Resilient Interface Shear Modulus from Short-Strip, Cyclic, Pullout Tests

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Abstract

The national movement to develop a mechanistic-empirical design guide for pavements requires that the fundamental material properties for all components of the design be quantified. When geosynthetics are used to reinforce the base course layers of flexible pavements, one of the two main design parameters is the interaction between the geosynthetic and the surrounding aggregates. Interaction at this interface can be quantified in terms of a stiffness parameter, G_i, the resilient interface shear modulus. The most relevant interaction tests use cyclic loads like those experienced in transportation applications. Currently, however, there is no standard test to quantify soil/geosynthetic interaction using cyclic loads. This research effort modified the standard pullout test protocol to resemble the resilient modulus tests for unbound aggregates which utilizes cyclic loads at various levels of normal confinement. The resilient modulus for unbound aggregates (M_R) closely resembles G_i, since they are both simultaneously dependent on shear load and confinement. Overall, the results from the cyclic pullout tests conducted on six geosynthetics showed that cyclic pullout testing has great potential for describing a stress dependent interface shear modulus. A three-parameter, log-log equation developed in the NCHRP Project 1-28a (NCHRP, 2000) was used to predict G_i. Correlations between predicted and measured values were somewhat erratic. Additional research is planned to improve the test equipment and establish specific test protocols.

Introduction

Geosynthetics have been used to reinforce the base course of roadways for more than two decades. A typical application includes roads on poor subgrade that will likely experience high plastic deformations. In this case, geosynthetic reinforcement increases the life span of paved roads and may require less granular base, thereby decreasing costs (Ashmawy and Bourdeau, 1995). Based on research conducted on geosynthetic reinforced test sections, it has been suggested that in cases where the geosynthetic interacts well with the soil, the reinforcement may allow the road base thickness to be significantly reduced. Conversely, geosynthetics provide little structural benefit when a firm subgrade is present (Ashmawy and Bourdeau, 1995). The ultimate goal for using geosynthetics within the base course and subgrade materials of a road is to reduce permanent deformations within the pavement substructure, generally caused by repeated traffic loading.

Geosynthetic reinforced pavements are typically designed based on empirically derived relationships. Research has shown that geosynthetics can, in some cases, add strength and longevity to a roadway; but up to this point the mechanics of how reinforcement benefit is accomplished are less understood. Empirically-based design methods are generally area specific and limited to specific design conditions, thus making it difficult to transfer knowledge in a broader sense. Recently, however, the American Association of State Highway and Transportation Officials (AASHTO) has promoted a more broad-based method, commonly known as a mechanistic-empirical flexible pavement design, through the National Cooperative Highway Research Program (NCHRP) Project 1-37A (NCHRP, 2003). This new method includes mechanics-based pavement response models to sufficiently describe material models for the various pavement layers, but does not address geosynthetic reinforcement of the base layer in its material models. As such, material models that include geosynthetic reinforcement need to be developed.

Perkins et al. (2004) began work to develop design methods for geosynthetic-reinforced pavements that are compatible with the methods being developed in NCHRP 1-37A Design Guide (NCHRP, 2003). A finite element model (FEM), developed by Perkins et al. (2004), used material and damage models for the different layers of the pavement cross section, that included geosynthetic reinforcement. Mechanistic material models are an essential component; therefore, material models that describe the geosynthetic reinforcement interaction with the surrounding aggregate needed to be developed. Since the mechanistic pavement response models used by NCHRP (2003) and Perkins et al. (2004) describe resilient response and involve relatively small strains and displacements, parameters describing the shear stiffness or shear modulus of the aggregate/geosynthetic interface are most important and pertinent. The aim of the work described in this paper was to provide parameters for the aggregate/geosynthetic interface shear moduli that are used as input parameters into the FEM.

Background

Several laboratory tests, such as direct shear tests, triaxial tests, and pullout tests have commonly been used to describe and quantify soil-geosynthetic interaction. Of these, pullout tests were selected because the relative displacements between the soil and the geosynthetic can be more precisely controlled and measured, especially when cyclic loads are applied. Generally, a pullout test is conducted by applying axial loads to a geosynthetic sample embedded in a mass of soil at various levels of confinement. Applied load and corresponding displacement of the embedded geosynthetic are monitored to quantify interaction.

In the past, both monotonic (displacement-controlled) and cyclic (load-controlled) pullout tests have been used to determine soil-geosynthetic interaction. While monotonic testing allows interaction properties to be evaluated for situations where movements are slow and steady, it does not accurately emulate the loading conditions that occur within the subsurface of roads. It is well known that loading from traffic produces cyclic reactions throughout the pavement structure. Therefore, cyclic pullout tests are better suited to describe the dynamic interaction between geosynthetics and the surrounding aggregate. As such, the standard pullout test protocol was modified to use cyclic loads.

The protocol for these tests was adapted from the standard for determining the resilient modulus (M_R) of unbound materials as developed by NCHRP Project 1-28A (NCHRP, 2000). In this protocol, a series of steps consisting of different levels of confining pressure and cyclic axial stress are followed such that resilient modulus is measured for varying confinement and shear stress levels. The confining pressure is held constant within each load step, while cyclic loading, consisting of repeated cycles of a haversine shaped load pulses, is delivered to the sample. Resilient modulus, defined as the change in axial stress divided by the change in axial strain, is averaged over the last 10 cycles of each load step.

Similar to resilient modulus tests on aggregates, cyclic pullout tests are performed for a series of steps consisting of different levels of normal stress and cyclic pullout load. The latter creates different levels in shear stress on the geosynthetic/aggregate interface. Using the results from the pullout tests, the interface shear modulus, G_i, is defined as the change in shear stress at the soil-geosynthetic interface divided by the relative displacement between the soil and geosynthetic, averaged over the last 10 cycles of each load step.

A series of cyclic pullout tests were performed at the Western Transportation Institute, Montana State University – Bozeman, to better understand and quantify soil-to-geosynthetic interaction properties under cyclic loading. Two types of geosynthetics were considered in this study: biaxial, polypropylene geogrids, and woven, polypropylene geotextiles (Table 1). Individual geosynthetics will be referred to by their generic name throughout the remainder of this paper.

Table 1: Geosynthetic materials used in testing

Geosynthetic Type	Manufacturer & Brand Name	Generic Name	Polymer Type / Structure
Geotextile	Amoco ProPex 2006	Geosynthetic A	polypropylene / woven
	Synthetic Industries Geotex 3×3	Geosynthetic B	polypropylene / woven
	Ten Cate Nicolon Geolon HP570	Geosynthetic C	polypropylene / woven
Geogrid	Colbond Enkagrid Max 20	Geosynthetic D	polypropylene / welded grid
	Tensar BX1100	Geosynthetic E	polypropylene / biaxial, punched, drawn
	Tensar BX1200	Geosynthetic F	polypropylene / biaxial, punched, drawn

Description of Test Equipment

The pullout box used for cyclic testing is a full-sized box built to the specifications provided in ASTM D6706 (ASTM, 2003). The inside dimensions of the pullout box are 1.10 m high by 0.90 m wide by 1.25 m long. The pullout box is rigidly constructed of steel to limit distortion during testing, thereby increasing the accuracy of displacement measurements and ensuring that the load is properly transferred to the test specimen. A pneumatic load actuator, connected to a load frame at the front of the box, is connected to the sample using a double-pinned connection. The geosynthetic test specimen is glued between two pieces of 18 gage sheet metal (load transfer sheets) using a rigid epoxy to transfer the point load from the actuator into a uniform line load at the edge of the geosynthetic. A slit at the front of the pullout box accommodates the sample with minimal friction. A similar slit exists at the back of the pullout box to allow the displacement wires, connected to the embedded end of the geosynthetic sample, to be connected to linearly varying differential transducers (LVDTs), which are mounted externally (Figure 1).

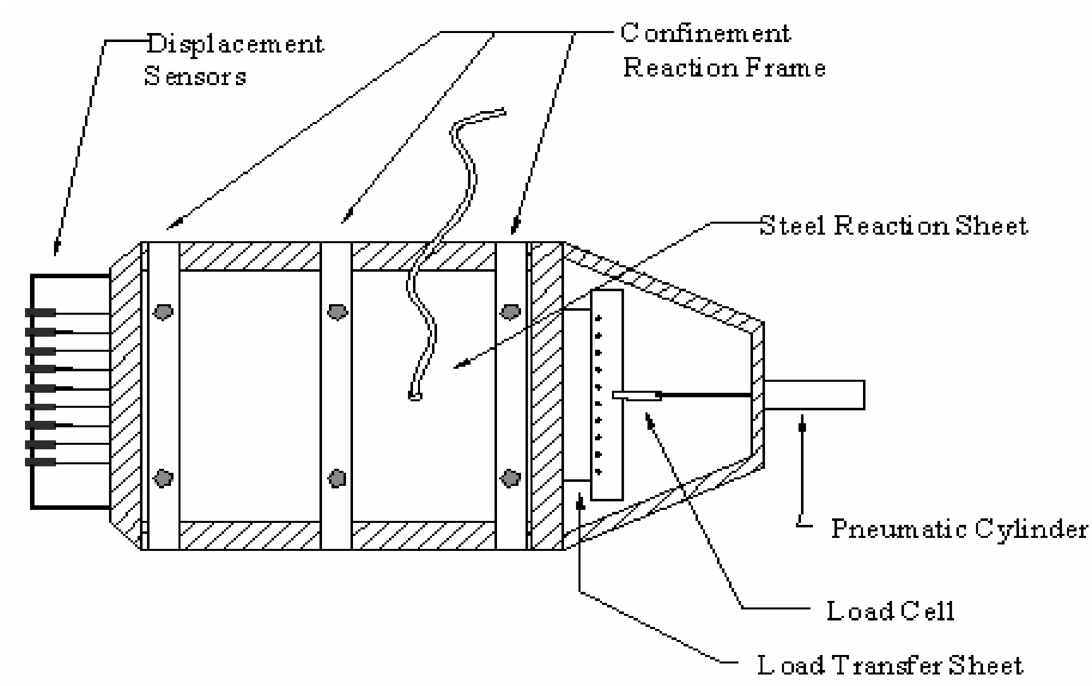

Figure 1: Plan view of pullout box.

Additional normal confinement is provided using a flexible pneumatic bladder on top of the soil. This bladder reacts against a flat, rigid steel plate held in place by steel framing attached to the top of the pullout box (see Figure 2). The axial load is delivered to the sample using a pneumatic cylinder connected to a computer-controlled variable regulator. Axial loads were measured using a load cell located between the pneumatic cylinder and the load transfer sleeves.

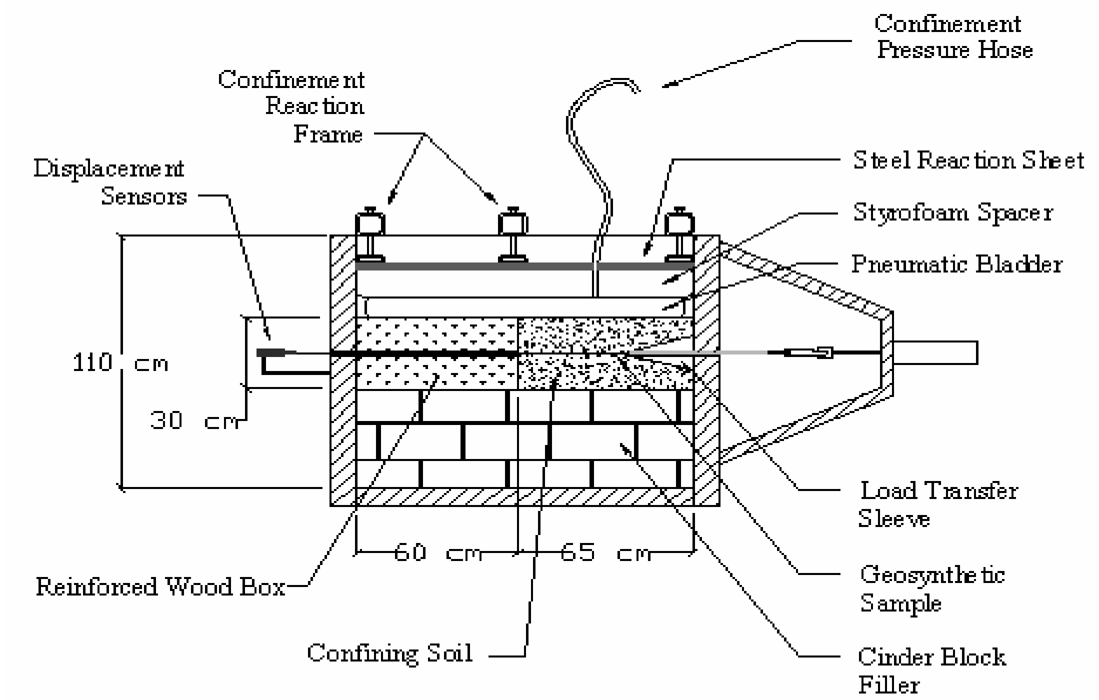

Figure 2: Side view of pullout box.

The pullout box was originally constructed to accommodate samples up to 75 cm long. The entire capacity of the pullout box is not needed because the geosynthetic sample lengths are very small for these tests. Therefore, for efficiency, a reinforced wood box approximately 30 cm high by 60 cm long was used to reduce the soil volume by approximately 50 percent (Figure 2). Similarly, the bottom third of the pullout box (below the wooden box) was also filled with bricks. This left a volume 30 cm high by 90 cm wide by 65 cm long for the soil that confines the geosynthetic.

To minimize strains along the embedded length of the geosynthetic, sample lengths were limited to approximately 50 to 80 mm. Sample widths were generally 450 mm, depending on the geosynthetic type. These small sample lengths made it possible to engage the entire length of the sample simultaneously during loading without inducing large strains typical of monotonic pullout testing.

The confining soil was a crushed aggregate having a maximum dry density of 21.4 kN/m^3 and optimum moisture content of 6.6% – classified as A-1-a (AASHTO M145-87) or GW-GM (ASTM D2487). A pneumatic compactor was used to compact soil lifts 4 to 8 cm thick. After the soil was compacted to the height of the bottom load transfer sleeve, the soil was slightly scarified and the geosynthetic sample was put into place so that the leading edge (front) of the sample was aligned with the embedded edge of the load transfer sleeve. Thin metal rollers between the load transfer sheets and the load transfer sleeves minimized friction during testing.

With the sample temporarily held in place, thin stainless steel wires were connected to the back (trailing edge) of the geosynthetic to measure the displacement of the sample. Two other sensors were connected to the sheet metal load transfer sheet to measure the displacement of the front (leading edge) of the sample. The displacement sensors have an accuracy of 1.3 x 10^{-3} mm, and a range of approximately 4 mm. The displacement wires were encased in brass tubes that extended through the soil and out the back of the pullout box.

Minimum and maximum load and displacements were collected from all sensors for each cycle delivered to the geosynthetic. These minimum and maximum values were used to calculate geosynthetic/soil interaction properties.

Test Protocol

As mentioned previously, the loading protocol for these tests is based on the NCHRP Project 1-28a (NCHRP, 2000) – designed to determine the resilient modulus of unbound granular materials. Generally, this protocol specified that cyclic loads be applied to the geosynthetic at various levels of confinement. Therefore, the cyclic pullout tests began with a conditioning step which applied 1000 cycles to the sample at a confinement of 51.7 kPa (11.25 psi). This step is designed to minimize anomalies inherent in experiments associated with compacted soils. Following the conditioning step, six separate loading sequences, based on a theoretical failure line, are followed (as illustrated in Figure 3).

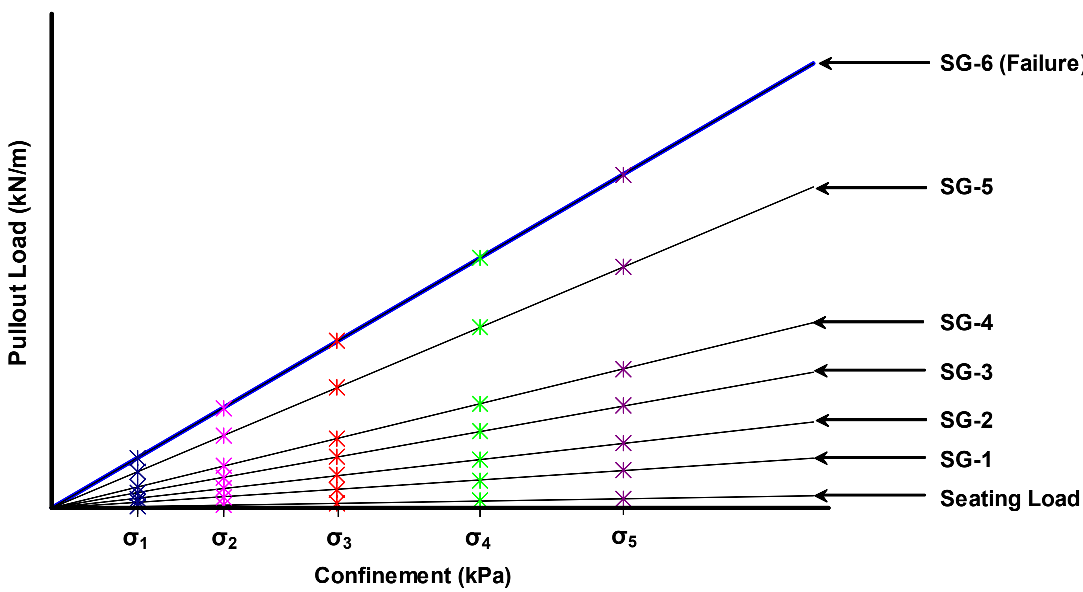

Figure 3: Cyclic pullout loading protocol.

The sixth load sequence represents a failure line and the remaining five are based on a percentage of the sixth (Table 2). The slope of the failure line is determined from the area of the geosynthetic sample and an assumed ultimate interaction friction angle between the soil and geosynthetic (51.5°) determined from monotonic pullout tests. Five levels of confinement (15.5, 31.0, 51.7, 77.6, and 103.4 kPa) are used within each load sequence to define a line called a "sequence group." Testing begins with the first sequence group (SG-1) at the lower confinements first, and progresses to the sixth sequence group (SG-6) unless pullout failure occurs earlier. Cyclic shear load is applied between the values on the seating load line and the points for the sequence group. Maximum and minimum loads applied to the geosynthetic for a particular load step are determined from the sequence group and the seating load lines, respectively. For the first two confinement levels, 300 shear load cycles were applied to ensure that the resilient behavior had stabilized. For the remaining confinements, 100 cycles of shear load were applied.

Table 2: Percent of failure load for each sequence group.

Load Level	Percent of Failure Load
Seating Load	2.8 %
SG 1	9.7 %
SG 2	16.7 %
SG 3	30.6 %
SG 4	44.4 %
SG 5	72.2 %
SG 6	100.0 %

Analysis & Results

An average value of the resilient interface shear modulus, G_i, defined as the cyclic shear stress at the soil-geosynthetic interface divided by the resilient relative displacement between the aggregate and the reinforcement for the shear stress applied, was calculated using the maximum and minimum values of displacement and load from the last ten cycles for each confinement level within each sequence group. A graphical illustration of how G_i is determined is shown in Figure 4. This analysis is similar to the analysis used to determine the resilient modulus of unbound aggregates as described by NCHRP Project 1-28a.

The shear stress was determined by dividing the applied load by the engaged area of the sample, which was doubled to include both the top and bottom of the geosynthetic (Equation 1). The area of the embedded geosynthetic reduces slightly as the test progresses making it necessary to correct the area. This is done by subtracting the maximum displacement of the rear of the sample from the embedded length.

$$\tau = \frac{F}{2 \cdot w \cdot (l - \Delta_b)} \qquad \text{Equation 1}$$

In Equation 1, F is the applied load, 2 represents the two sides of the material, w is the width of the sample, l is the length of the sample, and Δ_b is the average displacement of the back of the sample, which is subtracted from the length to account for the loss of area during testing.

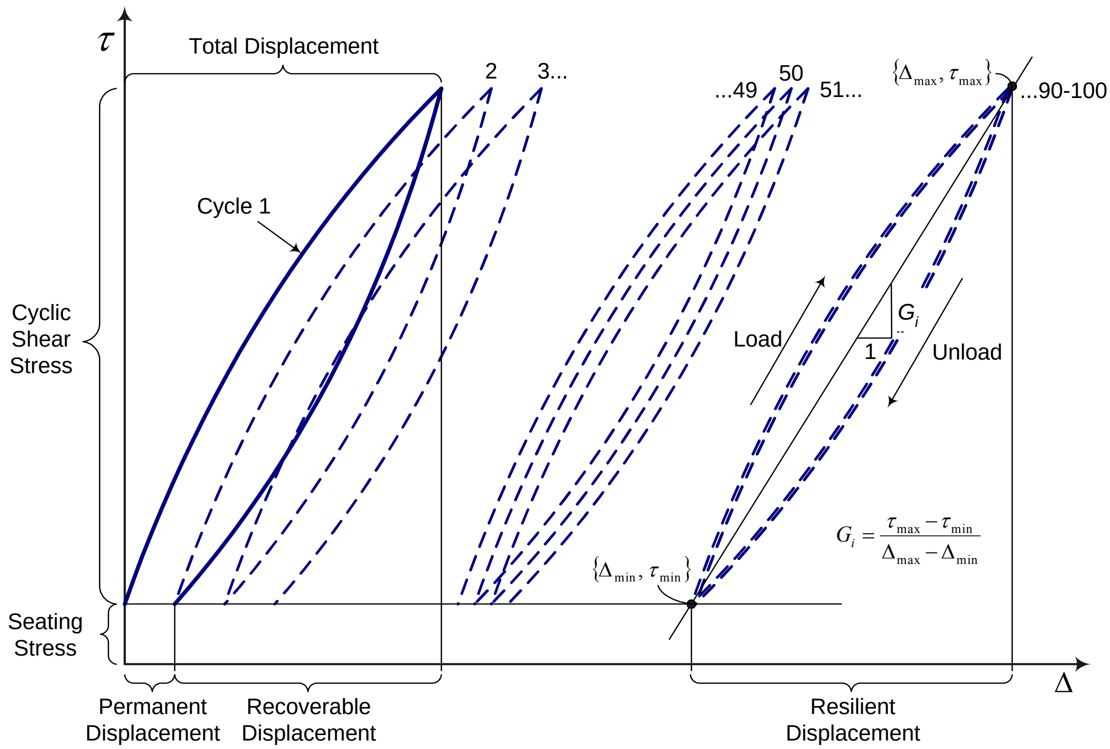

Figure 4: Illustration of interface shear modulus calculation.

Although short samples were used to provide uniform pullout displacement across the length of the sample (i.e., minimize strain in the geosynthetic), small differences in the displacement at the front and rear of the embedded geosynthetic were observed. Therefore, it was necessary to average the displacement along the sample's length. Displacements at the rear of the sample were averaged to determine a single average displacement of the rear. The average rear displacement was added to the displacement of the load transfer sheets (i.e., the front of the sample) and divided by two to determine a single, average displacement of the embedded geosynthetic sample. Therefore, the Δ_{max} and Δ_{min} terms shown in the equation in Figure 4 are averages for the entire embedded geosynthetic sample.

The resilient interface shear modulus was determined for each confinement level in each sequence group for all the materials tested. For example, the shear modulus for Geosynthetic D oriented in the machine direction is shown as a function of the confinement and shear stress in Figure 5. As expected, the interface shear modulus shows a strong dependency on the shear stress. Namely, that the interface shear modulus decreased for higher shear stresses, but increased slightly as the confinement increased. Hence, the interface shear modulus is mutually dependent on the confinement and shear load. The other materials tested in this study generally followed similar trends.

Most of the results showed very high values of G_i in the first three sequence groups (SG-1, SG-2 and SG-3), especially at lower levels of confinements. This was because measured displacements within these sequence groups were very small. In fact, many of the measured displacements were near or less than the sensitivity of the LVDTs, therefore, noise and other deviations had a greater effect when actual measurements were small. As a result, small changes in the displacement measurements had the potential to greatly affect the shear modulus. Consequently, the accuracy of these measurements was critical, since LVDTs with lower sensitivity would not be able to perceive these small displacements with greater accuracy. The sensitivity of the displacement transducers was ± 0.0013 mm (5.0 x 10^{-5} inches). For lower sequence groups, displacements at the embedded end of the sample were very small, and therefore had the potential to create very large (and sometimes unreasonable) interface shear modulus values. The analysis showed that, overall, the average error due to sensor sensitivity was approximately 11 percent. However, at lower load and confinement levels, changes of 40 percent were sometimes discovered. Increasing the accuracy of the displacement sensors would significantly reduce this error.

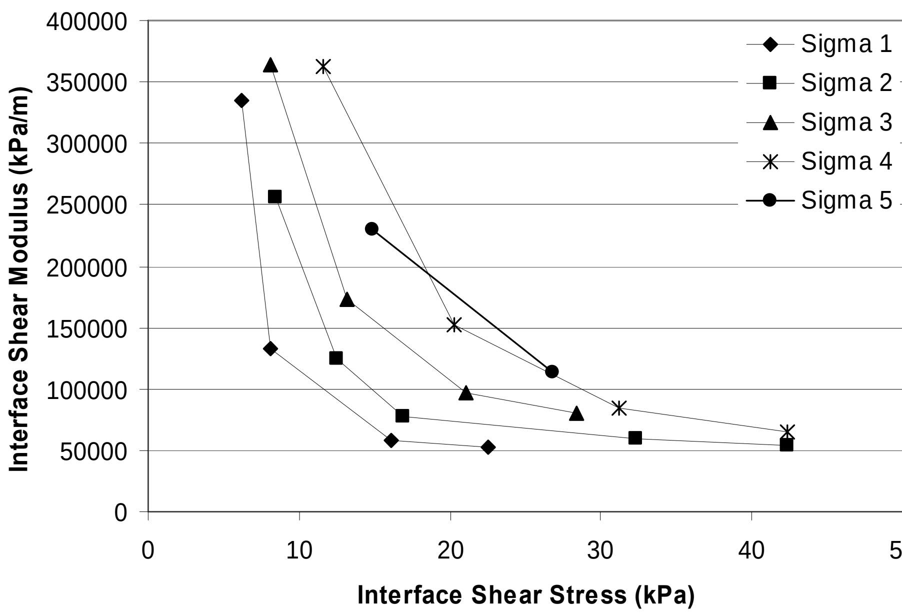

Figure 5: Interface shear modulus versus shear stress for various confinements for Geosynthetic D, machine direction.

Results of the cyclic pullout tests conducted to mimic a resilient modulus test on unbound aggregates have shown that the interface shear modulus is stress dependent and increases with increasing normal stress and decreases with increasing shear stress. This is similar to trends exhibited from resilient modulus tests on unbound aggregates and should not be surprising since aggregates are used in both tests. The stress dependency exhibited in the cyclic pullout tests and the similarity to resilient modulus tests led to the adoption of an equation for resilient modulus to describe the stress dependency of the interface shear modulus from cyclic pullout tests. This equation (see Equation 2) is used for resilient modulus of the unbound materials as part of NCHRP Project 1-37a (NCHRP 2003).

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a} \right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1 \right)^{k_3} \qquad \text{Equation 2}$$

where p_a is the atmospheric pressure (101.3 kPa), θ is the bulk stress ($\sigma_1 + 2\sigma_3$), τ_{oct} is the octahedral shear stress $\sqrt{2}/3 \cdot (\sigma_1 - \sigma_3)$, and k_1, k_2 and k_3 are dimensionless regression constants corresponding to material properties, where k_1 and $k_2 \geq 0$ and $k_3 \leq 0$.

The equation proposed for the interface shear modulus (G_i) from cyclic pullout tests is given by Equation 3, where new dimensionless material constants k_1, k_2 and k_3 are used. The normal stress on the interface (σ_i) replaces the bulk stress and the shear stress on the interface (τ_i) replaces the octahedral shear stress. These stresses are still normalized by atmospheric pressure (p_a). The leading p_a term has been replaced by a term labeled P_a and is the atmospheric pressure divided by a unit length of 1 meter (101.3 kPa/m) and is done to develop consistent units for G_i.

$$G_i = k_1 \cdot P_a \cdot \left(\frac{\sigma_i}{p_a} \right)^{k_2} \cdot \left(\frac{\tau_i}{p_a} + 1 \right)^{k_3} \qquad \text{Equation 3}$$

Values of k_1, k_2, and k_3 for Geosynthetic D in the machine direction were determined using a statistical optimization routine (k_1=12,260, k_2=0.5256, and k_3=-11.41). Predicted values of G_i were determined by substituting these constants into Equation 3. The predicted values were plotted with respect to measured values, resulting in a good correlation (Figure 6). This result shows good promise for using Equation 3 to provide a predictive equation for G_i, and also calibrating this equation using the results from cyclic pullout tests. Further work is planned to evaluate this equation for other geosynthetics and aggregate materials.

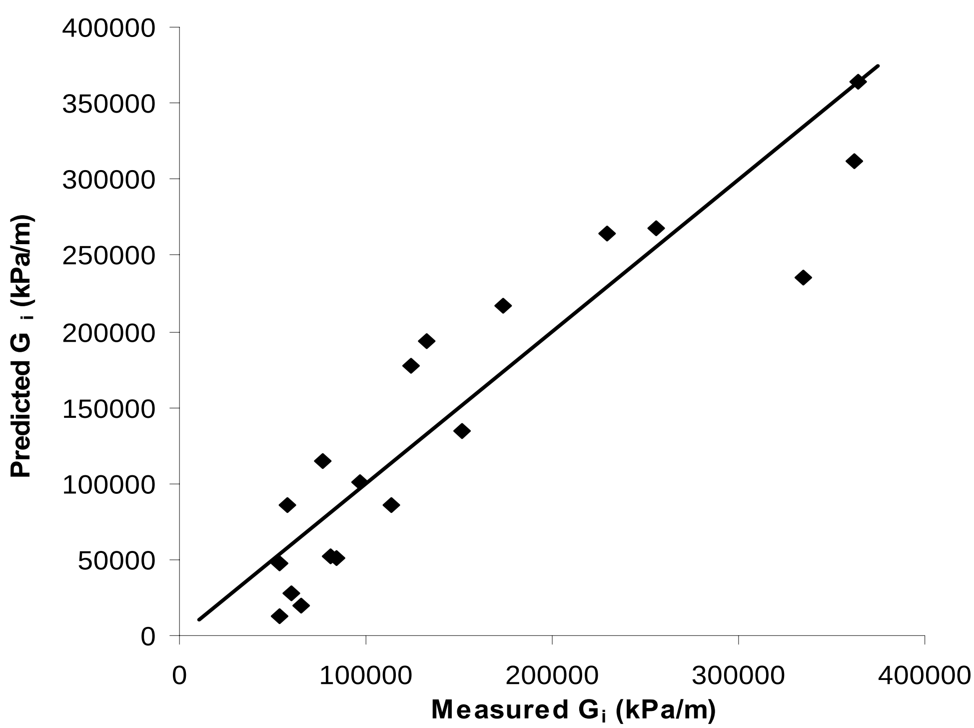

Figure 6: Measured versus predicted G_i for Geosynthetic D, machine direction.

Summary & Conclusions

Overall, cyclic pullout testing shows great potential for describing a stress dependent interface shear modulus. The standard pullout protocol, as established by ASTM D6706, was used as a template for these tests, with the exception of the geosynthetic specimen length and the cyclic loading protocol. Cyclic pullout tests were conducted that emulated the established protocol used to determine the resilient modulus of unbound materials as outlined in the NCHRP Project 1-28a (NCHRP, 2000). The resilient modulus (M_R) closely resembles the resilient interface shear modulus (G_i) determined from cyclic pullout tests since they are both simultaneously dependent on shear load and confinement. A three-parameter, log-log equation developed in the NCHRP Project 1-28a (NCHRP, 2000) was used to predict G_i. In some cases, predicted values showed good correlation with measured values, but in other cases, correlations were not as strong. Therefore, more testing is needed to improve these relationships.

In general, duplicate tests showed poor repeatability. Differences in results between repeated tests using the cyclic test protocol were greater than those obtained in the past using monotonic loading. Low load levels and corresponding low displacement levels were highly sensitive to differences between repeated tests, even though a strict routine was established and followed. Additional research is needed to identify the source of these differences and establish specific test protocols to address them. Specifically, specimen dimensions, instrumentation and loading conditions must be established to provide meaningful and repeatable results.

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