect of increasing gas pressure in the unsaturated nonwoven geotextile is not as significant as the effect of increasing water pressure in reducing the interface shear strength (providing that the geotextile is not air saturated). For example, consider a long landfill cover slope such as that shown on Figure 1. Assume that the cover is sloped at an angle of 5 horizontal to 1 vertical (or 11.3°) and that there is 1 m of soil with a unit weight of 15 kN/m^3 on the geomembrane (or a vertical pressure of $15\ \mathrm{kN/m^3} \times 1\ \mathrm{m} = 15\ \mathrm{kPa}$). The factor of safety for the interface between the nonwoven geotextile and the overlying geomembrane can be calculated for different conditions. First, consider the case of no water and no gas pressure:

$$FS = \frac{-0.5 + (15\cos 11.3° - 0.0)\tan 18.4° + (0.0 - 0.0)\tan 12.4° \quad kPa}{15 \sin 11.3° \quad kPa} = 1.49 \qquad (6)$$

Next, consider the case of a 5.0 kPa water pressure with a saturated geotextile:

$$FS = \frac{-0.5 + (15\cos 11.3° - 5.0)\tan 18.4° + (5.0 - 5.0)\tan 12.4° \quad kPa}{15 \sin 11.3° \quad kPa} = 0.93 \qquad (7)$$

Finally, consider the case of a 5.0 kPa gas pressure with an unsaturated geotextile and no water pressure:

$$FS = \frac{-0.5 + (15\cos 11.3° - 0.0)\tan 18.4° + (0.0 - 5.0)\tan 12.4° \quad kPa}{15 \sin 11.3° \quad kPa} = 1.12 \qquad (8)$$

Hence, the cover slope would fail with a water pressure of 5 kPa [Equation (7)] but be stable with a gas pressure of 5 kPa [Equation (8)]. This example demonstrates that gas and water pressures cannot be treated in the same manner, and it highlights the practical importance of understanding the shear strength properties for unsaturated geotextiles.

CONCLUSIONS

The following conclusions have been drawn from our preliminary work at developing an apparatus to measure interface shear strength for nonwoven geotextiles:

- The new apparatus is relatively simple, it allows for independent control of both air and water pressures in the pores, and it is capable of producing repeatable and seemingly valid test results.

- The new apparatus provides valuable data that can benefit design, as demonstrated for a landfill cover slope.
- The apparatus could be improved by reducing the effects of the rubber membrane that surrounds the specimen in the triaxial cell and the potential effects of eccentricity and friction for the loading piston.
- Conventional principles about the shear strength behavior for unsaturated soils apparently can be applied generally to the interface shear strength for unsaturated geosynthetics.

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