

A TECHNICAL NOTE REGARDING INTERPRETATION OF COHESION AND FRICTION ANGLE IN DIRECT SHEAR TESTS

There is often confusion expressed in the geosynthetics industry over how laboratory direct shear results should be interpreted, specifically whether one should use both the friction angle and cohesion (or adhesion) parameters. The attached technical note from the April/May 2009 issue of *Geosynthetics* provides some guidance regarding this question, as well as several other issues related to direct shear results.

Please note that this article is not intended to replace education or experience and should only be used in conjunction with professional judgment. In the end, all data should be evaluated by an experienced practitioner qualified to use the test results properly.

A technical note regarding interpretation of cohesion (or adhesion) and friction angle in direct shear tests

By Richard Thiel

Introduction

Direct shear testing with geosynthetics is generally performed in accordance with ASTM D5321, *Standard Test Method for Determining the Coefficient of Soil to Geosynthetic or Geosynthetic to Geosynthetic Friction by the Direct Shear Method*. There is also a related standard, D6243, *Standard Test Method for Determining the Internal and Interface Shear Resistance of Geosynthetic Clay Liner by the Direct Shear Method*. This technical note applies to both equally.

Interpreting lab results

There is often confusion expressed in the industry regarding how laboratory results should be interpreted, specifically: whether one should use both the friction angle and cohesion (or adhesion) parameters; whether cohesion should be ignored; whether secant friction angles are more appropriate; what to do if the data are nonlinear; and how the data should be interpolated or extrapolated.

The goal of this technical note is to provide some guidance to take the mystery out of these questions. In the end, all data should be evaluated by an experienced practitioner qualified to use the test results properly.

What this note will not do is go into the subtleties of requesting, setting up, calibrating, and performing a direct shear test. That would be the subject of additional articles.

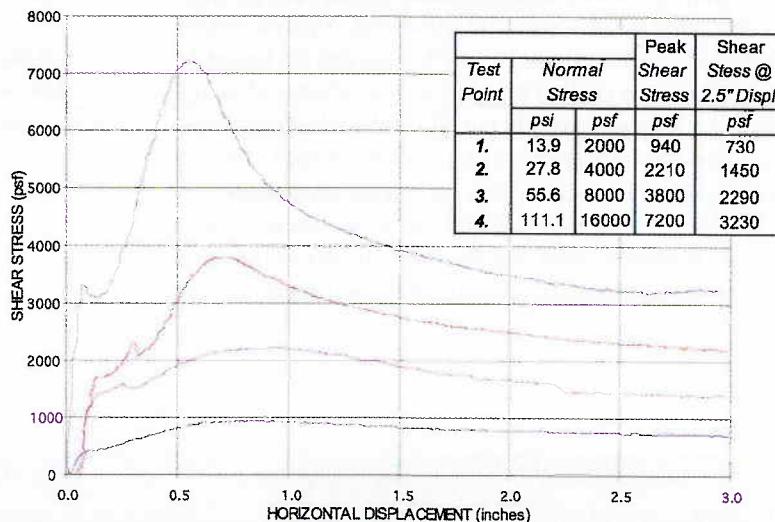
This article will also not definitively describe how direct shear test data should be interpreted. That is the responsibility of a professional with specific expertise, and one article could never presume to cover all of the considerations that might apply to any unique design problem that might arise. That is why professionals are trained and mentored in basic geotechnical principles: so they can appropriately account for

the various factors affecting a design and make appropriate decisions regarding test data interpretations.

The typical sequence of events related to direct shear testing includes the following:

1. An engineer requests a direct shear test series to obtain data to help solve a problem. The request should be very specific with regard to all the necessary details regarding

Material 1:	← GSE 40 mil HDPE Tex / Tex (White side towards GCL)
Material 2:	→ Bentomat DN GCL (black side up) Roll # 00000481
Substrate:	→ GSE 60 mil HDPE Tex-white / Tex-black (Black side toward GCL)



The "gap" between shear boxes was set at 80 mil (2.0 mm)
The test specimens were flooded during testing.
High Normal Stresses, >5psi (35 kPa) was applied using air pressure.
Low Normal Stresses, <5psi (35 kPa) was applied using dead weights.
The tests were terminated after 3.0" (75 mm) of displacement unless otherwise noted.
Tests were performed in general accordance with ASTM procedure D-5321 using a Brainard-Killman LG-112 direct shear machine with an effective area of 12" x 12" (300 x 300 mm).
Each specimen of 60 mil geomembrane was cut to 14" x 20" and clamped to the lower shear box. Avg. Asperity =0.025"
Each specimen of 40 mil geomembrane was cut to 14" x 16" and clamped to the upper shear box. Avg. Asperity =0.016"
Each GCL specimen was Hydrated for 48 hrs at the 250 psf, then placed, unclamped between upper & lower HDPEs
The grouped specimens were consolidated 16 hrs. under the specified normal stress, then sheared
Shearing occurred at the interface of the GCL's and 40 mil geomembrane specimens.
Extrusion of bentonite was noted on the surface of the 40 mil & white side of the GCL contact area for points 2,3 & 4
The Friction Angle and Adhesion (or Cohesion) results given here are based on a mathematically determined best fit line.
Further interpretation should be conducted by a qualified professional experienced in geosynthetic and geotechnical engineering.

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sampling, specimen preparation and setup in the testing device, and test execution in accordance with both project-specific conditions and industry standards.

2. A competent and certified laboratory performs the test series in accordance with the request and the industry standard test method (e.g., ASTM D5321 or D6243). The laboratory reports results to the engineer.

3. The engineer interprets and applies the results to the project design.

What we are measuring in the direct shear test is shear strength as a function of normal load. The test does not measure "friction" or "cohesion," as these are simply mathematical parameters derived from the laboratory test results.

Ideally the engineer who originally specified and required the shear test would be the same one who reviews and interprets the results. Sometimes, such as in a third-party construction quality assurance (CQA) project, an engineer other than the original designer will commission and review the testing. Interactions with test laboratories and other engineers over time have shown that there are often misconceptions and misunderstandings related to the interpretation of direct shear test data. Thus, this article is intended to serve the purpose of helping project participants avoid confusion. The key point of this article is that what we are measuring in the direct shear test is shear strength as a function of normal load. The test does not measure "friction" or "cohesion," as these are simply mathematical parameters derived from the laboratory test results.

Figure 1 presents shear test results of a 4-point test for an interface between a textured geomembrane and a reinforced GCL. Three shear points, each at a different normal stress, are the most common number of points used to run a test series, but the number of points could

vary from as few as one, to perhaps as many as six points, depending on many factors beyond the scope of this article. The figure shows: (a) a table of the normal stresses vs. peak and large-displacement shear strengths measured at 2.5in. of displacement, (b) graphs of the shear stress vs. displacement measurements, and (c) notes describing test conditions and observations.

There is adequate information in this figure for a trained practitioner to evaluate and use the data. The laboratory has performed its duty, which is to measure and report the shear strength under specified normal stresses (we are simplifying the dis-



cussion here by not elaborating on other factors such as hydration, consolidation, etc.), showing how the shear strength changed with displacement of the two surfaces, and providing descriptive and observational notes.

Figure 2 shows additional information that can be provided by a laboratory in the form of a graph of the peak and large-displacement strengths plotted as a function of normal stress. Best-fit straight lines, called Mohr-Coulomb strength envelopes, named after the gentlemen who first publicized the relationship between shear strength and normal stress, have been drawn through the two sets (peak and large-displacement) of data points.

Equations can be written for these lines, as we learned in first-year algebra class, in the form of $y = mx + b$. In this case we define y as the shear strength (S); m as the slope of the line that we call the “coefficient of friction” and whose angle is ϕ (ϕ), which we call the “friction angle” (and thus $\tan[\phi]$ is the slope of the line); x is the normal stress (N); and b is the y-intercept of the line that we call either “adhesion” (a , usually used for geosynthetics-only tests) or “cohesion” (c , usually used for tests involving soils, which will be used for the remainder of this article).

Mohr-Coulomb

In geotechnical engineering, we write the Mohr-Coulomb equation for these lines as:

$$S = N \cdot \tan(\phi) + c$$

This equation is written for peak, large-displacement, or residual shear strength conditions. The fundamental points in this article regarding the presentation of the data in Figure 2 include the following:

1. **The Mohr-Coulomb envelope should not be extrapolated beyond the limits of the normal stresses under which the testing was conducted.** To do so would never be conservative and, in fact, may be significantly nonconservative. The reason that simple extension-extrapolations of the Mohr-Coulomb

envelope are nonconservative is presented in Figure 3. Most shear strength envelopes are truly curved (nonlinear). This tendency for a curved failure envelope is exaggerated in Figure 3, but can clearly be identified for the real-life strength envelopes presented in Figure 2, in particular for large-displacement conditions.

The Mohr-Coulomb model is merely a linear simplification of a portion of the entire envelope over a limited range of normal stresses. If testing were performed over a large enough range of normal stresses the curvature would become

more apparent. True shear strength envelopes are found to be most accurately described by hyperbolic functions. Giroud et al. (1993) provides a good method to describe hyperbolic strength envelopes.

2. **The values of ϕ and c should be considered nothing more than mathematical parameters to describe the shear strength vs. normal stress over the normal-load range the test was conducted.** It is perhaps better not to think of “friction” and “cohesion” as real material properties, but simply as mathematical parameters to describe the failure envelope.

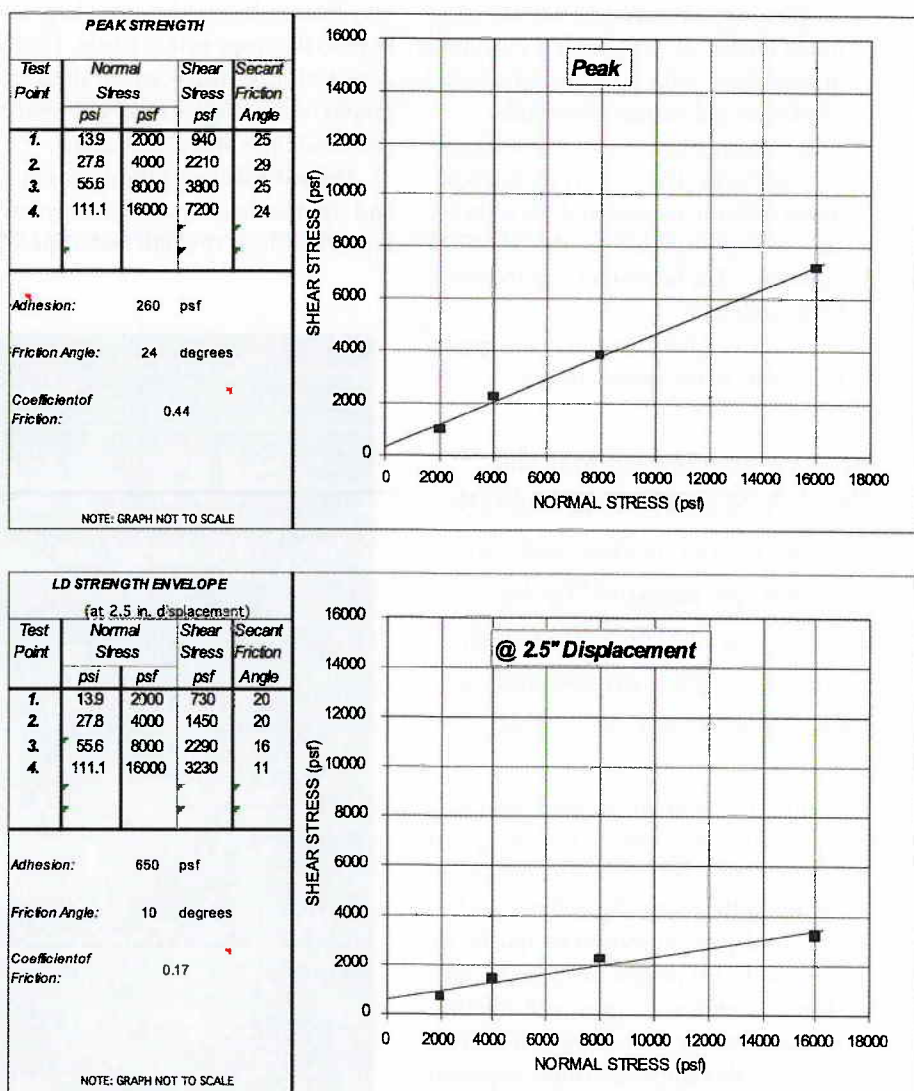


Figure 2 | Example of supplemental data interpretation provided by the laboratory.

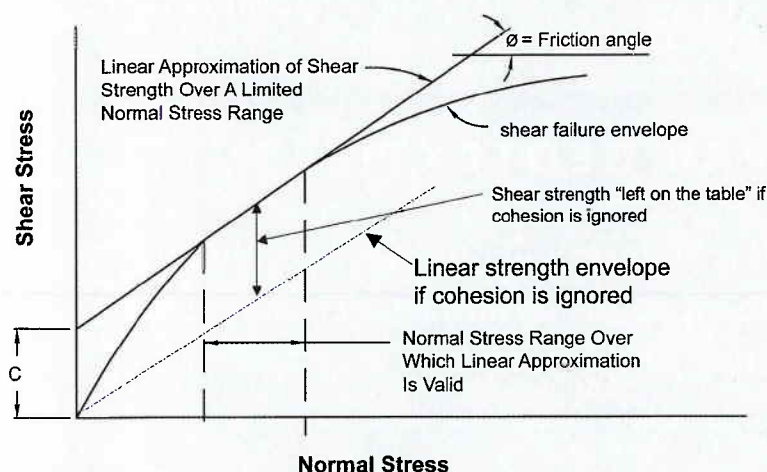


Figure 3 | Exaggerated schematic of true curvilinear shear strength envelope, linear interpretation over a selected normal stress range, and the penalty for ignoring cohesion.

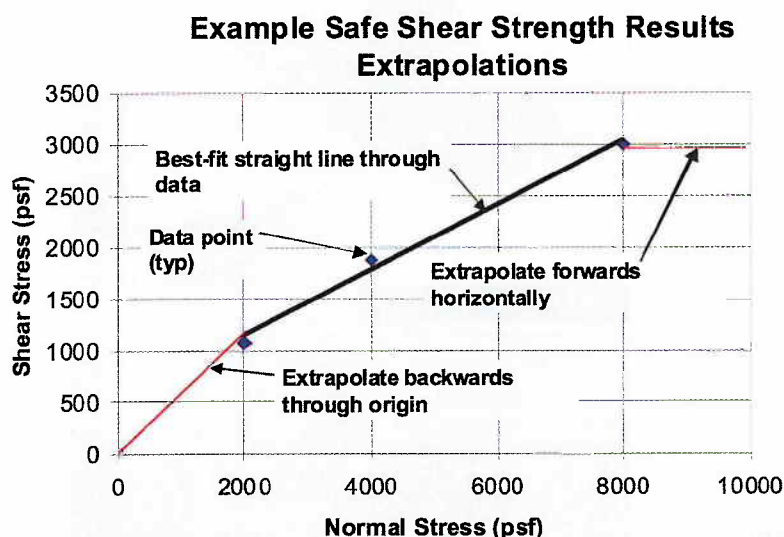


Figure 4 | Example of safe shear strength extrapolation.

In geotechnical practice with soils, there are situations and examples where the cohesion parameter is evaluated separately from the friction parameter, but these are sophisticated considerations that involve very project-specific materials and conditions and should only be done by experienced professionals.

For many geosynthetic interfaces and in the context of many types of projects, there is absolutely no reason to dissociate the slope of the line from its y-intercept, and the shear strength should be taken as

a whole in those cases. Other situations may occur, however, where it is appropriate, but those considerations are beyond the scope of this article.

3. In many, if not most, cases with geosynthetics where there is no reason to ignore the cohesion value, it is important to re-emphasize that shear strength should only be defined within the range of normal stresses for which the Mohr-Coulomb envelope was derived. Ignoring the cohesion may be unjustifiably penalizing the shear strength values that

were measured in the test, as illustrated in **Figure 3**.

Using the cohesion value at normal stresses extrapolated below the range of testing, however, could have dire consequences on the safety of a design project. This problem may occur when designers consider only the operational or final build-out of a facility and they ignore the construction condition. Several failures have occurred during construction because of this. For example, an embossed geomembrane against a geotextile may perform well under high normal loads by providing a good friction angle and a modest y-intercept for operating and final build-out conditions. However, under the low normal loads experienced during construction of a thin soil veneer on a steep sideslope, testing might reveal that the adhesion extrapolated from the high-normal load results do not exist at low normal loads. In this case, a more aggressive texturing that exhibits a "Velcro®-effect" type of adhesion, or a very high friction angle, at low normal loads may be needed and should be verified at the proper normal loads.

4. **Figures 1 and 2** also report *secant* friction angles for each point. These are the angles of the straight lines from each point drawn back to the origin. A key concept regarding secant friction angles is that you should never extrapolate a secant angle line beyond the normal load for which it is measured. Secant values are conservative as long as the secant values are derived from a test whose normal stress was greater than the normal stresses of the design. They can quickly become nonconservative if the same friction angle is used for higher normal loads.

5. If users wish to extrapolate shear strength data, **Figure 4** illustrates the only "safe" way to accomplish this. Going from the low end of the Mohr-Coulomb envelope and extrapolating backward, the data can be extrapolated by drawing a straight line back to the origin. Going from the high end of the Mohr-Coulomb envelope and extrapolating forward, the data can be extrapolated by drawing a straight line

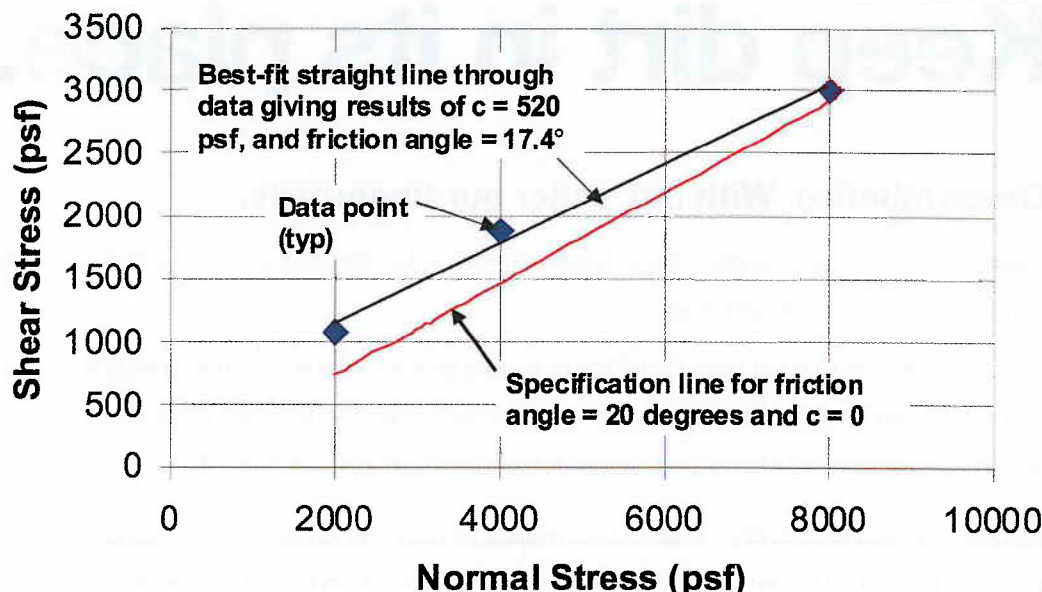


Figure 5 | Example project results where interpretation of test data results in lower friction angle than specified value, even though shear strength results are higher than the failure envelope implied by the specifications.

horizontally forward. This extrapolation rule is safe only when considering a single interface. When multiple interfaces are involved, it is not safe to extrapolate a multi-layered system on the high side of the Mohr-Coulomb envelope.

From the discussion above, we can now look at the ASTM standard D5321 with more understanding and critical thought. The first thing to note is that the title of that standard is poorly worded. The title is “*Determining the Coefficient of...Friction...*” This is somewhat misleading because it implies that the designer is simply after a coefficient of friction. In fact, what designers need is a relationship between shear strength and normal stress. Therefore, a more appropriate title for this method would be “*Determining the Relationship between Shear Strength and Normal Stress for Soil-to-Geosynthetic or Geosynthetic-to-Geosynthetic Interfaces Using the Direct Shear Method.*” Note that ASTM D6243 has already rectified this problem in its title.

Another misleading element in ASTM D5321 is the definition of *adhesion* (which applies equally to cohesion), which it states as: “The shearing resistance between two adjacent materi-

als *under zero normal stress* (emphasis added). Practically, this is determined as the y-intercept to a straight line relating the limiting value of shear stress that resists slippage between two materials and the normal stress across the contact surface of the two materials.”

This is actually *two separate definitions*, which are most likely not the intent of the standard. The first part of this definition, which defines the adhesion as the shear strength at zero normal stress, is not applicable relative to the test method. It *could be true* if we proposed to test the interface at zero normal load, but that is rarely done and generally of no use. The industry would be better served by deleting the first part of the definition. In reality, the second part of the definition is the controlling aspect of the definition, and the “y-intercept” concept is the true nature of the adhesion value which, as stated above, is simply a mathematical parameter.

Note that ASTM D6243 has a different set of definitions, and it is not clear if those definitions are unique to that standard, or are intended to be industry norms. ASTM D6243 suggests that adhesion is the true shear strength when

there is truly zero normal load, and that cohesion is the mathematical parameter of the y-intercept obtained from the Mohr-Coulomb envelope. In the author’s opinion these definitions are acceptable as stated, but the audience should know that the definition of *adhesion* may conflict with other definitions put forward in the industry. Also, other authors have introduced other terms for the measurable shear strength under zero normal load, such as Lambe and Whitman’s (1969) “*true cohesion*.” Interested readers can research ASTM D6243 and the literature and judge for themselves.

Example problem 1

The following situation illustrates a common example of a problem that occurs with shear test data interpretation:

- A specification is written that requires a certain minimum interface friction angle to be achieved between a textured geomembrane and a GCL. For purposes of this example, the requirement is 20° peak shear strength for normal loads tested between 2,000 and 8,000 pounds per square foot (psf).
- The laboratory results, shown as an

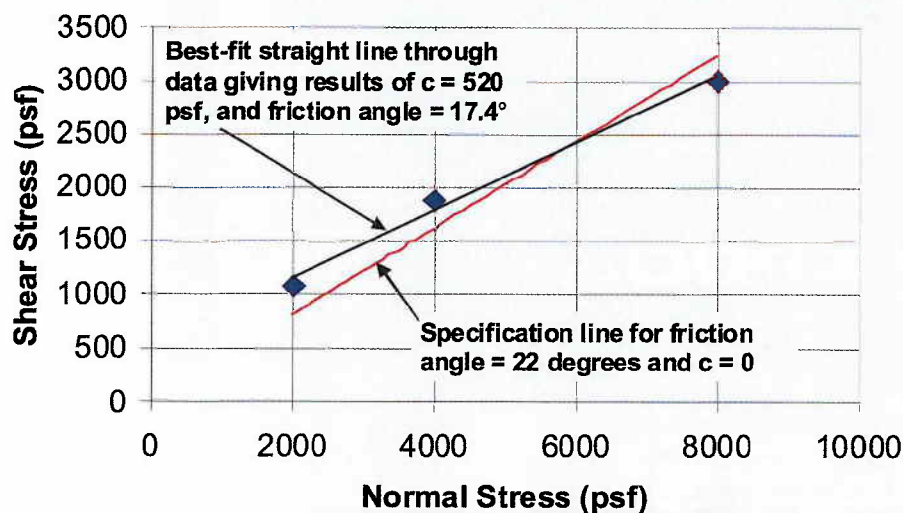


Figure 6 | Example project results where the two lower points are above the specification and the upper point is below the specification.

example in **Figure 5**, report a best-fit Mohr-Coulomb peak strength envelope with shear strength parameters of 500 psf cohesion and 15° friction. **Figure 5** also shows the line representing the minimum project specification.

Inspection of **Figure 5** shows that the shear strengths achieved in the direct shear test plot above the shear strength envelope required by the specification. Even though the plot appears to clearly indicate that the minimum required shear strength is achieved by the products tested, the author has experienced several projects where one of the project parties (e.g., the design engineer or perhaps a regulator) have declared the test a failure because the reported Mohr-Coulomb friction angle was less than the specified friction angle.

In the author's opinion, in many cases involving this particular interface, there is no reason to consider this a failing test.

This example illustrates the confusion that might arise when specification is written in terms of a shear-strength *parameter*, when the real objective is to achieve a certain value of absolute shear strength. Even though the materials provided the shear strength required by the specification, there is some confusion because one of the strength *parameters* did not meet the specified value for that parameter.

It is possible that the original specifier had taken into account the potential for cohesion, and had wished to discount cohesion, and really wanted a true minimum friction angle of 20°. If the specifier were truly that sophisticated and had such complex reasoning, then more than likely the specification would have also been more sophisticated in explaining these constraints on the test results.

In the author's experience it is rare that other designers and specifiers are discounting cohesion with geosynthetic interfaces, and usually it is simply a matter of proper interpretation and communication of the design intent compared to the actual test results. Nevertheless, as stated at the beginning of this article, it is not the intent of this article to provide guidance and suggestions on interpreting test results. Rather, the intent is to shed light on some common misunderstandings.

Example problem 2

The following problem has the same laboratory shear strength results as Problem 1, but the specification requirement is increased to 22° peak shear strength.

The relationship between the test results and the specification is shown in **Figure 6**. In this example, the two lower-normal load shear strength test results plot above the specification line, while the up-

per-normal load shear strength test result plots below the specification line. Based on the failing result of the upper-normal load test, most reviewers would initially say that this is a noncompliant test result and fails to meet the specification.

In the author's experience, curved failure envelopes are common, and the tendency for the highest normal-load result to fall beneath a straight-line friction-based specification is not unusual.

In this case, a more detailed review by the design engineer might reveal that the shear strength results provide an acceptable factor of safety for the intended purpose. It may be that the additional strength capacity provided in the lower normal load range that is above the specification more than offsets the reduced strength capacity in the upper normal load range that is below the specification. Clearly, the only person who can evaluate this issue, and who carries the requisite authority and responsibility, is the design engineer.

The following lessons can be gleaned from this example:

- Design engineers often attempt to specify a unique set of shear strength parameters as a minimum requirement for a given design. In reality, there may be an infinite combination of shear strength variations over the applicable range of normal loads that may satisfy the stability and shear resistance requirements, and many of these combinations may have a portion of their failure envelopes that fall below the specification.
- The tendency for natural and geosynthetic interfaces to yield curved failure envelopes can present a challenge to engineers, owners, and manufacturers who wish to optimize a design using simple straight-line shear strength specifications.
- A learned interpretation of direct shear testing data by an experienced practitioner may allow acceptance of apparently failing test results. This can occur because overly simplistic specification parameters may not ac-

count for other combinations of shear strength results that could provide acceptable overall shear resistance.

Summary

The direct shear test measures shear strengths as a function of normal stress. Period.

The test does not measure "friction angle" or "cohesion," as these values are parameters that are derived from the test results. Consideration of "friction angle" and "cohesion" simply as mathematical parameters used to describe shear strength data is of great benefit to practitioners for the following four reasons:

1. Interpretation of laboratory shear strength data should not be confused with the mathematical parameters used to describe it.

2. Proper data interpretation may avoid unnecessary penalization of the results by arbitrarily reducing the measured values.

3. This understanding can improve a designer's sensitivity to how important it is that shear strength is measured within the range of normal stresses that represent the design. Thus, the only defensible extrapolation of data should be: (a) back through the origin from the lowest normal stress, and (b) horizontally from the highest normal stress.

4. Laboratory shear strength data should be interpreted by a qualified practitioner experienced in the use and application of the results.

Often of much more importance than deciding whether to include or omit the cohesion (or adhesion) parameter is the

decision of whether to use peak, post-peak, or residual shear strength. This discussion is beyond the scope of this technical note, and anyone commissioning and interpreting shear strength testing should be well versed in the issues surrounding this topic, as well.

Acknowledgements

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