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DIRECT SHEAR TESTS USED IN SOIL-GEOMEMBRANE INTERFACE FRICTION STUDIES

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The Bureau of Reclamation Canal Lining Systems Program funded a series of direct shear tests on interfaces between a typical cover soil and different geomembrane liner materials. The purposes of the testing program were to determine the shear strength parameters at the soil-geomembrane interface and to examine the precision of the direct shear test. This report presents the results of the testing program.

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by

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INTRODUCTION

Interface friction or interface shear strength between geosynthetics and other engineered materials, including soil, is a topic of great interest in the geosciences. Mitchell et al. (1990) investigated a major slope failure which occurred in 1988 at a hazardous waste storage facility in California. After performing a series of direct shear tests on a variety of material interfaces, their investigation traced the cause of the failure to inadequate interface shear strength. One conclusion of their investigation was that "variations in measured interface shear strength parameters for various liner-system interfaces indicate the desirability of performing similar test programs (*direct shear tests*) for proposed new facilities to establish design parameters until such time as more data and experience are available."

Soil-covered geomembrane canal and reservoir liner systems, although not as critical as hazardous waste liner systems, have performed poorly on some Reclamation (Bureau of Reclamation) projects. To aid in establishing design parameters for future projects, the research program on geosynthetic canal lining systems funded a series of direct shear tests on interfaces between a typical cover soil and different geomembrane liner materials. The purposes of the testing program were to determine the shear strength parameters at the soil-geomembrane interface and to examine the precision of the direct shear test. Precision is the closeness of agreement between test results obtained under prescribed conditions. Single-operator-apparatus, multi-day precision for the direct shear test interface shear strength between cohesionless soil and geomembranes such as those used in this study was found to range from ± 2.4 to ± 0.5° for the friction angle and from ± 0.21 to ± 0.05 lbf/in^2 for the shear stress intercept. As expected, the results also show that roughened geomembranes provide higher friction angles and, therefore, better cover stability than smooth geomembranes. This report presents the results of the testing program.

CONCLUSIONS

Precision in the direct shear test is a combination of precision in measurement of shear stress and the effect of that precision on the shear strength envelope.

Measured maximum shear stress had the following statistics: sample standard deviation ranged from 0.02 to 0.28 lbf/in^2, range values were from 0.06 to 0.74 lbf/in^2, range as a percent of the average ranged from 3.5 to 18.3%, and coefficient of variation ranged from 1.4 to 7.0 %.

Precision of the shear stress measurements, based on coefficient of variation and range as a percent of the average, is within published values for *Single Operator Precision* published in various ASTM construction materials test standards in Volume 04.08.

Shear stress measurement precision combined with the Mohr-Coulomb shear strength model resulted in the following shear strength parameters and variations for normal stresses ranging from 1 to 5 lbf/in^2:

Mohr-Coulomb Model

Interface	Peak Shear Strength: Friction Angle (°)	Peak Shear Strength: Shear Stress (lbf/in^2)	Post-Peak Shear Strength: Friction Angle (°)	Post-Peak Shear Strength: Shear Stress (lbf/in^2)
Soil-on-Soil	47.5 ± 1.6	1.23 ± 0.21	35.8 ± 1.0	0.85 ± 0.10
Soil-on-PVC	29.7 ± 0.9	0.54 ± 0.07	28.2 ± 0.8	0.37 ± 0.06
Soil-on-VLDPE	29.3 ± 1.3	0.46 ± 0.10	27.4 ± 0.7	0.36 ± 0.05
Soil-on-Geotextile/PVC Composite	40.8 ± 1.8	0.95 ± 0.18	35.2 ± 1.2	0.76 ± 0.11
Soil-on-Texturized HDPE	45.2 ± 1.1	1.11 ± 0.13	34.4 ± 1.6	0.56 ± 0.14

Shear stress measurement precision combined with the one-point shear strength model resulted in the following shear strength parameters and variations for normal stresses ranging from 1 to 5 lbf/in^2:

One-Point Model

Interface	1.0 lbf/in^2 Friction Angle (°)	3.0 lbf/in^2 Friction Angle (°)	3.0 lbf/in^2 Friction Angle (°)
	Peak Shear Strength — Normal Stress		
Soil-on-Soil	66.4 ± 1.2	56.7 ± 1.0	53.1 ± 1.3
Soil-on-PVC	48.6 ± 1.7	36.3 ± 0.9	34.4 ± 0.5
Soil-on-VLDPE	45.6 ± 1.7	35.7 ± 0.8	33.1 ± 1.3
Soil-on-Geotextile/PVC Composite	61.6 ± 1.0	49.1 ± 0.8	46.7 ± 2.4
Soil-on-Texturized HDPE	64.9 ± 1.3	53.7 ± 1.7	50.9 ± 1.0
	Post-Peak Shear Strength		
Soil-on-Soil	57.6 ± 0.8	45.1 ± 0.7	41.7 ± 0.8
Soil-on-PVC	42.5 ± 0.5	33.0 ± 0.7	31.4 ± 0.7
Soil-on-VLDPE	42.0 ± 0.7	31.9 ± 0.5	30.7 ± 0.5
Soil-on-Geotextile/PVC Composite	55.7 ± 0.8	43.9 ± 1.1	40.6 ± 0.9
Soil-on-Texturized HDPE	51.7 ± 1.4	40.7 ± 1.3	38.7 ± 1.3

The Mohr-Coulomb model resulted in soil-on-soil friction angles that are somewhat higher than values reported by other investigators. The differences are likely caused by the particle size and angularity of the sand and by the low normal stresses used in testing.

The soil-on-geomembrane friction angles from the Mohr-Coulomb model are in general agreement with data published by other investigators. Efficiency ratios for friction angles also agree well with published values. The soil-on-geomembrane shear stress intercepts are somewhat higher than data published by other investigators. The differences are likely caused by the particle size and angularity of the sand and by the low normal stresses used in testing.

The one-point model resulted in soil-on-soil friction angles that are somewhat higher than values reported by other investigators. The differences are likely caused by the angularity of the sand and by the low normal stresses used in testing.

The soil-on-geomembrane friction angles computed using the one-point model are in general agreement with data published by other investigators. Efficiency ratios also agree well with published values.

Single operator precisions for the direct shear test interface shear-strength between cohesionless soil and geomembranes reported in this study ranged from ± 2.4 to $\pm 0.5°$ for the friction angle and from ± 0.21 to ± 0.05 lbf/in^2 for shear strength intercept. These limits apply to shear strength computed using either the Mohr-Coulomb model or the one-point model.

As expected, the results of this testing program show that roughened geomembranes provide higher friction angles and, therefore, better cover stability than smooth geomembranes.

DISCUSSION

General

The direct shear test is the oldest test method for determining soil shear strength. Head (1982), in his volume on soil laboratory testing, credits Alexandre Collin with the development of a direct shear apparatus in 1846 and Arthur Casagrande with development of the modern direct shear apparatus at Harvard University in 1932.

Despite a 60-year history of use in soil mechanics, a literature review reveals that very little has been published concerning the precision of the direct shear test. ASTM (American Society for Testing Materials) D 3080, Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions (ASTM, 1993), in the section on *Precision and Bias*, simply states that "Data are being evaluated to determine the precision of this test method." Other references such as Head (1982) and the U.S. Army Corps of Engineers (1970) do not address precision.

Direct shear testing of soil against geosynthetics is a recent application and dates only to the late 1970s or early 1980s (Collios et al., 1980). ASTM D 5321, Standard Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method (ASTM, 1993) states only that "The precision of this test method is being established."

The only data in the literature on precision of soil-geosynthetic interface direct shear testing are reported by Mitchell et al. (1990). For one series of three direct shear tests using compacted clay on HDPE (high density polyethylene), they reported the standard deviation for the friction angle to be ± 2.4° for peak shear strength and ± 1.1° for residual shear strength.

Test Program Design

The test program was designed to determine single-operator-apparatus, multi-day precision. The program is based on tests performed by one operator using one direct shear machine on one soil and several geomembranes over a period of several weeks. The object of the program was to control as many variables as possible. The total program consisted of 63 individual direct shear tests. Normal pressures of 1, 3, and 5 lbf/in² were used in each test to model the low normal stresses on a geomembrane buried under a soil cover about 1 to 5 ft thick. A cohesionless sand was selected to model a typical cover soil and four geomembranes were selected as typical liner materials. These materials were combined to form five interfaces: one soil-on-soil interface and four soil-on-geomembrane interfaces. Five replicate tests were performed for three of the interfaces and three replicate tests were performed for the other two interfaces.

Interface shear strength was evaluated at peak or maximum shear stress and at a post-peak shear stress; that is, at some shear stress lower than peak that was attained at displacements beyond those required to reach peak shear stress. To evaluate both peak and post-peak interface shear strength, each direct shear test consisted of four distinct shear displacements. The first or initial shear displacement from each test was used to compute peak interface shear strength. The second, third, and fourth shear displacements were used to compute post-peak interface shear strength.

A random testing sequence was used to minimize testing bias, and one operator performed all tests to minimize variations induced by changing operators. Sand for each test specimen was compacted to the same dry density to minimize variation caused by density. Each specimen was wetted and allowed to fully consolidate under the applied normal stress prior to application of the shear load. New sand and geomembrane specimens were used for each test to minimize variations caused by particle breakdown or scarring of the geomembrane surface. The complete testing matrix is shown in table 1 and the randomized testing sequence is shown in table 2.

Equipment

All tests were performed on the same direct shear apparatus. The direct shear apparatus applies a constant vertical load (applied normal stress) to the top of the test specimen while applying a constant rate of horizontal displacement (pure shear) to one half of the shearbox. The equipment is described in detail in USBR 5725, Procedure for Performing Direct Shear Testing of Soils (Bureau of Reclamation, 1990), and a schematic of the equipment is shown on figure 1. A shearbox with nominal inside dimensions of 4 by 4 by 1 in. high was used in all tests. A horizontal displacement rate of 0.05 in/min was selected to ensure rapid dissipation of any pore pressures generated during shear. The load cell used to measure shear load was calibrated in accordance with USBR 1045, Procedure for Calibrating Force Transducers (Load Cells) (Bureau of Reclamation, 1990), prior to the start of the testing program. The LVDTs (linear variable differential transformers) used to measure horizontal and vertical displacement were calibrated in accordance with USBR 1008, Procedure for Calibrating Linear Variable Differential Transformers (Bureau of Reclamation, 1990), prior to the start of the testing program. One calibration prior to the start of testing meets all requirements specified in USBR 1045 and UBSR 1008 for the entire test program.

Tests involving geomembranes used a shearbox modified to provide a stiff base for the geomembrane. The modification consisted of filling the bottom half of the shearbox with Hydrostone™, a quick-setting, high-strength gypsum cement. The geomembrane specimen was placed on top of the hardened Hydrostone and anchored to the shearbox. Tests involving only soil used a shearbox filled completely with soil as in conventional soil direct shear testing.

Materials

Four geomembranes were tested in this program: (a) a smooth 40-mil (0.04-in) thick PVC (polyvinyl chloride) geomembrane, (b) a smooth 40-mil (0.04-in) thick VLDPE (very low density polyethylene) geomembrane, (c) a texturized co-extruded HDPE (high density polyethylene) geomembrane, and (d) a composite geosynthetic consisting of a 3.6-oz/yd^2 nonwoven needle-punched geotextile bonded to a 30-mil (0.03-inch) thick PVC membrane. The geotextile side on the geosynthetic composite was used against soil in the direct shear tests on this material. Rectangular test specimens 7.0 in. long by 4.2 in. wide were cut from larger sheets of geomembrane. A fresh geomembrane specimen was used for each test.

A sample of about 40 lb of concrete sand (ASTM C 33, Standard Specification for Concrete Aggregates, Fine Aggregate [ASTM, 1991a]) was obtained from a commercial aggregate source. The subangular to angular, cohesionless sand was used as the soil in all tests. A gradation test and maximum and minimum index unit weight tests were performed on specimens taken from the sample. Results of these tests are shown on figures 2 and 3. The sand is classified as SP (poorly graded sand). The predominately medium-size sand has a maximum particle size of 4.75 mm and a D_{60} size of 1.04 mm. The maximum index dry unit weight was 122.7 lbf/ft^3 and the minimum index dry unit weight was 99.0 lbf/ft^3. The remainder of the sample was separated into size fractions by dry sieving on the 2.36-mm (No. 8), 1.18-mm (No. 16), 600-µm (No. 30), 300-µm (No. 50), 150-µm (No. 100), and 75-µm (No. 200) sieves.

The sand was placed at about 50% relative density for all direct shear tests. The target dry unit weight (109 lbf/ft^3) was selected to approximate the in-place dry unit weight of a dumped soil cover. The weight of dry sand required for each direct shear specimen was determined from the volume of the shearbox and the target dry unit weight. Based on the gradation of the sand (see fig. 2), the weight of sand required from each size fraction was determined. The appropriate weight of sand from each size fraction was obtained and mixed together to form the sand portion of each direct shear test specimen.

Possible variation in gradation from specimen to specimen caused by the specimen preparation method was evaluated by performing gradation tests on eight specimens after direct shear testing. The results of the eight specimen gradations are shown on figure 4. The individual gradations plot almost on top of each other. The gradation results are also presented in table 3. Very little variation exists between the specimen gradations. Standard deviations are well within the guidelines for single-operator precision for fine aggregate set by ASTM C 136, Standard Method for Sieve Analysis of Fine and Coarse Aggregates (ASTM, 1991a). Slight variation exists between the sample gradation and the average specimen gradation. The maximum variation occurs on the 600-µm (No. 30) sieve, where the average specimen gradation has about 2% more material than the sample gradation. This variation is not considered significant, and for all intents and purposes the sand specimens were identical and matched the desired gradation.

Test Procedures

After preparing the materials as described above, each direct shear specimen was assembled as described below and tested in the order prescribed by the random testing sequence in table 2.

Specimen assembly.-For soil/geomembrane interface tests the following procedure was used:

1. The bottom half of the shear box, which had been filled with Hydrostone, was fitted into the shear box bowl (reservoir).
2. The geomembrane specimen was mounted over the Hydrostone and attached in position using the shear box lock screws.
3. The top half of the shear box was aligned and attached to the bottom half using the alignment screws.
4. The prepared dry soil was thoroughly mixed and poured into the top half of the shear box. The soil was compacted by tamping or rodding to the target dry unit weight (109 lbf/ft^3) and leveled with the top of the shear box.
5. The shear box bowl and specimen were moved to the direct shear apparatus for testing.

For tests without geomembrane (i.e., soil-on-soil) the following procedure was used:

1. The bottom half of the shear box was fitted into the shear box bowl (reservoir) and attached in position using the shear box lock screws.
2. The top half of the shear box was aligned and attached to the bottom half using the alignment screws.
3. The prepared dry soil was thoroughly mixed and poured into the shear box. The soil was compacted by tamping or rodding to the target dry unit weight (109 lbf/ft^3) and leveled with the top of the shear box.
4. The shear box bowl and specimen were moved to the direct shear apparatus for testing.

Direct shear testing.-The shear box bowl and specimen are mounted to the direct shear apparatus and the shear load cell and horizontal displacement LVDT attached to the shear box bowl. Water is added to the shear box bowl to a level just below the top of the shear box and water enters the specimen from the bottom, flowing upward because of the slight differential head across the specimen. When moisture is seen on the surface of the soil, the top porous stone and load transfer plate are placed on the specimen. The loading yoke system is assembled and the vertical displacement LVDT is attached to the top of the yoke. The specimen is inundated. The required normal stress is applied to the specimen and the specimen is allowed to consolidate. Consolidation is monitored using the vertical LVDT. After consolidation is complete, a 0.0125-in. gap is formed between the shear box halves using the gap screws. With the gap set and the gap screws retracted, the specimen is sheared at the prescribed horizontal displacement rate. Horizontal and vertical displacement and shear load are monitored throughout the test.

Following initial shear displacement under the prescribed normal stress, the normal stress is released and the shear box halves are realigned to their original positions. The specimen is subjected to a 1-lbf/in^2 normal stress and is then consolidated. Following consolidation at 1 lbf/in^2 normal stress, the specimen is sheared a second time. Following this second shear displacement, the consolidation/shearing sequence is repeated a third and fourth time at 3 and 5 lbf/in^2, respectively. Thus, each direct shear test consists of four separate shear displacements: the initial shear displacement for determining peak shear strength and three subsequent shear displacements for determining post-peak shear strength.

Data reduction and analysis.-The initial shear displacement provides data to evaluate peak interface shear strength. The three subsequent shear displacements provide data to evaluate post-peak interface shear strength. Data collected during each shear displacement include shear load, horizontal displacement, and vertical displacement. Figure 5 is a plot of vertical displacement versus time for the soil-on-soil interface. This plot is typical of all tests performed for this study, including both soil-on-soil and soil-on-geomembrane tests. Shear load and horizontal displacement are reduced to shear stress and relative horizontal displacement in percent of specimen width. Figures 6, 7, and 8 are typical shear stress versus relative horizontal displacement curves for initial shear displacements for three of the five interfaces. Figures 9, 10, and 11 are typical shear stress versus relative horizontal displacement curves for subsequent shear displacements for three of the five interfaces.

The maximum shear stress was determined for each shear displacement. Normal stress and corresponding maximum shear stress data are used to compute the shear strength envelopes for each interface. Linear regression techniques are used to compute the best-fit curve to the shear stress-normal stress data and 95% confidence intervals about the best-fit curve. Common sample statistics including average, standard deviation, range, range as a percent of the average, and coefficient of variation are used to evaluate the precision of measured maximum shear stress for the various interface-pressure combinations. Shear stress data for each test and statistics for various data groupings are presented in table 4.

Precision of the Direct Shear Test

Direct shear test results are presented in the form of a shear strength envelope which defines the relationship between shear stress and normal stress. The shear strength envelope may or may not be linear. Precision in the direct shear test is therefore a combination of precision in measurement of shear stress and the effect of that precision on the shear strength envelope.

Shear stress precision.-Precision is defined in ASTM E 456, Standard Terminology Relating to Quality and Statistics (ASTM, 1991b), as "the closeness of agreement between test results obtained under prescribed conditions." In addition, ASTM E 177, Use of the Terms Precision and Bias in ASTM Test Methods (ASTM, 1991b), states, "The greater the dispersion or scatter of the test results, the poorer the precision."

Range as a percent of the average and coefficient of variation are direct measures of precision and have been used by ASTM Committee D-18 on Soil and Rock (ASTM, 1993) to define *Single Operator Precision* in the few standards for which precision has been determined (see table 5). Sample standard deviation and range are also measures of data dispersion, and the smaller the value of these statistics the better the precision. These four statistics will be examined to evaluate the precision of the shear stress measurements.

Shear stress data for each test and statistics for various data groupings are presented in table 4. Table 4 is arranged in the following manner. Columns (1) and (2) are the material combinations at the interface and specimen numbers, respectively. Column (3) is the number of replicate tests for each interface/normal stress combination. Columns (4) through (6) are the applied normal stress, maximum shear load, and the maximum shear stress, respectively, for the initial shear displacement. Columns (7) through (11) are common sample statistics for maximum shear stress, including average, sample standard deviation, range, range as a percent of the average (ratio of range to average), and coefficient of variation (ratio of standard deviation to average) for the initial shear displacement. The remaining columns repeat this sequence for the subsequent shear displacements, that is, columns (12) through (19) for the second shear displacement, columns (20) through (27) for the third shear displacement, and columns (28) through (35) for the fourth shear displacement.

In the remainder of this report the following abbreviations will be used for the common sample statistics: *SD* — sample standard deviation, *R* — range, *RPA* — range as a percent of the average, and *CV* — coefficient of variation.

Maximum shear stress data may be analyzed in groups with common boundary conditions. The most obvious groups are the sets of replicate tests for each interface/normal stress/displacement cycle combination. For example, columns (4) through (11) are results for initial shear displacements for each of the five material interfaces. These data can be further grouped by applied normal stress into nine groups containing five replicate tests, five groups containing three replicate tests, and one group containing four replicate tests. Thus, tests SS-1-1 through SS-1-5 (lines 1 through 5) are five replicate tests of soil-on-soil at an applied normal stress of 1 lbf/in^2; tests SS-3-1 through SS-3-5 (lines 6 through 10) are five replicate tests of soil-on-soil tested at 3 lbf/in^2, and so on through the table. Columns (12) through (19), (20) through (27), and (28) through (35) can be grouped the same way for the second, third, and fourth shear displacements, respectively. A total of 60 groups of replicate tests are formed in this manner. For the 60 groups of replicate tests, *SD* for maximum shear stress ranged from 0.01 to 0.30 lbf/in^2, *R* ranged from 0.02 to 0.73 lbf/in^2, *CV* ranged from 0.7 to 8.7%, and *RPA* ranged from 1.3 to 18.4%.

For the subsequent shear displacements (i.e., the second, third, and fourth displacements), shear stress data can also be grouped by interface and applied normal stress. Columns (12) through (19), for example, are data from the second shear displacement for each test. The data on lines 1 through 15 are from 15 tests performed on the soil-on-soil interface at an applied normal stress of 1 lbf/in^2. Likewise, lines 17 through 31 are tests at 1 lbf/in^2 on the soil-on-PVC interface; lines 33 through 47 are soil-on-VLDPE at 1 lbf/in^2, and so on for the other interfaces at the same conditions. In this manner, 9 groups of 15 tests each, 3 groups of 10 tests each, and 3 groups of 9 tests each can be formed. Statistics for these groups are presented on lines 16, 32, 48, 58, and 69 of table 4. For these groups of subsequent shear displacements, *SD* for maximum shear stress ranged from 0.03 to 0.26 lbf/in^2, *R* ranged from 0.08 to 0.78 lbf/in^2, *CV* ranged from 3.0 to 6.9%, and *RPA* ranged from 9.0 to 21.1 %.

A logical question to ask is: "Are these values of *RPA* and *CV* reasonable?" To find the answer to this question, the *1993 Annual Book of ASTM Standards*, Volume 04.08, Soil and

Rock; Dimension Stone; Geosynthetics (ASTM, 1993), was reviewed for standards containing numeric values of precision. Each ASTM standard test method is required to have a section addressing precision and bias; however, precision has been determined for only a small percentage of the standards in this volume. These standards are listed in table 5. A review of table 5 indicates that *RPA* between 1.9 and 11.1% and *CV* between 2.4 and 12.0% have been established for these ASTM standards.

For numeric data taken from a normally distributed population, a linear relationship exists between *R* and *SD*. Because the ratio of *R* to *SD* equals the ratio of *RPA* to *CV*, this linear relationship also applies to *RPA* and *CV*. The relationship is: $R = \boldsymbol{k}\ SD$, where $\boldsymbol{k}$ varies with sample size. The value of $\boldsymbol{k}$, for a 5% significance level, is 2.43 for a sample size of 4 and 3.68 for a sample size of 10 (see ASTM E 178, Dealing With Outlying Observations, Table 3 [ASTM, 1991b]). This relationship can then be written as $RPA = \boldsymbol{k}\ CV$.

Precision statements in two ASTM standards confirm this relationship; D 2216 and D 4221 present values for both *RPA* and *CV* and can therefore be used to compute $\boldsymbol{k}$. D 2216 reports RPA = 7.8% and CV = 2.7%, for which $\boldsymbol{k}$ = 2.9. D 4221 reports RPA = 11.1% and CV = 3.9%, for which $\boldsymbol{k}$ = 2.8. This relationship is consistent with ASTM E 691, Conducting an Interlaboratory Study to Determine the Precision of a Test Method, which recommends a sample size of 3 (minimum), although 6 samples are preferred (ASTM, 1991b).

At first, the *RPA* for maximum shear stress obtained in this study appears to exceed the maximum value reported in the standards presented in ASTM Volume 04.08 (11.1% in ASTM versus 21.1% measured in this study). If the relationship $RPA = 2.9\ CV$ is applied to the precision data from standards in ASTM Volume 04.08, as shown in table 5, then *RPA* could be as high as 34.8% (D 4884, with CV = 12.0%). The sample size in this study was 5 for most tests, 3 for some tests, and 4 for one test, which meets the requirements of ASTM E 691. If the relationship $RPA = 2.9\ CV$ is applied to the data from this study, then *RPA* could range as high as 25.2% and still be considered acceptable. Because the maximum value of *RPA* reported in this study (21.1%) is below 25.2%, the precision of the tests in this study is considered acceptable.

Shear strength envelopes and test results.-The true shear strength envelope for most cohesionless soils at low normal stresses is curved (i.e., nonlinear) and passes through the origin of the shear stress-normal stress plot. Two models have been used in practice to approximate the nonlinearity. The first model uses a straight line to approximate a relatively small portion of the true envelope. This model is the Mohr-Coulomb model, which produces a friction angle that is defined by the slope of the straight line and a term called either cohesion or adhesion that defines the shear stress intercept of the straight line. The envelope thus defined is applicable only to the range of normal stresses used in the direct shear test and should not be used to predict shear strength outside this range. Myles (1982), Martin et al. (1984), Richards and Scott (1985), Williams and Houlihan (1987), and Carey and Swyka (1991) illustrate use of the Mohr-Coulomb model for geosynthetic interface shear strength.

The second model, called the *one-point model* in this report, treats each shear stress/normal stress data point on the true envelope as a one-point direct shear test. Using one shear stress/normal stress data point and the origin as two points on a straight line envelope, a friction angle can be computed for each normal stress. Because the envelope goes through the origin, the shear stress intercept of the envelope is zero. A relationship can be developed between friction angle and normal stress which does not involve a shear stress intercept. The relationship is applicable only to the range of normal stresses used in the direct shear test and should not be used to predict shear strength outside this range. Akber et al. (1985), Degoutte and Mathieu (1986), and Koutsourais et al. (1991) illustrate use of the one-point model for geosynthetic interface-shear-strength.

Mohr-Coulomb shear strength envelopes were computed using least squares regression techniques. Two envelopes were developed for each material interface. The first envelope was developed for the initial shear displacement (fifteen data points for most interfaces) and represents the peak shear strength envelope. The second envelope was developed from the second, third, and fourth shear displacements (45 data points for most interfaces) and represents the post-peak shear strength envelope. In keeping with the Mohr-Coulomb strength theory, only linear equations were used in the regression analyses. Figures 12 through 16 present the peak shear strength envelopes and figures 17 through 21 present the post-peak shear strength envelopes for the five material interfaces. Table 6 presents a summary of the Mohr-Coulomb shear strength parameters.

One-point shear strength envelopes were also computed using least squares regression techniques. Two envelopes were developed for each material interface-pressure combination. The first envelope was developed for the initial shear displacement (five data points per interface/pressure combination for most interfaces) and represents the peak shear strength envelope. The second envelope was developed from the second, third, and fourth shear displacements (15 data points per interface/pressure combination for most of the interfaces) and represents the post-peak shear strength envelope. In keeping with the one-point model, only straight lines were used in the regression analyses. Figure 22 presents the peak shear strength envelopes for the soil-on-soil interface at normal stresses of 1, 3, and 5 lbf/in^2. Table 7 presents a summary of the shear strength parameters for the one-point model. Figures 23 and 24 present the relationship between friction angle and normal stress derived using the one-point model for peak shear strength and post-peak shear strength, respectively.

Confidence intervals for a 95% probability of occurrence were computed for the coefficients of each best-fit straight line from each model. Confidence intervals for a straight line form curves (ellipsoids) above and below the line as seen on figure 12. Variation in friction angle or shear stress intercept can be computed from the confidence intervals. Tables 6 and 7 summarize the variation based on the 95% confidence intervals for the Mohr-Coulomb and the one-point models, respectively.

Also presented in tables 6 and 7 is the so-called interface efficiency or efficiency ratio, the ratio of the shear strength component at the interface (either friction angle or shear stress intercept) to the corresponding soil-on-soil shear strength component. The ratio was apparently coined by Martin et al. (1984) to show the drop in mobilized shear strength caused by the presence of the interface and to allow easy comparison of one interface to another. The ratio for friction angles for sand-geomembrane interfaces has been reported to vary from near 0.6 to slightly over 1.0 (for the Mohr-Coulomb model see Martin et al. [1984], and for the one-point model see Koutsourais et al. [1991]). The ratio for shear stress intercept for clay-geomembrane interfaces has been reported to vary from 0.1 to 0.9 (see Koerner et al. [1986]).

The Mohr-Coulomb model resulted in soil-on-soil friction angles which are somewhat higher than values reported by other investigators (Williams and Houlihan [1987] and Martin et al. [1984]). The differences are likely caused by the particle size and angularity of the sand and by the low normal stresses used in testing. Most reported investigations used normal stresses above 10 lbf/in^2.

The Mohr-Coulomb model resulted in soil-on-geomembrane friction angles which are in general agreement with data published by other investigators (Williams and Houlihan [1987] and Martin et al. [1984]). Efficiency ratios for friction angles also agree well with published values. The soil-on-geomembrane shear stress intercepts are somewhat higher than data published by other investigators and the differences are likely caused by the particle size and angularity of the sand and by the low normal stresses used in testing.

The one-point model resulted in soil-on-soil friction angles which are somewhat higher than values reported by other investigators (Akber et al. [1985], Degoutte and Mathieu [1986], and Koutsourais et al. [1991]). The difference is likely caused by the particle size and angularity of the sand and by the low normal stresses used in testing.

The one-point model resulted in soil-on-geomembrane friction angles which are in general agreement with data published by other investigators (Akber et al. [1985], Degoutte and Mathieu [1986], and Koutsourais et al. [1991]). Efficiency ratios agree well with published values.

Single operator precisions for the direct shear test interface shear strength between cohesionless soil and geomembranes reported in this study ranged from ± 2.4 to ± 0.5° for the friction angle and from ± 0.21 to ± 0.05 lbf/in^2 for shear strength intercept. These values apply to shear strength computed using either the Mohr-Coulomb model or the one-point model.

CONVERSION TABLE

SI/metric	English
4.448 N	1 lbf
6.89 kPa	1 lbf/in^2
0.0283 m^3	1 ft^3
0.000645 m^2	1 in^2
2.54 mm	1 in
0.1571 kN/m^3	1 lbf/ft^3

Note: 1 N/m^2 = 1 Pa

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Table 1. — Geomembrane direct shear tests: testing matrix.

Testing matrix: Material interface - normal pressure combinations

Materal Interface	Normal pressure (lbf/in²)														
	1					3					5				
	Replicate tests					Replicate tests					Replicate tests				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Soil-on-Soil	SS-1-1	SS-1-2	SS-1-3	SS-1-4	SS-1-5	SS-3-1	SS-3-2	SS-3-3	SS-3-4	SS-3-5	SS-5-1	SS-5-2	SS-5-3	SS-5-4	SS-5-5
Soil-on-PVC	PV-1-1	PV-1-2	PV-1-3	PV-1-4	PV-1-5	PV-3-1	PV-3-2	PV-3-3	PV-3-4	PV-3-5	PV-5-1	PV-5-2	PV-5-3	PV-5-4	PV-5-5
Soil-on-VLDPE	VL-1-1	VL-1-2	VL-1-3	VL-1-4	VL-1-5	VL-3-1	VL-3-2	VL-3-3	VL-3-4	VL-3-5	VL-5-1	VL-5-2	VL-5-3	VL-5-4	VL-5-5
Soil-on-Geotextile/PVC Composite	SG-1-1	SG-1-2	SG-1-3			SG-3-1	SG-3-2	SG-3-3			SG-5-1	SG-5-2	SG-5-3		
Soil-on-Texturized HDPE	ST-1-1	ST-1-2	ST-1-3	ST-1-3R*		ST-3-1	ST-3-2	ST-3-3			ST-5-1	ST-5-2-R	ST-5-3		

* Repeat test

Table 2. — Geomembrane direct shear tests: random testing sequence.

Initial test series									
Material Interface-Pressure Combination	Test Order	Material Interface-Pressure Combination	Test Order	Material Interface-Pressure Combination	Test Order	Material Interface-Pressure Combination	Test Order	Material Interface-Pressure Combination	Test Order
PV-3-1	1	SS-3-4	10	VL-3-4	19	SS-1-2	28	SS-5-1	37
VL-5-4	2	PV-1-5	11	SS-3-3	20	VL-5-5	29	VL-1-5	38
PV-1-2	3	SS-5-5	12	SS-1-5	21	VL-1-2	30	VL-5-1	39
VL-3-5	4	PV-1-4	13	VL-1-1	22	VL-3-2	31	VL-1-4	40
VL-3-3	5	PV-5-2	14	VL-5-2	23	PV-5-1	32	VL-1-3	41
SS-5-3	6	SS-1-4	15	PV-1-1	24	SS-3-2	33	SS-5-2	42
VL-5-3	7	SS-1-3	16	PV-3-2	25	SS-1-1	34	PV-3-4	43
SS-5-4	8	VL-3-1	17	PV-3-5	26	PV-5-3	35	PV-5-5	44
PV-3-3	9	PV-1-3	18	PV-5-4	27	SS-3-5	36	SS-3-1	45

Second test series			
Material Interface-Pressure Combination	Test Order	Material Interface-Pressure Combination	Test Order
SG-3-2	46	ST-5-1	55
SG-5-2	47	SG-1-3	56
SG-3-1	48	ST-1-2	57
ST-3-1	49	ST-1-3	58
SG-1-1	50	ST-5-3	59
ST-1-1	51	SG-5-1	60
ST-3-2	52	SG-1-2	61
ST-5-2	53	SG-5-3	62
SG-3-3	54	ST-3-3	63

Table 3. — Geomembrane direct shear tests: gradation test results.

Sieve Size	Specimen number: SS-1-3 Percent Passing (%)	SS-3-1 Percent Passing (%)	SS-3-3 Percent Passing (%)	SS-5-1 Percent Passing (%)	PV-3-5 Percent Passing (%)	VL-1-2 Percent Passing (%)	VL-1-3 Percent Passing (%)	VL-5-2 Percent Passing (%)	Specimen statistics: Average (%)	Range (%)	Sample Standard Deviation (%)	Coefficient of Variation (%)	Percent Retained Based on Average (%)	ASTM C 136-84a: Acceptable Range (%)	Acceptable Standard Deviation (%)	65K-1 Target Percent Passing (%)	Difference Between Target and Specimen Average (%)
4.75 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.00	0.0	0.0	0.4	0.14	100.0	0.0
2.36 mm	81.0	80.7	80.8	81.1	80.9	80.6	80.6	80.3	80.8	0.8	0.26	0.3	19.2	1.7	0.60	80.1	-0.7
1.18 mm	64.8	64.3	64.9	64.8	64.6	65.1	64.1	64.5	64.6	1.0	0.33	0.5	16.2	1.7	0.60	64.1	-0.5
600 µm	44.4	44.4	44.3	45.0	45.2	44.2	44.7	44.9	44.6	1.0	0.37	0.8	20.0	1.8	0.64	42.7	-1.9
300 µm	20.8	20.5	21.0	20.8	20.7	21.3	20.6	20.5	20.8	0.8	0.27	1.3	23.8	1.8	0.64	19.7	-1.1
150 µm	7.8	8.0	8.0	8.3	8.3	8.1	8.2	8.0	8.1	0.5	0.17	2.1	12.7	1.7	0.60	7.5	-0.6
75 µm	2.3	2.2	2.5	2.4	2.4	2.6	2.1	2.2	2.3	0.5	0.17	7.3	5.8	1.2	0.43	2.3	0.0

Table 4. — Geomembrane interface-friction direct shear tests (sheet 1 of 16).

Specimen area = 15.76 in²				Initial shear displacement							
Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Normal Stress (lbf/in²) (4)	Maximum Shear Load (lbf) (5)	Maximum Shear Stress (lbf/in²) (6)	Average Maximum Shear Stress (lbf/in²) (7)	Standard Deviation (lbf/in²) (8)	Range (lbf/in²) (9)	Range as Percent of Average (%) (10)	Coefficient of Variation (%) (11)
1	Soil - on - Soil	SS-1-1	5	1	36.2	2.30	2.28	0.11	0.29	12.5	4.7
2		SS-1-2		1	36.7	2.33					
3		SS-1-3		1	35.0	2.22					
4		SS-1-4		1	33.8	2.14					
5		SS-1-5		1	38.3	2.43					
6		SS-3-1	5	3	69.4	4.40	4.56	0.14	0.36	7.9	3.1
7		SS-3-2		3	73.0	4.63					
8		SS-3-3		3	75.1	4.77					
9		SS-3-4		3	70.5	4.47					
10		SS-3-5		3	71.7	4.55					
11		SS-5-1	5	5	104.0	6.60	6.65	0.26	0.71	10.7	3.8
12		SS-5-2		5	104.4	6.62					
13		SS-5-3		5	110.4	7.01					
14		SS-5-4		5	106.0	6.73					
15		SS-5-5		5	99.2	6.29					
16											

Table 4. — Geomembrane interface-friction direct shear tests (sheet 2 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Second shear displacement: Normal Stress (lbf/in²) (12)	Maximum Shear Load (lbf) (13)	Maximum Shear Stress (lbf/in²) (14)	Average Maximum Shear Stress (lbf/in²) (15)	Standard Deviation (lbf/in²) (16)	Range (lbf/in²) (17)	Range as Percent of Average (%) (18)	Coefficient of Variation (%) (19)
1	Soil - on - Soil	SS-1-1	5	1	25.4	1.61	1.52	0.10	0.19	12.5	6.3
2		SS-1-2		1	22.4	1.42					
3		SS-1-3		1	25.3	1.61					
4		SS-1-4		1	24.5	1.55					
5		SS-1-5		1	22.4	1.42					
6		SS-3-1	5	1	25.0	1.59	1.59	0.07	0.17	10.8	4.2
7		SS-3-2		1	24.9	1.58					
8		SS-3-3		1	24.2	1.54					
9		SS-3-4		1	24.5	1.55					
10		SS-3-5		1	26.9	1.71					
11		SS-5-1	5	1	24.9	1.58	1.61	0.09	0.22	13.4	5.6
12		SS-5-2		1	26.4	1.68					
13		SS-5-3		1	25.9	1.64					
14		SS-5-4		1	26.3	1.67					
15		SS-5-5		1	23.0	1.46					
16			15				1.57	0.09	0.29	18.1	5.5

Table 4. — Geomembrane interface-friction direct shear tests (sheet 3 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Third shear displacement: Normal Stress (lbf/in²) (20)	Maximum Shear Load (lbf) (21)	Maximum Shear Stress (lbf/in²) (22)	Average Maximum Shear Stress (lbf/in²) (23)	Standard Deviation (lbf/in²) (24)	Range (lbf/in²) (25)	Range as Percent of Average (%) (26)	Coefficient of Variation (%) (27)
1	Soil - on - Soil	SS-1-1	5	3	45.3	2.87	2.93	0.15	0.37	12.5	5.2
2		SS-1-2		3	44.5	2.82					
3		SS-1-3		3	50.3	3.19					
4		SS-1-4		3	46.6	2.96					
5		SS-1-5		3	44.5	2.82					
6		SS-3-1	5	3	48.3	3.06	3.05	0.10	0.27	9.0	3.3
7		SS-3-2		3	47.8	3.03					
8		SS-3-3		3	45.5	2.89					
9		SS-3-4		3	49.8	3.16					
10		SS-3-5		3	48.6	3.08					
11		SS-5-1	5	3	47.3	3.00	3.05	0.12	0.29	9.4	3.8
12		SS-5-2		3	48.7	3.09					
13		SS-5-3		3	46.4	2.94					
14		SS-5-4		3	50.9	3.23					
15		SS-5-5		3	46.9	2.98					
16			15				3.01	0.13	0.41	13.5	4.3

Table 4. — Geomembrane interface-friction direct shear tests (sheet 4 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Fourth shear displacement: Normal Stress (lbf/in²) (28)	Maximum Shear Load (lbf) (29)	Maximum Shear Stress (lbf/in²) (30)	Average Maximum Shear Stress (lbf/in²) (31)	Standard Deviation (lbf/in²) (32)	Range (lbf/in²) (33)	Range as Percent of Average (%) (34)	Coefficient of Variation (%) (35)
1		SS-1-1		5	69.6	4.42					
2		SS-1-2		5	65.6	4.16					
3		SS-1-3	5	5	73.9	4.69	4.36	0.28	0.70	16.0	6.5
4		SS-1-4		5	71.7	4.55					
5		SS-1-5		5	62.9	3.99					
6		SS-3-1		5	70.3	4.46					
7	Soil - on -	SS-3-2		5	68.2	4.33					
8	Soil	SS-3-3	5	5	69.5	4.41	4.46	0.12	0.34	7.5	2.8
9		SS-3-4		5	73.5	4.66					
10		SS-3-5		5	70.3	4.46					
11		SS-5-1		5	66.5	4.22					
12		SS-5-2		5	71.0	4.51					
13		SS-5-3	5	5	74.2	4.71	4.55	0.21	0.51	11.3	4.6
14		SS-5-4		5	74.6	4.73					
15		SS-5-5		5	72.4	4.59					
16			15				4.46	0.21	0.74	16.6	4.8

Table 4. — Geomembrane interface-friction direct shear tests (sheet 5 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Initial shear displacement							
				Normal Stress (lbf/in²) (4)	Maximum Shear Load (lbf) (5)	Maximum Shear Stress (lbf/in²) (6)	Average Maximum Shear Stress (lbf/in²) (7)	Standard Deviation (lbf/in²) (8)	Range (lbf/in²) (9)	Range as Percent of Average (%) (10)	Coefficient of Variation (%) (11)
17		PV-1-1		1	16.6	1.05					
18		PV-1-2		1	17.7	1.12					
19		PV-1-3	5	1	18.8	1.19	1.14	0.06	0.14	12.3	4.9
20		PV-1-4		1	18.6	1.18					
21		PV-1-5		1	17.8	1.13					
22		PV-3-1		3	34.9	2.21					
23	Soil - on -	PV-3-2		3	35.4	2.25					
24	PVC	PV-3-3	5	3	34.0	2.16	2.20	0.06	0.13	5.8	2.5
25	Membrane	PV-3-4		3	35.6	2.26					
26		PV-3-5		3	33.6	2.13					
27		PV-5-1		5	53.8	3.41					
28		PV-5-2		5	54.8	3.48					
29		PV-5-3	5	5	53.5	3.39	3.42	0.05	0.12	3.5	1.4
30		PV-5-4		5	52.9	3.36					
31		PV-5-5		5	54.5	3.46					
32											

Table 4. — Geomembrane interface-friction direct shear tests (sheet 6 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Second shear displacement: Normal Stress (lbf/in²) (12)	Maximum Shear Load (lbf) (13)	Maximum Shear Stress (lbf/in²) (14)	Average Maximum Shear Stress (lbf/in²) (15)	Standard Deviation (lbf/in²) (16)	Range (lbf/in²) (17)	Range as Percent of Average (%) (18)	Coefficient of Variation (%) (19)
17		PV-1-1		1	14.1	0.89					
18		PV-1-2		1	15.1	0.96					
19		PV-1-3	5	1	14.8	0.94	0.92	0.02	0.06	6.9	2.7
20		PV-1-4		1	14.4	0.91					
21		PV-1-5		1	14.4	0.91					
22		PV-3-1		1	15.0	0.95					
23	Soil - on -	PV-3-2		1	14.1	0.89					
24	PVC	PV-3-3	5	1	14.5	0.92	0.92	0.03	0.07	7.6	3.5
25	Membrane	PV-3-4		1	15.1	0.96					
26		PV-3-5		1	14.0	0.89					
27		PV-5-1		1	14.1	0.89					
28		PV-5-2		1	14.2	0.90					
29		PV-5-3	5	1	14.1	0.89	0.90	0.02	0.06	7.0	2.6
30		PV-5-4		1	13.8	0.88					
31		PV-5-5		1	14.8	0.94					
32			15				0.92	0.03	0.08	9.0	3.0

Table 4. — Geomembrane interface-friction direct shear tests (sheet 7 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Third shear displacement							
				Normal Stress (lbf/in²) (20)	Maximum Shear Load (lbf) (21)	Maximum Shear Stress (lbf/in²) (22)	Average Maximum Shear Stress (lbf/in²) (23)	Standard Deviation (lbf/in²) (24)	Range (lbf/in²) (25)	Range as Percent of Average (%) (26)	Coefficient of Variation (%) (27)
17		PV-1-1		3	28.5	1.81					
18		PV-1-2		3	31.1	1.97					
19		PV-1-3	5	3	30.9	1.96	1.92	0.07	0.16	8.6	3.6
20		PV-1-4		3	30.8	1.95					
21		PV-1-5		3	29.8	1.89					
22		PV-3-1		3	33.6	2.13					
23	Soil - on -	PV-3-2		3	30.3	1.92					
24	PVC	PV-3-3	5	3	30.7	1.95	1.95	0.10	0.26	13.3	5.3
25	Membrane	PV-3-4		3	29.9	1.90					
26		PV-3-5		3	29.5	1.87					
27		PV-5-1		3	29.6	1.88					
28		PV-5-2		3	31.7	2.01					
29		PV-5-3	5	3	29.4	1.87	1.97	0.12	0.30	15.2	6.3
30		PV-5-4		3	30.1	1.91					
31		PV-5-5		3	34.1	2.16					
32			15				1.95	0.10	0.36	18.3	5.0

Table 4. — Geomembrane interface-friction direct shear tests (sheet 8 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Fourth shear displacement							
				Normal Stress (lbf/in²) (28)	Maximum Shear Load (lbf) (29)	Maximum Shear Stress (lbf/in²) (30)	Average Maximum Shear Stress (lbf/in²) (31)	Standard Deviation (lbf/in²) (32)	Range (lbf/in²) (33)	Range as Percent of Average (%) (34)	Coefficient of Variation (%) (35)
17	Soil - on - PVC Membrane	PV-1-1	5	5	45.0	2.86	3.05	0.21	0.49	16.2	7.0
18		PV-1-2		5	51.9	3.29					
19		PV-1-3		5	49.1	3.12					
20		PV-1-4		5	50.3	3.19					
21		PV-1-5		5	44.1	2.80					
22		PV-3-1	5	5	45.3	2.87	3.01	0.08	0.20	6.7	2.7
23		PV-3-2		5	48.3	3.06					
24		PV-3-3		5	48.5	3.08					
25		PV-3-4		5	47.3	3.00					
26		PV-3-5		5	47.7	3.03					
27		PV-5-1	5	5	47.2	2.99	3.11	0.11	0.25	8.2	3.4
28		PV-5-2		5	51.2	3.25					
29		PV-5-3		5	48.4	3.07					
30		PV-5-4		5	48.0	3.05					
31		PV-5-5		5	50.3	3.19					
32			15				3.06	0.14	0.49	16.2	4.6

Table 4. — Geomembrane interface-friction direct shear tests (sheet 9 of 16).

				Initial shear displacement							
Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Normal Stress (lbf/in²) (4)	Maximum Shear Load (lbf) (5)	Maximum Shear Stress (lbf/in²) (6)	Average Maximum Shear Stress (lbf/in²) (7)	Standard Deviation (lbf/in²) (8)	Range (lbf/in²) (9)	Range as Percent of Average (%) (10)	Coefficient of Variation (%) (11)
33	Soil - on - VLDPE Membrane	VL-1-1	5	1	15.8	1.00	1.02	0.05	0.13	13.1	4.8
34		VL-1-2		1	15.9	1.01					
35		VL-1-3		1	15.1	0.96					
36		VL-1-4		1	17.2	1.09					
37		VL-1-5		1	16.4	1.04					
38		VL-3-1	5	3	34.7	2.20	2.16	0.05	0.10	4.7	2.3
39		VL-3-2		3	33.2	2.11					
40		VL-3-3		3	34.5	2.19					
41		VL-3-4		3	34.6	2.20					
42		VL-3-5		3	33.1	2.10					
43		VL-5-1	5	5	51.1	3.24	3.26	0.14	0.31	9.5	4.1
44		VL-5-2		5	50.3	3.19					
45		VL-5-3		5	50.3	3.19					
46		VL-5-4		5	55.2	3.50					
47		VL-5-5		5	50.3	3.19					
48											

Table 4. — Geomembrane interface-friction direct shear tests (sheet 10 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Second shear displacement: Normal Stress (lbf/in²) (12)	Maximum Shear Load (lbf) (13)	Maximum Shear Stress (lbf/in²) (14)	Average Maximum Shear Stress (lbf/in²) (15)	Standard Deviation (lbf/in²) (16)	Range (lbf/in²) (17)	Range as Percent of Average (%) (18)	Coefficient of Variation (%) (19)
33		VL-1-1		1	13.5	0.86					
34		VL-1-2		1	13.5	0.86					
35		VL-1-3	5	1	13.8	0.88	0.89	0.04	0.08	9.3	4.1
36		VL-1-4		1	14.4	0.91					
37		VL-1-5		1	14.8	0.94					
38		VL-3-1		1	15.0	0.95					
39	Soil - on -	VL-3-2		1	14.1	0.89					
40	VLDPE	VL-3-3	5	1	14.4	0.91	0.91	0.04	0.10	10.5	3.9
41	Membrane	VL-3-4		1	13.5	0.86					
42		VL-3-5		1	14.5	0.92					
43		VL-5-1		1	14.6	0.93					
44		VL-5-2		1	13.7	0.87					
45		VL-5-3	5	1	13.3	0.84	0.90	0.05	0.11	12.7	5.1
46		VL-5-4		1	15.1	0.96					
47		VL-5-5		1	14.4	0.91					
48			15				0.90	0.04	0.11	12.7	4.2

Table 4. — Geomembrane interface-friction direct shear tests (sheet 11 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Third shear displacement: Normal Stress (lbf/in²) (20)	Maximum Shear Load (lbf) (21)	Maximum Shear Stress (lbf/in²) (22)	Average Maximum Shear Stress (lbf/in²) (23)	Standard Deviation (lbf/in²) (24)	Range (lbf/in²) (25)	Range as Percent of Average (%) (26)	Coefficient of Variation (%) (27)
33		VL-1-1		3	29.6	1.88					
34		VL-1-2		3	28.5	1.81					
35		VL-1-3	5	3	29.0	1.84	1.85	0.03	0.07	3.8	1.5
36		VL-1-4		3	29.4	1.87					
37		VL-1-5		3	29.4	1.87					
38		VL-3-1		3	30.8	1.95					
39	Soil - on -	VL-3-2		3	29.3	1.86					
40	VLDPE	VL-3-3	5	3	30.9	1.96	1.88	0.07	0.16	8.4	3.9
41	Membrane	VL-3-4		3	28.4	1.80					
42		VL-3-5		3	28.7	1.82					
43		VL-5-1		3	29.2	1.85					
44		VL-5-2		3	28.7	1.82					
45		VL-5-3	5	3	27.8	1.76	1.87	0.10	0.27	14.6	5.5
46		VL-5-4		3	32.1	2.04					
47		VL-5-5		3	29.3	1.86					
48			15				1.87	0.07	0.27	14.6	3.8

Table 4. — Geomembrane interface-friction direct shear tests (sheet 12 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Fourth shear displacement: Normal Stress (lbf/in²) (28)	Maximum Shear Load (lbf) (29)	Maximum Shear Stress (lbf/in²) (30)	Average Maximum Shear Stress (lbf/in²) (31)	Standard Deviation (lbf/in²) (32)	Range (lbf/in²) (33)	Range as Percent of Average (%) (34)	Coefficient of Variation (%) (35)
33	Soil - on - VLDPE Membrane	VL-1-1	5	5	47.5	3.01	2.91	0.09	0.21	7.2	3.2
34		VL-1-2		5	44.4	2.82					
35		VL-1-3		5	46.3	2.94					
36		VL-1-4		5	44.2	2.80					
37		VL-1-5		5	46.9	2.98					
38		VL-3-1	5	5	49.6	3.15	3.02	0.10	0.24	8.0	3.2
39		VL-3-2		5	47.4	3.01					
40		VL-3-3		5	48.6	3.08					
41		VL-3-4		5	46.6	2.96					
42		VL-3-5		5	45.8	2.91					
43		VL-5-1	5	5	46.7	2.96	2.99	0.10	0.27	9.1	3.4
44		VL-5-2		5	47.3	3.00					
45		VL-5-3		5	46.4	2.94					
46		VL-5-4		5	49.7	3.15					
47		VL-5-5		5	45.4	2.88					
48			15				2.97	0.10	0.35	11.7	3.4

Table 4. — Geomembrane interface-friction direct shear tests (sheet 13 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Initial shear displacement							
				Normal Stress (lbf/in²) (4)	Maximum Shear Load (lbf) (5)	Maximum Shear Stress (lbf/in²) (6)	Average Maximum Shear Stress (lbf/in²) (7)	Standard Deviation (lbf/in²) (8)	Range (lbf/in²) (9)	Range as Percent of Average (%) (10)	Coefficient of Variation (%) (11)
49		SG-1-1		1	28.7	1.82					
50		SG-1-2	3	1	29.7	1.88	1.85	0.03	0.06	3.4	1.7
51	Soil - on -	SG-1-3		1	29.2	1.85					
52	Geotextile/	SG-3-1		3	55.2	3.50					
53	PVC	SG-3-2	3	3	54.8	3.48	3.47	0.04	0.08	2.2	1.1
54	Membrane	SG-3-3		3	54.0	3.43					
55	Composite	SG-5-1		5	86.7	5.50					
56		SG-5-2	3	5	82.3	5.22	5.30	0.18	0.32	6.1	3.3
57		SG-5-3		5	81.6	5.18					
58											
59		ST-1-1		1	31.7	2.01					
60		ST-1-2	4	1	34.5	2.19	2.13	0.08	0.18	8.3	3.8
61		ST-1-3		1	34.2	2.17					
62	Soil - on -	ST-1-3-R		1	33.9	2.15					
63	Texturized	ST-3-1		3	65.2	4.14					
64	HDPE	ST-3-2	3	3	62.6	3.97	4.09	0.10	0.19	4.7	2.5
65	Membrane	ST-3-3		3	65.6	4.16					
66		ST-5-1		5	98.5	6.25					
67		ST-5-2-R	3	5	95.8	6.08	6.16	0.09	0.17	2.8	1.4
68		ST-5-3		5	97.1	6.16					
69											

Table 4. — Geomembrane interface-friction direct shear tests (sheet 14 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Second shear displacement: Normal Stress (lbf/in²) (12)	Maximum Shear Load (lbf) (13)	Maximum Shear Stress (lbf/in²) (14)	Average Maximum Shear Stress (lbf/in²) (15)	Standard Deviation (lbf/in²) (16)	Range (lbf/in²) (17)	Range as Percent of Average (%) (18)	Coefficient of Variation (%) (19)
49		SG-1-1		1	23.0	1.46					
50		SG-1-2	3	1	23.3	1.48	1.47	0.01	0.02	1.3	0.7
51	Soil - on -	SG-1-3		1	23.1	1.47					
52	Geotextile/	SG-3-1		1	22.2	1.41					
53	PVC	SG-3-2	3	1	24.5	1.55	1.45	0.09	0.16	11.4	6.2
54	Membrane	SG-3-3		1	21.9	1.39					
55	Composite	SG-5-1		1	22.6	1.43					
56		SG-5-2	3	1	24.2	1.54	1.48	0.05	0.10	6.8	3.4
57		SG-5-3		1	23.3	1.48					
58			9				1.47	0.05	0.16	11.2	3.7
59		ST-1-1		1	20.0	1.27					
60		ST-1-2	4	1	18.8	1.19	1.23	0.04	0.08	6.2	3.1
61		ST-1-3		1	19.7	1.25					
62	Soil - on -	ST-1-3-R		1	18.9	1.20					
63	Texturized	ST-3-1		1	18.5	1.17					
64	HDPE	ST-3-2	3	1	20.9	1.33	1.24	0.08	0.15	12.3	6.4
65	Membrane	ST-3-3		1	19.1	1.21					
66		ST-5-1		1	21.5	1.36					
67		ST-5-2-R	3	1	19.1	1.21	1.34	0.12	0.23	17.1	8.7
68		ST-5-3		1	22.7	1.44					
69			10				1.26	0.09	0.27	21.1	6.9

Table 4. — Geomembrane interface-friction direct shear tests (sheet 15 of 16).

				Third shear displacement							
Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Normal Stress (lbf/in²) (20)	Maximum Shear Load (lbf) (21)	Maximum Shear Stress (lbf/in²) (22)	Average Maximum Shear Stress (lbf/in²) (23)	Standard Deviation (lbf/in²) (24)	Range (lbf/in²) (25)	Range as Percent of Average (%) (26)	Coefficient of Variation (%) (27)
49	Soil - on - Geotextile/ PVC Membrane Composite	SG-1-1		3	43.8	2.78					
50		SG-1-2	3	3	45.5	2.89	2.84	0.06	0.11	3.8	2.0
51		SG-1-3		3	45.1	2.86					
52		SG-3-1		3	49.6	3.15					
53		SG-3-2	3	3	47.0	2.98	2.98	0.17	0.34	11.5	5.8
54		SG-3-3		3	44.2	2.80					
55		SG-5-1		3	42.2	2.68					
56		SG-5-2	3	3	47.1	2.99	2.83	0.16	0.31	11.0	5.5
57		SG-5-3		3	44.7	2.84					
58			9				2.88	0.14	0.47	16.3	4.8
59	Soil - on - Texturized HDPE Membrane	ST-1-1		3	39.2	2.49					
60		ST-1-2	4	3	41.4	2.63	2.58	0.20	0.48	18.4	7.9
61		ST-1-3		3	44.9	2.85					
62		ST-1-3-R		3	37.4	2.37					
63		ST-3-1		3	39.6	2.51					
64		ST-3-2	3	3	40.9	2.60	2.49	0.11	0.22	8.9	4.5
65		ST-3-3		3	37.4	2.37					
66		ST-5-1		3	42.4	2.69					
67		ST-5-2-R	3	3	39.7	2.52	2.67	0.14	0.29	10.7	5.4
68		ST-5-3		3	44.2	2.80					
69			10				2.58	0.16	0.48	18.4	6.3

Table 4. — Geomembrane interface-friction direct shear tests (sheet 16 of 16).

Line #	Material Combination (1)	Specimen Number (2)	Number of Replicate Tests (3)	Fourth shear displacement: Normal Stress (lbf/in²) (28)	Maximum Shear Load (lbf) (29)	Maximum Shear Stress (lbf/in²) (30)	Average Maximum Shear Stress (lbf/in²) (31)	Standard Deviation (lbf/in²) (32)	Range (lbf/in²) (33)	Range as Percent of Average (%) (34)	Coefficient of Variation (%) (35)
49		SG-1-1		5	66.2	4.20					
50		SG-1-2	3	5	64.1	4.07	4.22	0.16	0.32	7.7	3.9
51	Soil - on -	SG-1-3		5	69.2	4.39					
52	Geotextile/	SG-3-1		5	71.4	4.53					
53	PVC	SG-3-2	3	5	68.3	4.33	4.39	0.12	0.22	5.1	2.8
54	Membrane	SG-3-3		5	67.9	4.31					
55	Composite	SG-5-1		5	64.9	4.12					
56		SG-5-2	3	5	71.2	4.52	4.27	0.22	0.40	9.4	5.1
57		SG-5-3		5	65.6	4.16					
58			9				4.29	0.17	0.46	10.8	3.9
59		ST-1-1		5	65.1	4.13					
60		ST-1-2	4	5	64.2	4.07	4.07	0.30	0.73	17.9	7.4
61		ST-1-3		5	69.4	4.40					
62	Soil - on -	ST-1-3-R		5	57.9	3.67					
63	Texturized	ST-3-1		5	60.7	3.85					
64	HDPE	ST-3-2	3	5	61.5	3.90	3.79	0.15	0.28	7.4	3.9
65	Membrane	ST-3-3		5	57.1	3.62					
66		ST-5-1		5	66.3	4.21					
67		ST-5-2-R	3	5	60.5	3.84	4.12	0.25	0.47	11.4	6.0
68		ST-5-3		5	67.9	4.31					
69			10				4.00	0.26	0.78	19.5	6.6

Table 5. — Single operator precision in terms of range as a percent of average and coefficient of variation from ASTM precision statements.

ASTM Standard	Title	Single Operator Precision: Range as Percent of Average (%)	Single Operator Precision: Coefficient of Variation (%)	Property Measured
D 1633-84	Compressive Strength of Molded Soil-Cement Cylinders	8.1		Unconfined compressive strength
D 1635-87	Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading		6.4	Flexural strength; specimens with 6% cement
			5.7	Flexural strength; specimens with 14% cement
D 1883-92	CBR (California Bearing Ratio) of Laboratory - Compacted Soils		8.2	CBR using D 698 compaction
			5.9	CBR using D 1557 compaction
D 2216-92	Laboratory Determination of Water (Moisture) Content of Soil and Rock	7.8	2.7	Water content
D 2901-82	Cement Content of Freshly Mixed Soil Cement		2.4	Cement content
D 4221-92	Dispersive Characteristics of Clay Soil by Double Hydrometer	11.1	3.9	Percent dispersion
D 4253-93	Maximum Index Density and Unit Weight of Soils Using a Vibratory Table	2.7		Maximum index density - Fine to medium sands
		4.1		Maximum index density - Gravelly sands
D 4254-93	Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density	1.9		Minimum index density - Fine to medium sands
		3.7		Minimum index density - Gravelly sands
D 4318-84	Liquid Limit, Plastic Limit, and Plasticity Index of Soils		4.9	Soil A; Plastic limit; mean = 21.9; standard deviation = 1.07
			3.8	Soil A; Liquid limit; mean = 27.9; standard deviation = 1.07
			6.0	Soil B; Plastic limit; mean = 20.1; standard deviation = 1.21
			3.0	Soil B; Liquid limit; mean = 32.6; standard deviation = 0.98
D 4884-90	Seam Strength of Sewn Geotextiles		12.0	Tensile strength, 95% repeatability limit

Table 6. — Geomembrane direct shear tests: summary of Mohr-Coulomb parameters.

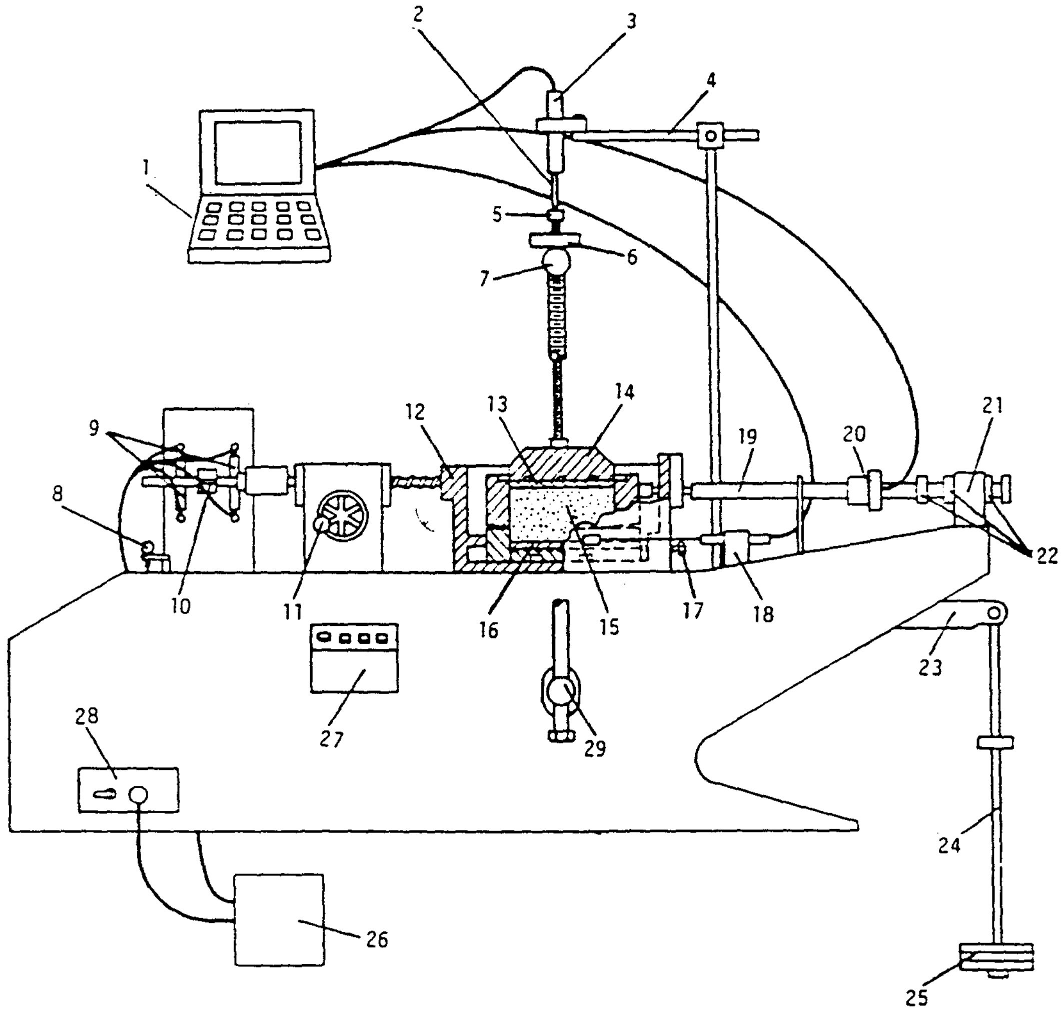
Peak shear strength						
Interface	Friction angle			Shear stress intercept		
	Average (°)	Variation (±°)	Efficiency	Average (lbf/in²)	Variation (± lbf/in²)	Efficiency
Soil-on-Soil	47.5	1.6	1.00	1.23	0.21	1.00
Soil-on-PVC	29.7	0.9	0.63	0.54	0.07	0.44
Soil-on-VLDPE	29.3	1.3	0.62	0.46	0.10	0.37
Soil-on-Geotextile/PVC Composite	40.8	1.8	0.86	0.95	0.18	0.77
Soil-on-Texturized HDPE	45.2	1.1	0.95	1.11	0.13	0.90

Post-peak shear strength						
Interface	Friction angle			Shear stress intercept		
	Average (°)	Variation (±°)	Efficiency	Average (lbf/in²)	Variation (± lbf/in²)	Efficiency
Soil-on-Soil	35.8	1.0	1.00	0.85	0.10	1.00
Soil-on-PVC	28.2	0.8	0.79	0.37	0.06	0.44
Soil-on-VLDPE	27.4	0.7	0.77	0.36	0.05	0.42
Soil-on-Geotextile/PVC Composite	35.2	1.2	0.98	0.76	0.11	0.89
Soil-on-Texturized HDPE	34.4	1.6	0.96	0.56	0.14	0.66

Table 7. - Geomembrane direct shear tests: shear strength summary—one-point model.

Peak shear strength									
	Normal stress, lbf/in²								
	1			3			5		
Interface	Friction Angle (°)	Variation (±°)	Efficiency	Friction Angle (°)	Variation (±°)	Efficiency	Friction Angle (°)	Variation (±°)	Efficiency
Soil-on-Soil	66.4	1.2	1.00	56.7	1.0	1.00	53.1	1.3	1.00
Soil-on-PVC	48.6	1.7	0.73	36.3	0.9	0.64	34.4	0.5	0.65
Soil-on-VLDPE	45.6	1.7	0.69	35.7	0.8	0.63	33.1	1.3	0.62
Soil-on-Geotextile/PVC Composite	61.6	1.0	0.93	49.1	0.8	0.87	46.7	2.4	0.88
Soil-on-Texturized HDPE	64.9	1.3	0.98	53.7	1.7	0.95	50.9	1.0	0.96

Post-peak shear strength									
	Normal stress, lbf/in²								
	1			3			5		
Interface	Friction Angle (°)	Variation (±°)	Efficiency	Friction Angle (°)	Variation (±°)	Efficiency	Friction Angle (°)	Variation (±°)	Efficiency
Soil-on-Soil	57.6	0.8	1.00	45.1	0.7	1.00	41.7	0.8	1.00
Soil-on-PVC	42.5	0.5	0.74	33.0	0.7	0.73	31.4	0.7	0.75
Soil-on-VLDPE	42.0	0.7	0.73	31.9	0.5	0.71	30.7	0.5	0.74
Soil-on-Geotextile/PVC Composite	55.7	0.8	0.97	43.9	1.1	0.97	40.6	0.9	0.97
Soil-on-Texturized HDPE	51.7	1.4	0.90	40.7	1.3	0.90	38.7	1.3	0.93



1. Data acquisition system
2. LVDT core
3. LVDT body
4. Consolidation LVDT arm
5. Yoke adjustment screw
6. Vertical yoke adjustment nut
7. Loading yoke
8. Gear change lever
9. Reversing microswitches
10. Reversing switch control bar
11. Handwheel
12. Shear box bowl
13. Top porous plate
14. Load transfer plate
15. Specimen
16. Bottom porous plate
17. Shear box lock screw
18. Horizontal strain LVDT bracket
19. Load cell coupling rod
20. Load cell retaining bolts
21. Tailstock
22. Adjusting nuts
23. Lever loading arm
24. Load hanger
25. Masses
26. Automatic reversing switch relays
27. Control panel
28. Selector switch — manual/automatic
29. Loading yoke pivot

Direct shear apparatus

Figure 1. - Schematic of direct shear apparatus equipment.

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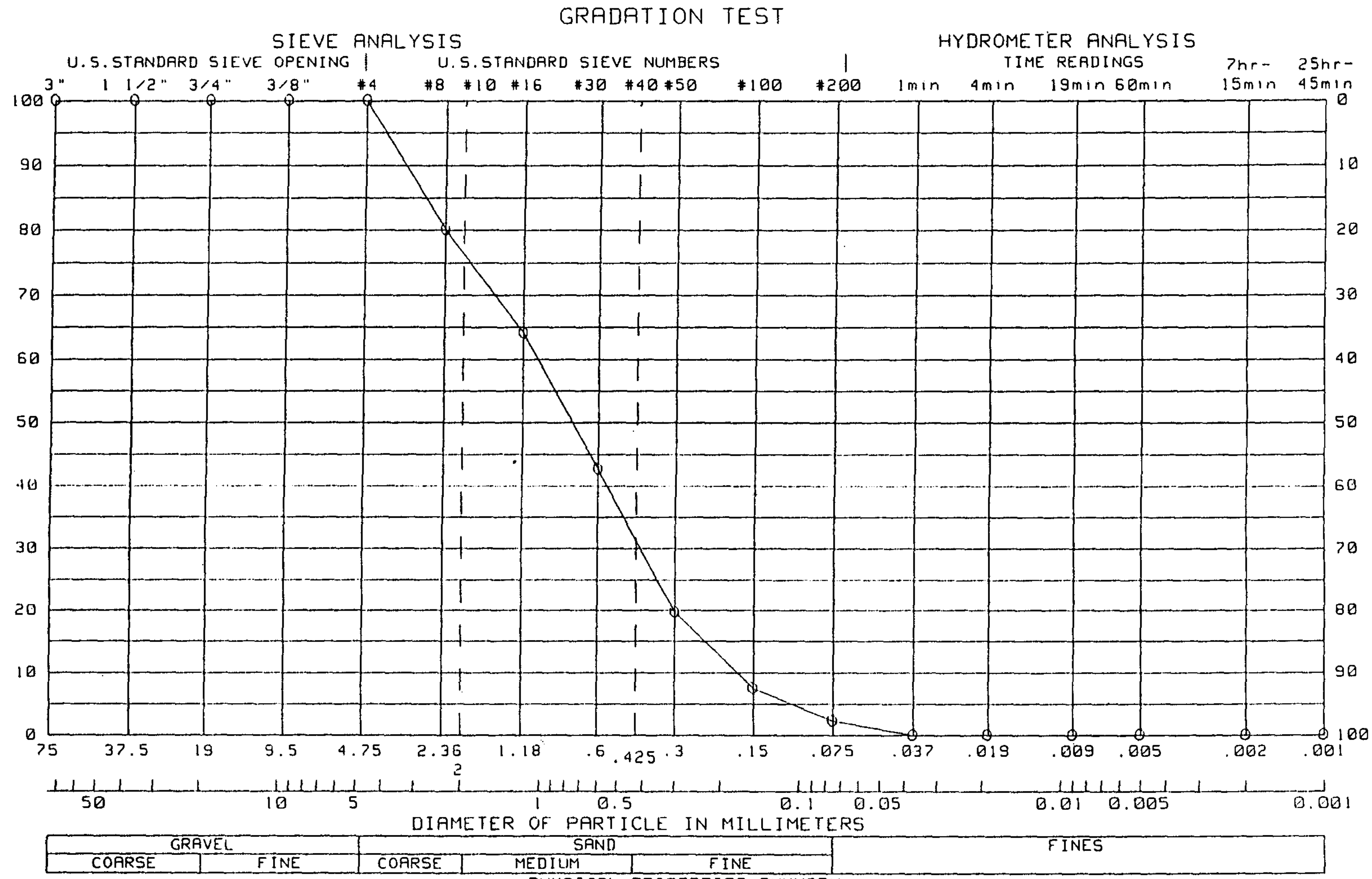


PHYSICAL PROPERTIES SUMMARY

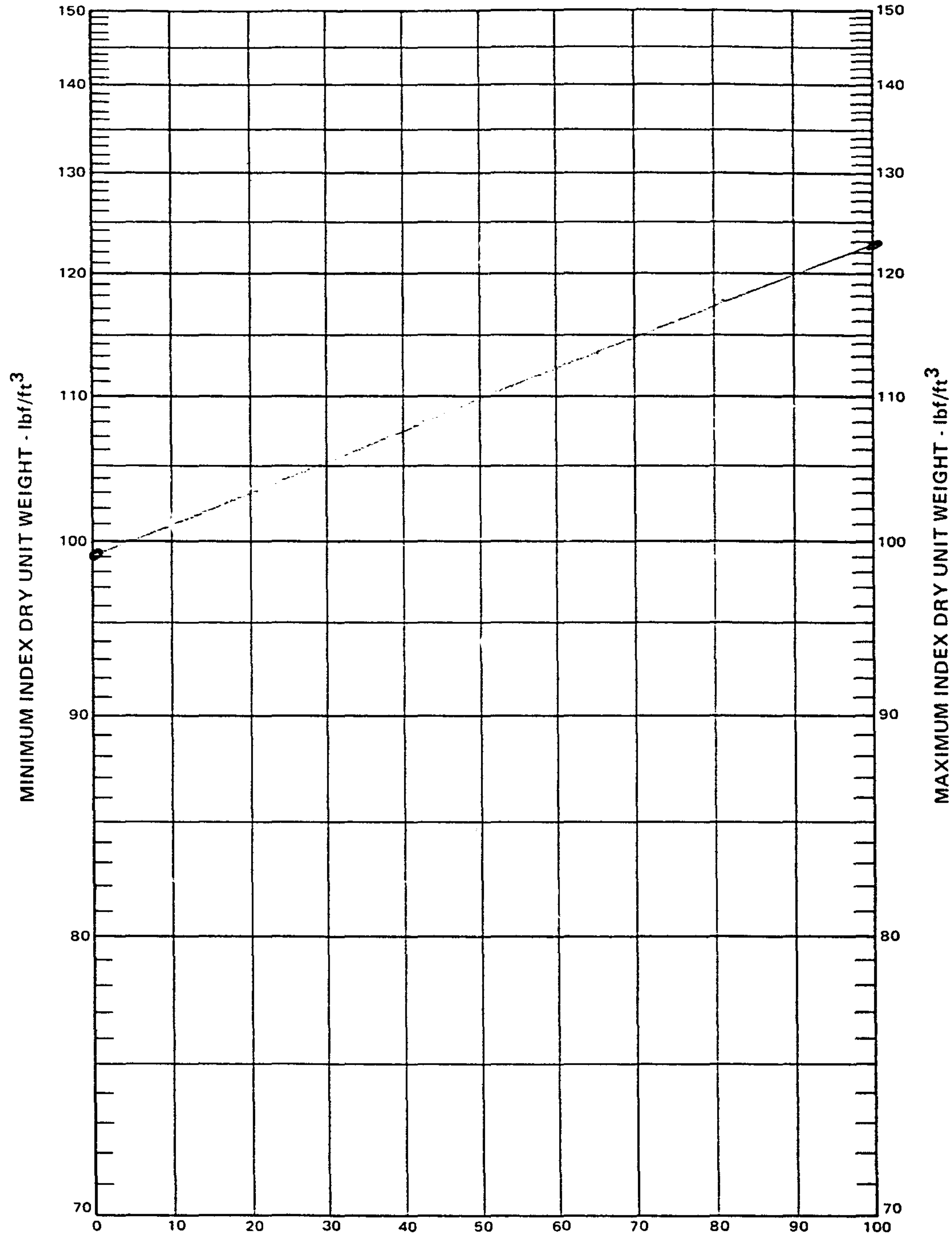
FEATURE: CLEAR CREEK PROJECT: GEOMEMBRANE RESEARCH
DRILL HOLE: DEPTH: 0.0-0.0 feet
SAMPLE NUMBER:
UNIFIED SOIL CLASSIFICATION: Group Symbol: SP Group Name: Poorly Graded Sand
ATTERBERG LIMITS: Non-Plastic
SPECIFIC GRAVITY: NO TEST PERFORMED
GRADATION: Percent Gravel: 0.0 Percent Sand: 97.7 Percent Fines: 2.3
D60 (mm): 1.037 D50 (mm): .756 D30: .409 D10 (mm): .173
Coefficient of Curvature Cc: .93 Coefficient of Uniformity Cu: 6.00

Figure 2. - Gradation test results.

7-1595 (11-85)
Bureau of Reclamation

RELATIVE DENSITY PLOT

Designation USBR 7250- __



MINIMUM INDEX DRY UNIT WEIGHT 99.0 lbf/ft^3 IN-PLACE DRY UNIT WEIGHT ______ lbf/ft^3

MAXIMUM INDEX DRY UNIT WEIGHT 122.7 lbf/ft^3 RELATIVE DENSITY ______ %

SAMPLE NO. 65K-1 HOLE NO. ______ DEPTH ______ FT.

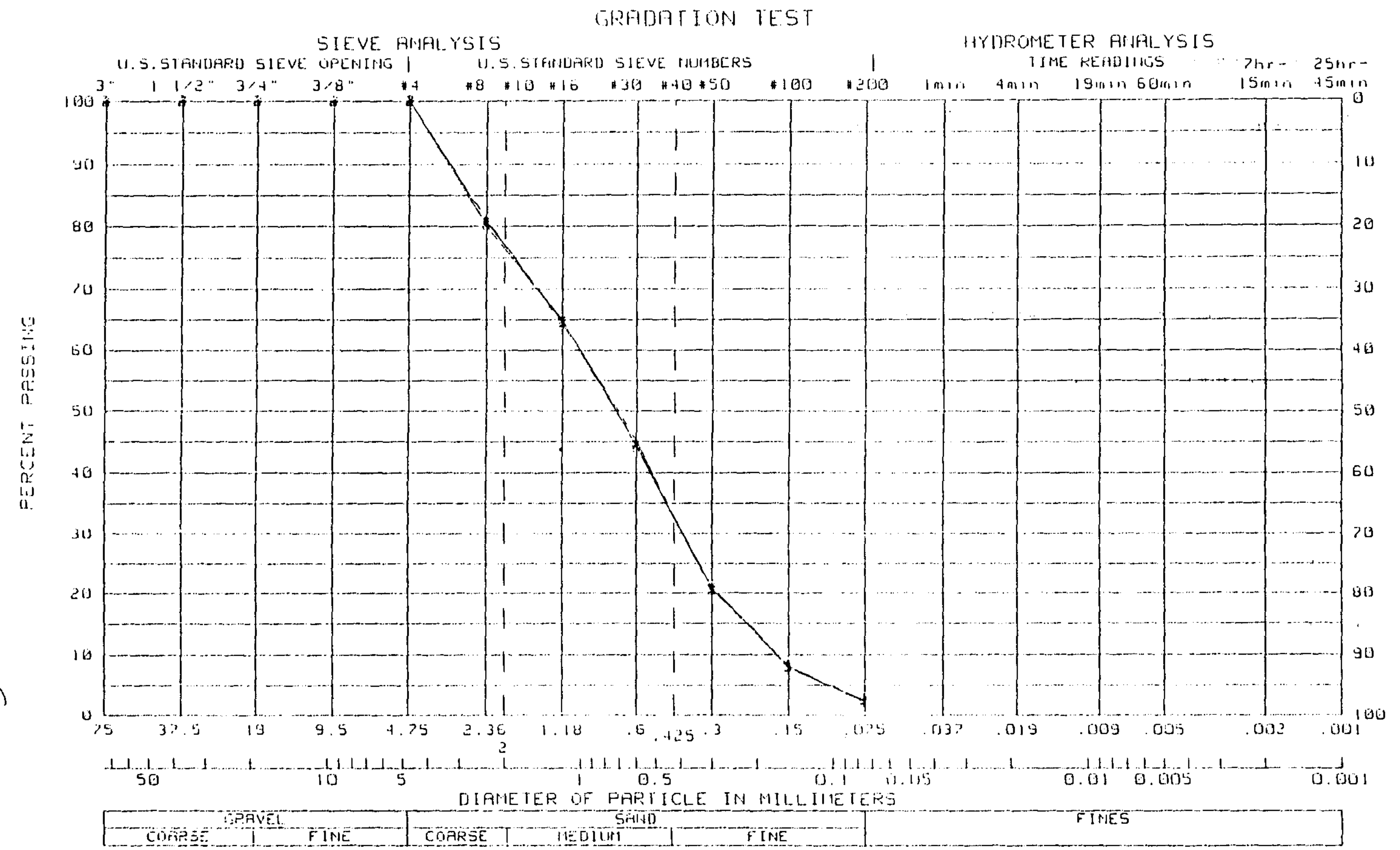
TEST NO. ______ STATION ______ ELEVATION ______ OFFSET ______

PREPARED BY S Bari CHECKED BY Burham

Figure 3. - Maximum and minimum index unit weight test results.

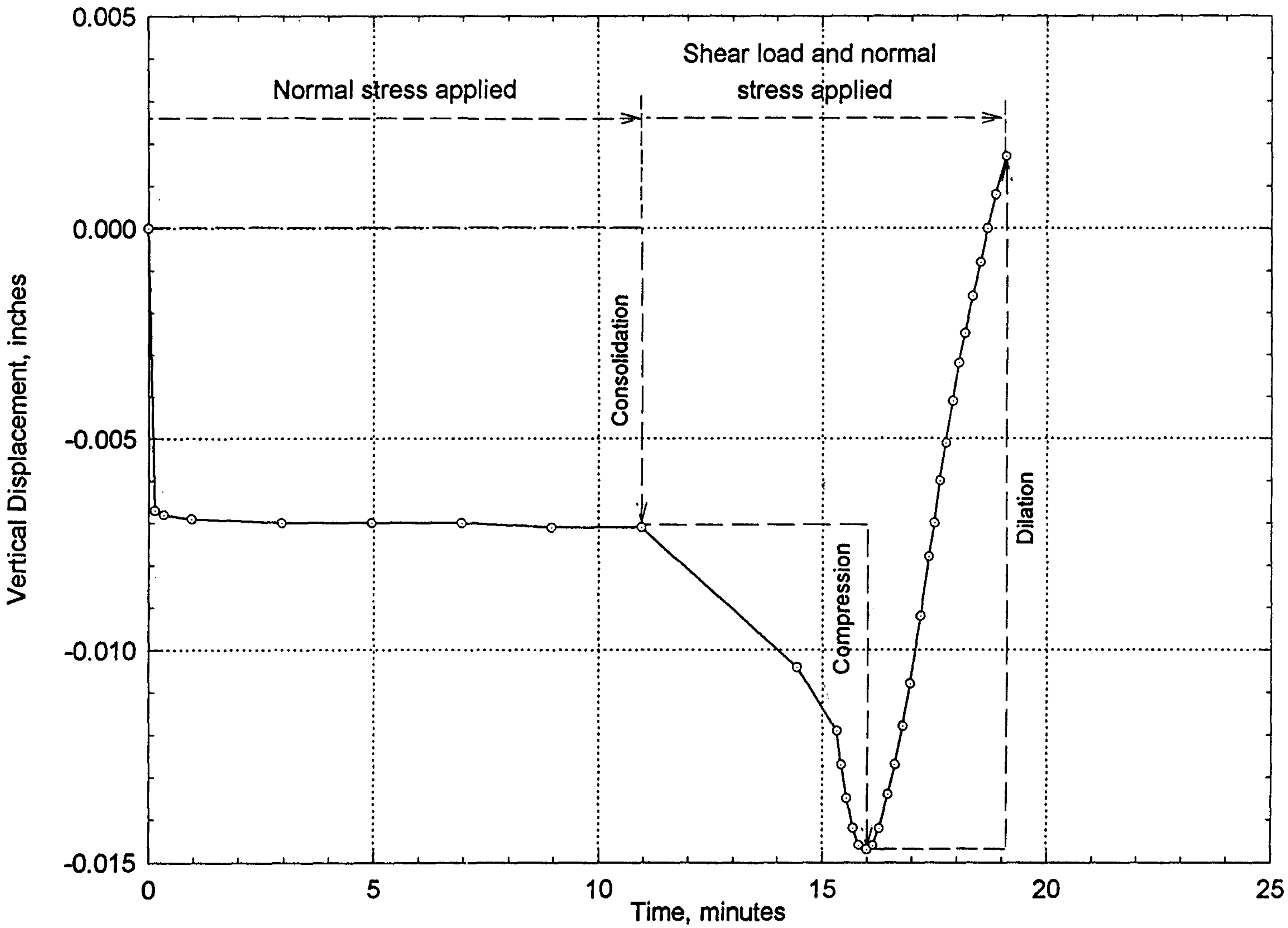
PREPARED BY

CHECKED BY



SAMPLE NO.	HOLE NO.	ELEV. OR DEPTH	UNIFIED SOIL CLASSIFICATION: GROUP SYMBOL	% GRAVEL	% SAND	% FINES	ATTERBERG LIMITS: LIQUID LIMIT(%)	PLASTICITY INDEX(%)	SHRINKAGE LIMIT(%)	SPECIFIC GRAVITY: MINUS NO. 4	OTHER	NOTES: LEGEND
SS-1-3			SP	0.0	97.7	2.3	0.0	0.0				O
SS-3-1			SP	0.0	97.0	2.2	0.0	0.0				X
SS-3-3			SP	0.0	97.5	2.5	0.0	0.0				^
SS-5-1												+
PV-3-5												1
VL-1-2												2
VL-5-2												3

Figure 4. - Specimen gradation results.



Specimen: SS-5-3; Normal pressure = 1 lbf/in^2; Second shear displacement

Figure 5. - Geomembrane direct shear tests: soil-on-soil—vertical displacement versus time.

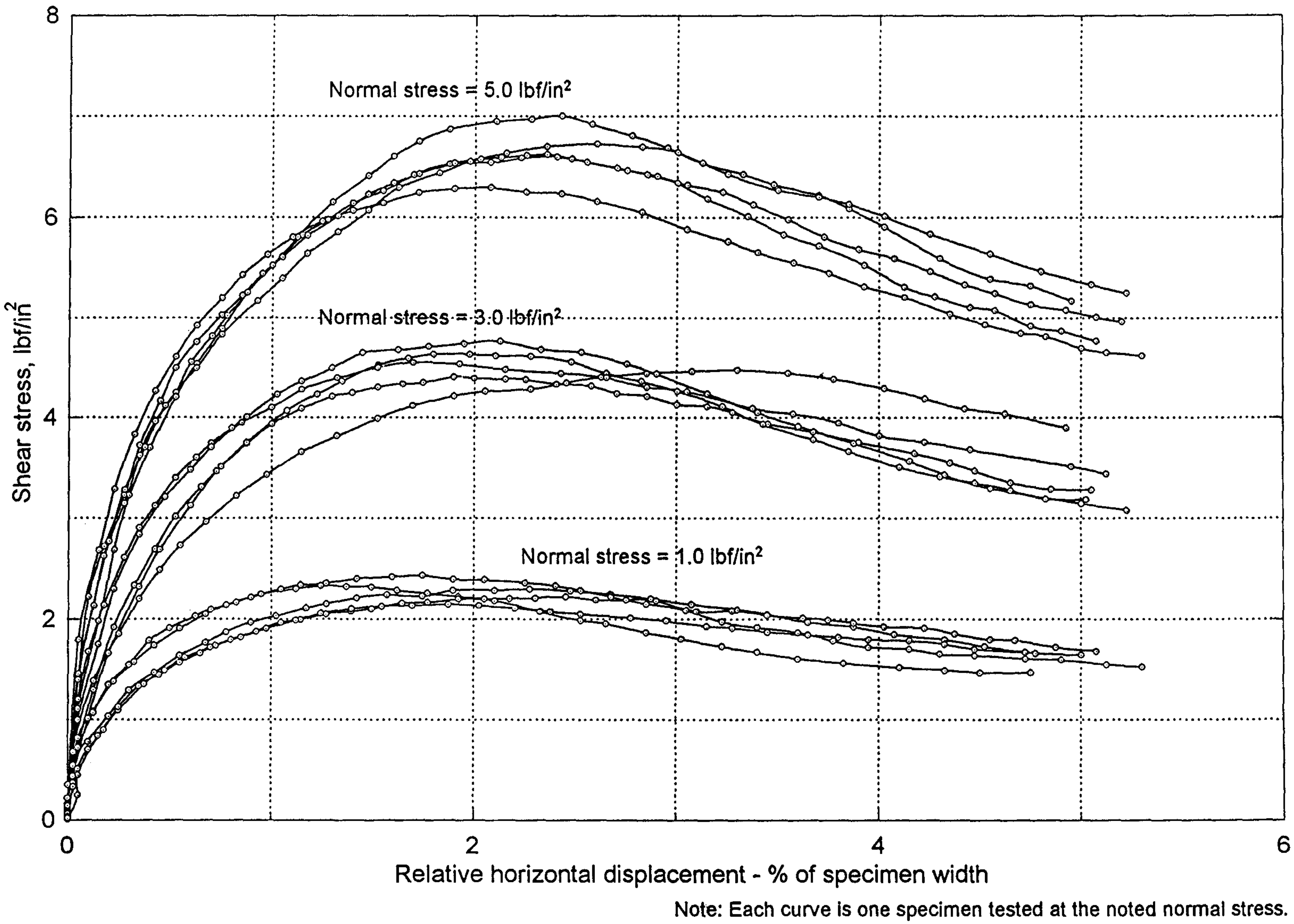


Figure 6. - Geomembrane direct shear tests: soil-on-soil—initial shear displacement—shear stress versus horizontal displacement.

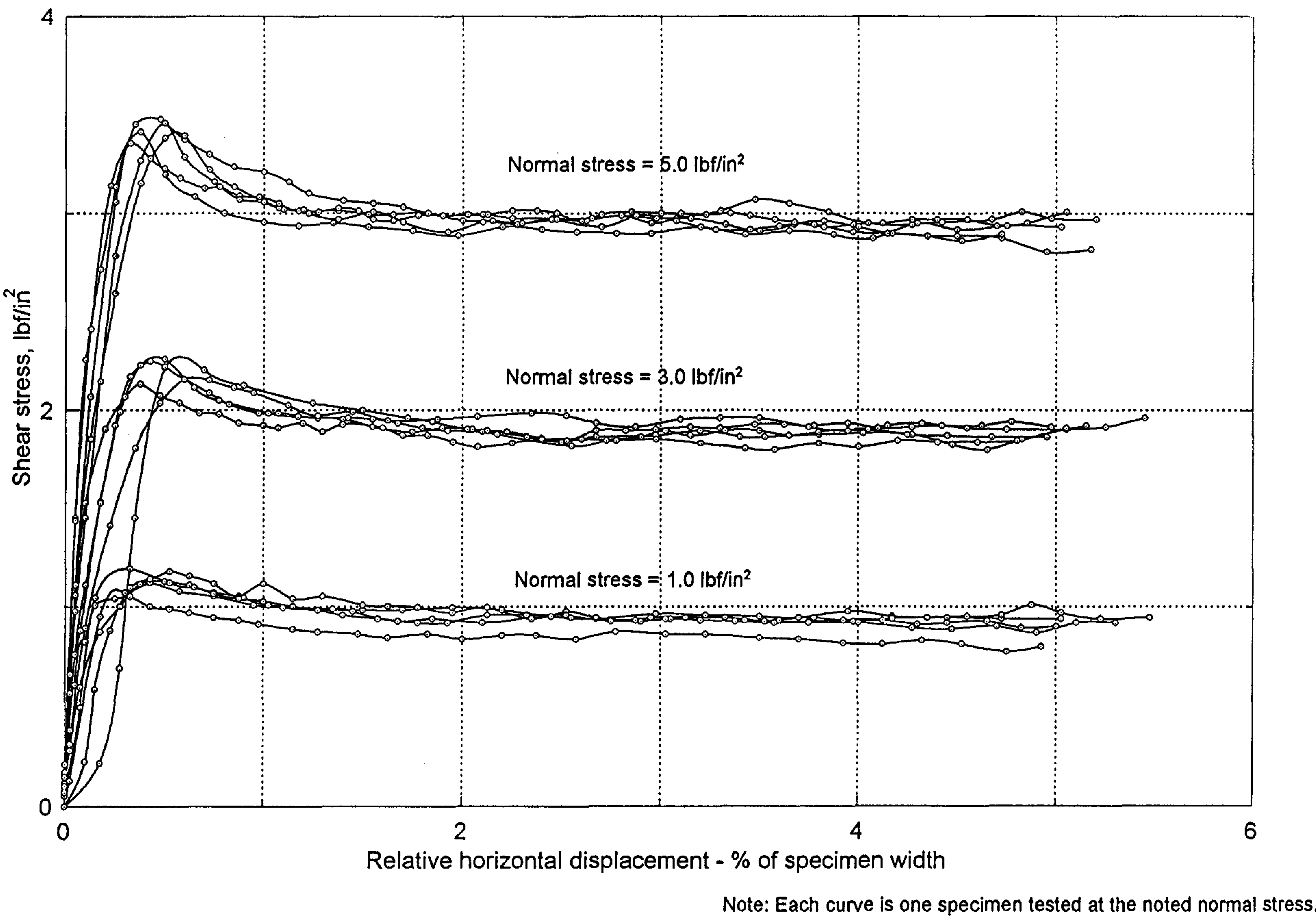


Figure 7. - Geomembrane direct shear tests: soil-on-PVC—initial shear displacement—shear stress versus horizontal displacement.

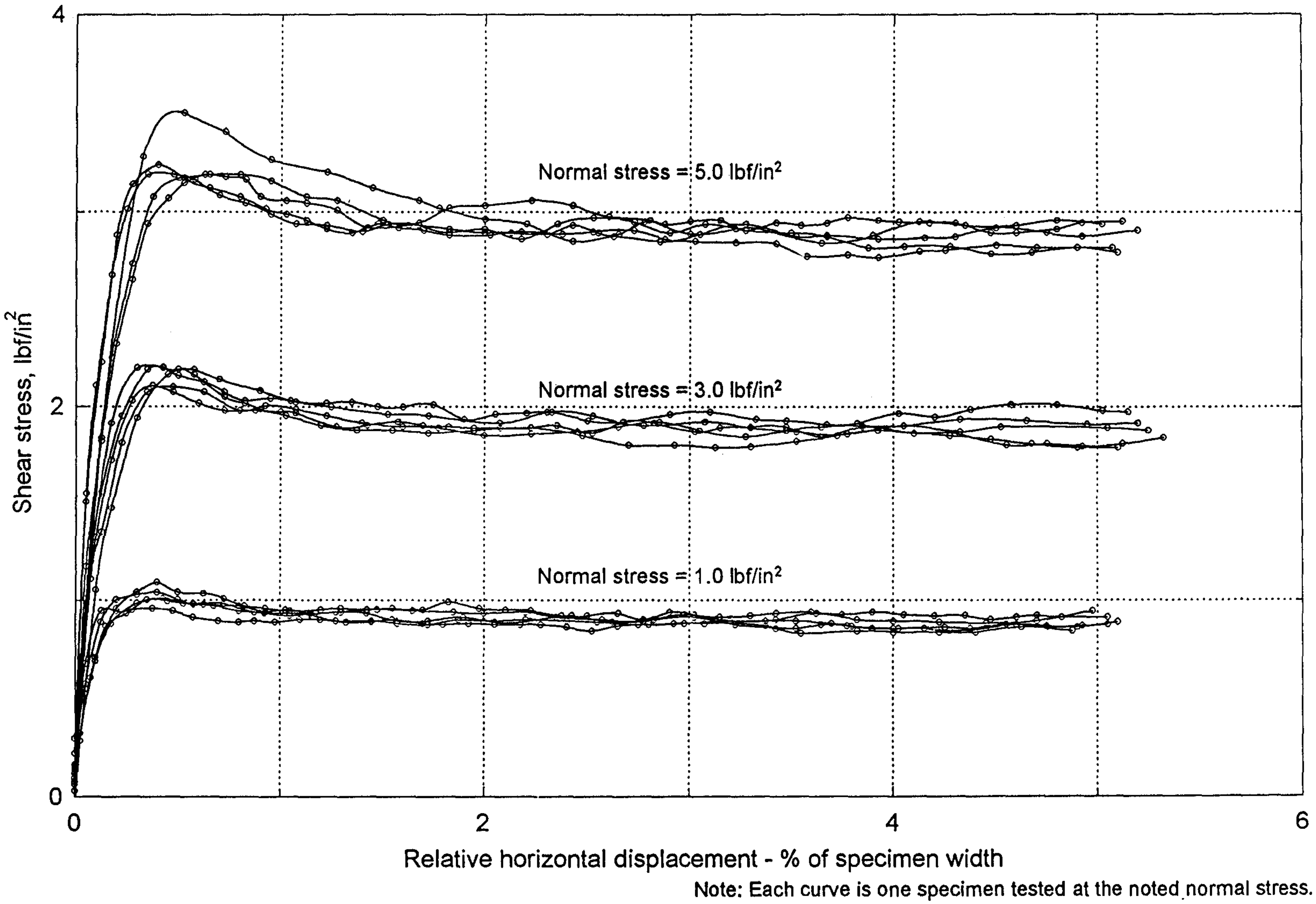


Figure 8. - Geomembrane direct shear tests: soil-on-VLDPE—initial shear displacement—shear stress versus horizontal displacement.

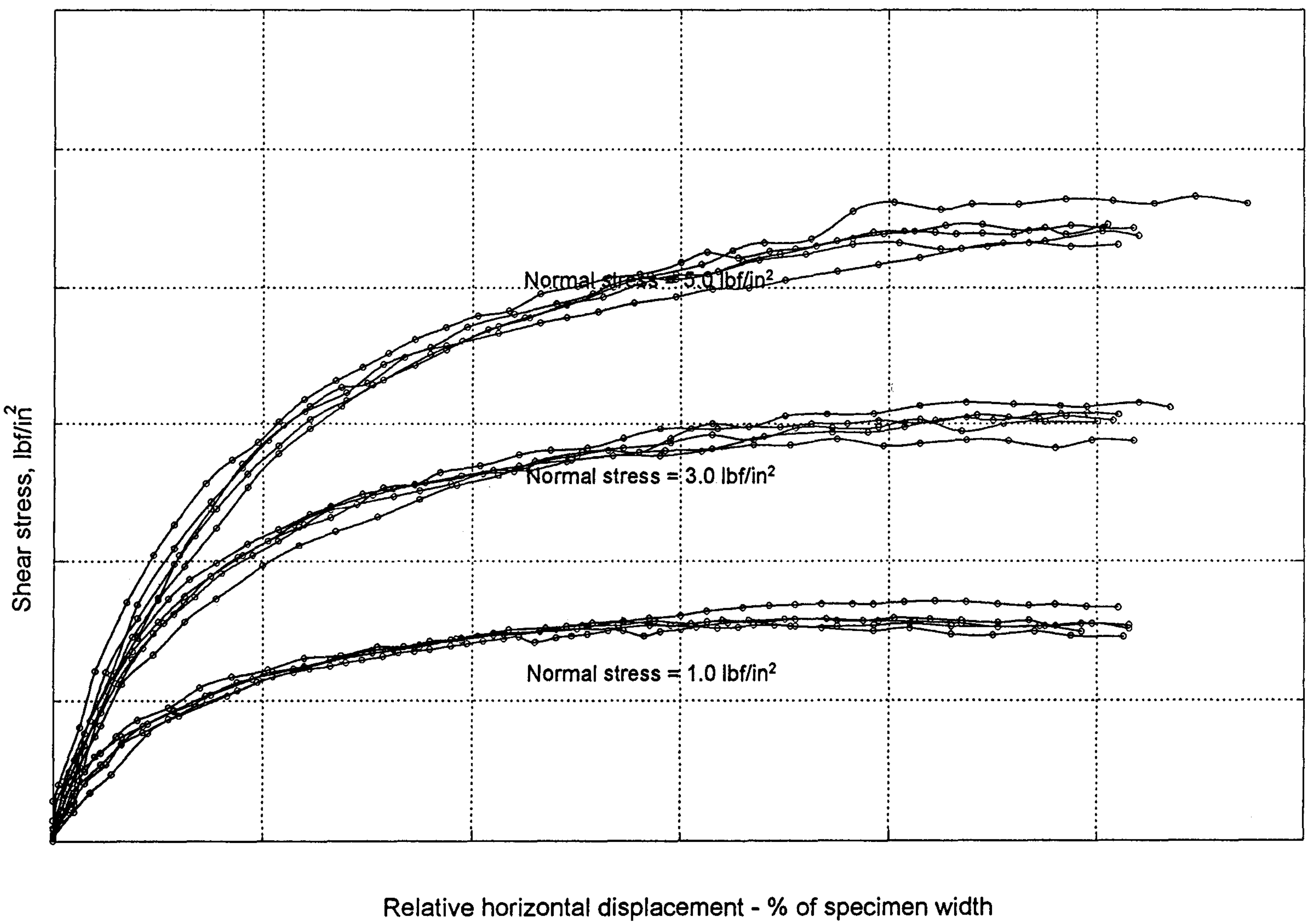


Figure 9. - Geomembrane direct shear tests: soil-on-soil—subsequent shear displacements—shear stress versus horizontal displacement.

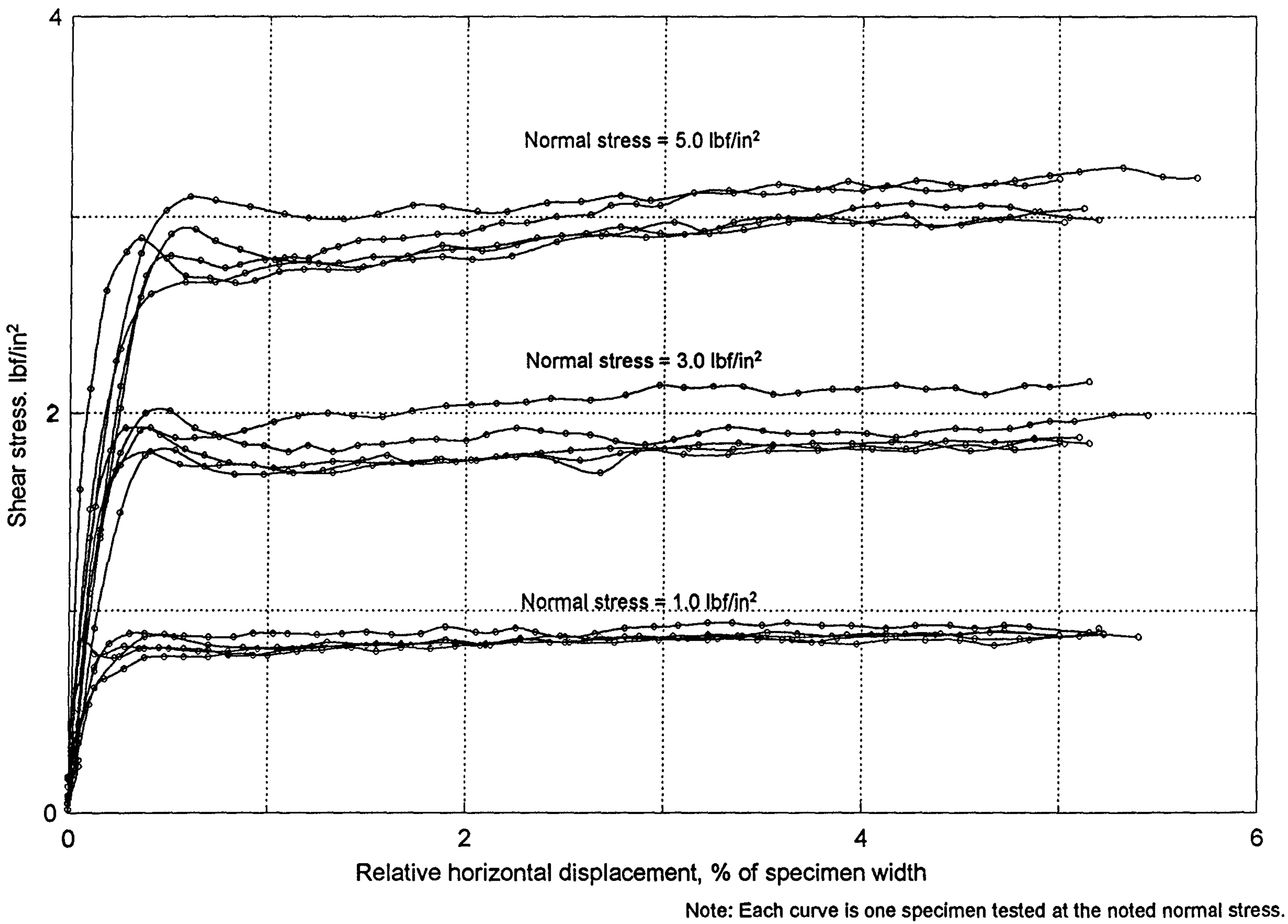


Figure 10. - Geomembrane direct shear tests: soil-on-PVC—subsequent shear displacements—shear stress versus horizontal displacement.

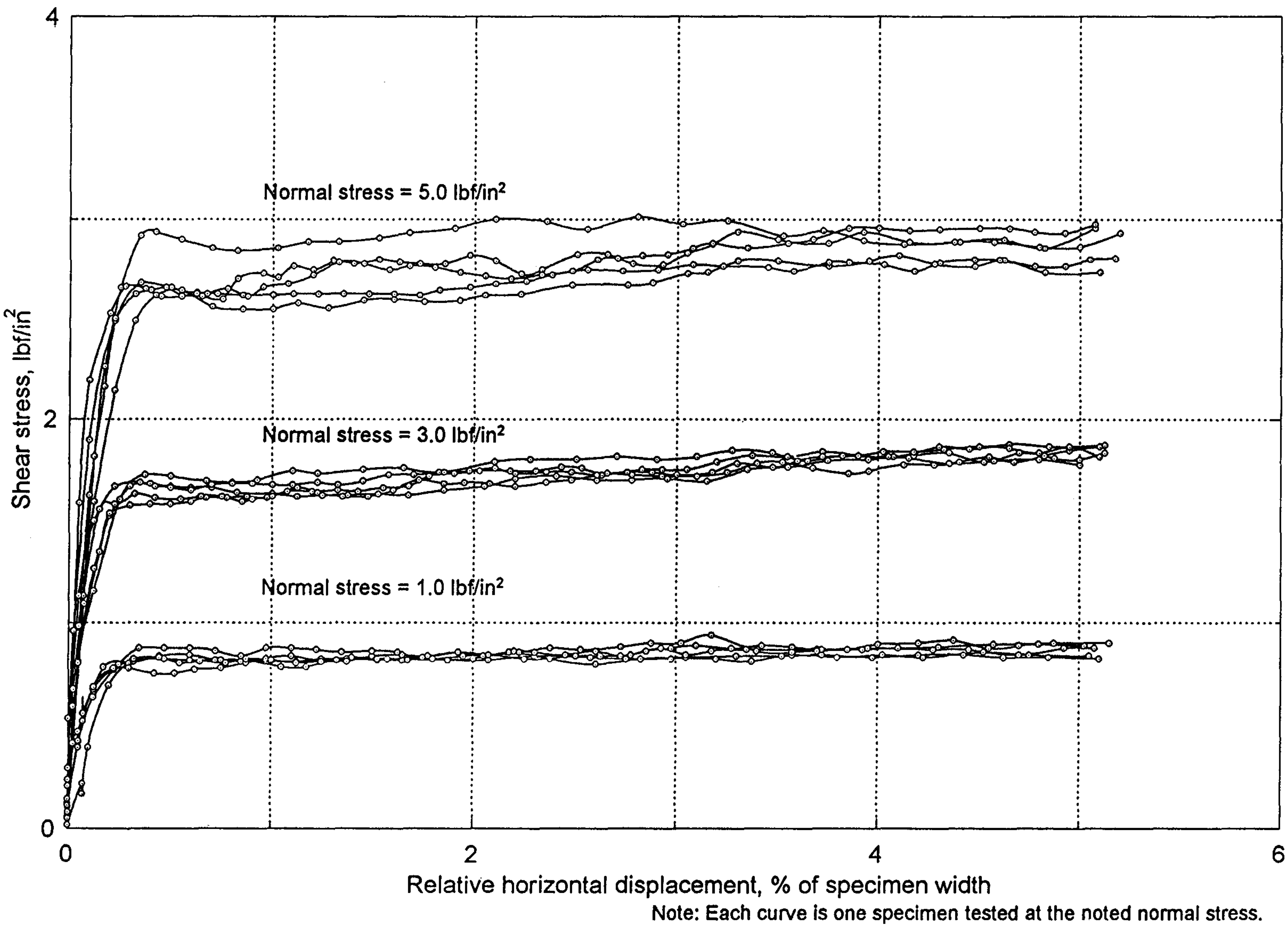
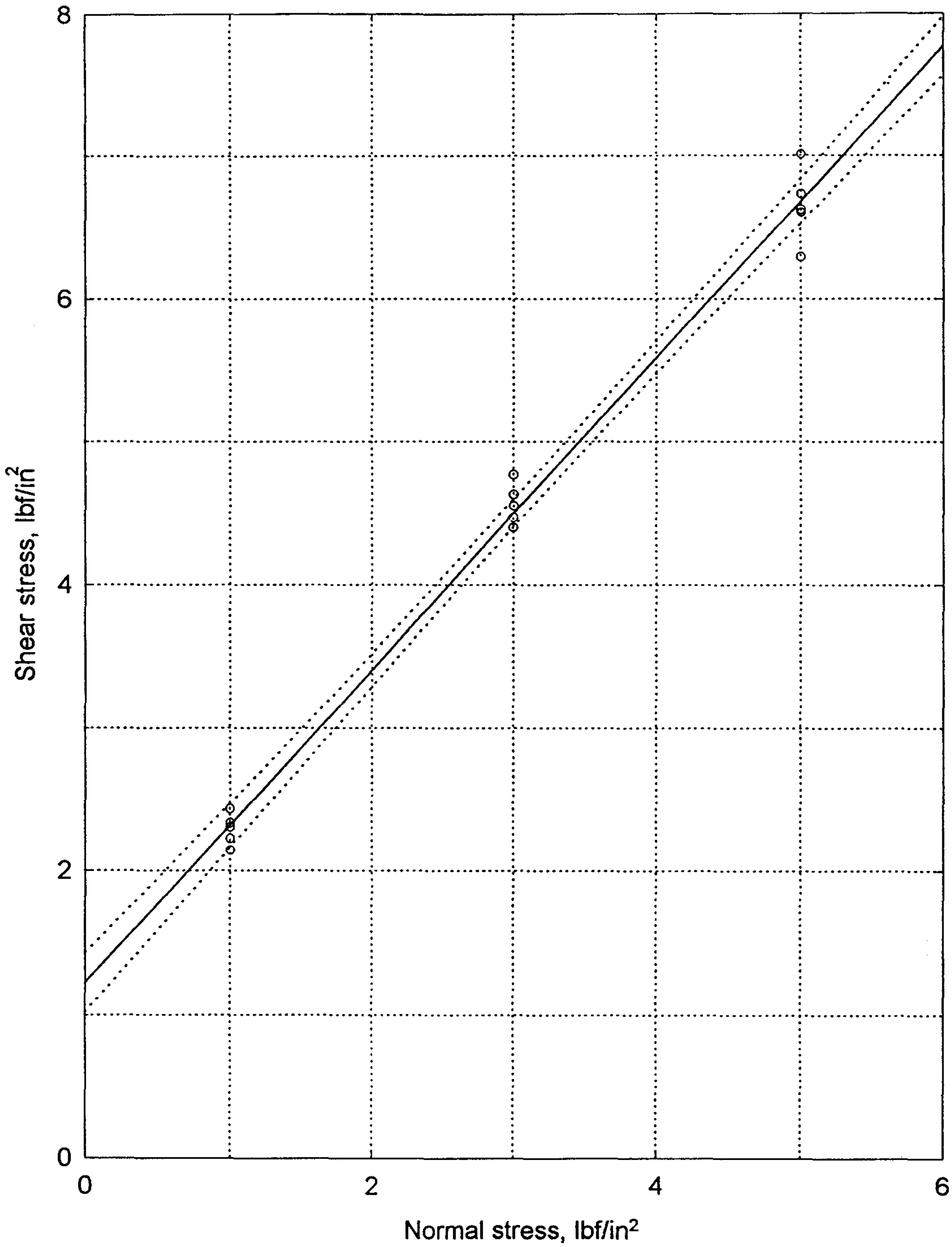


Figure 11. - Geomembrane direct shear tests: soil-on-VLDPE—subsequent shear displacements—shear stress versus horizontal displacement.

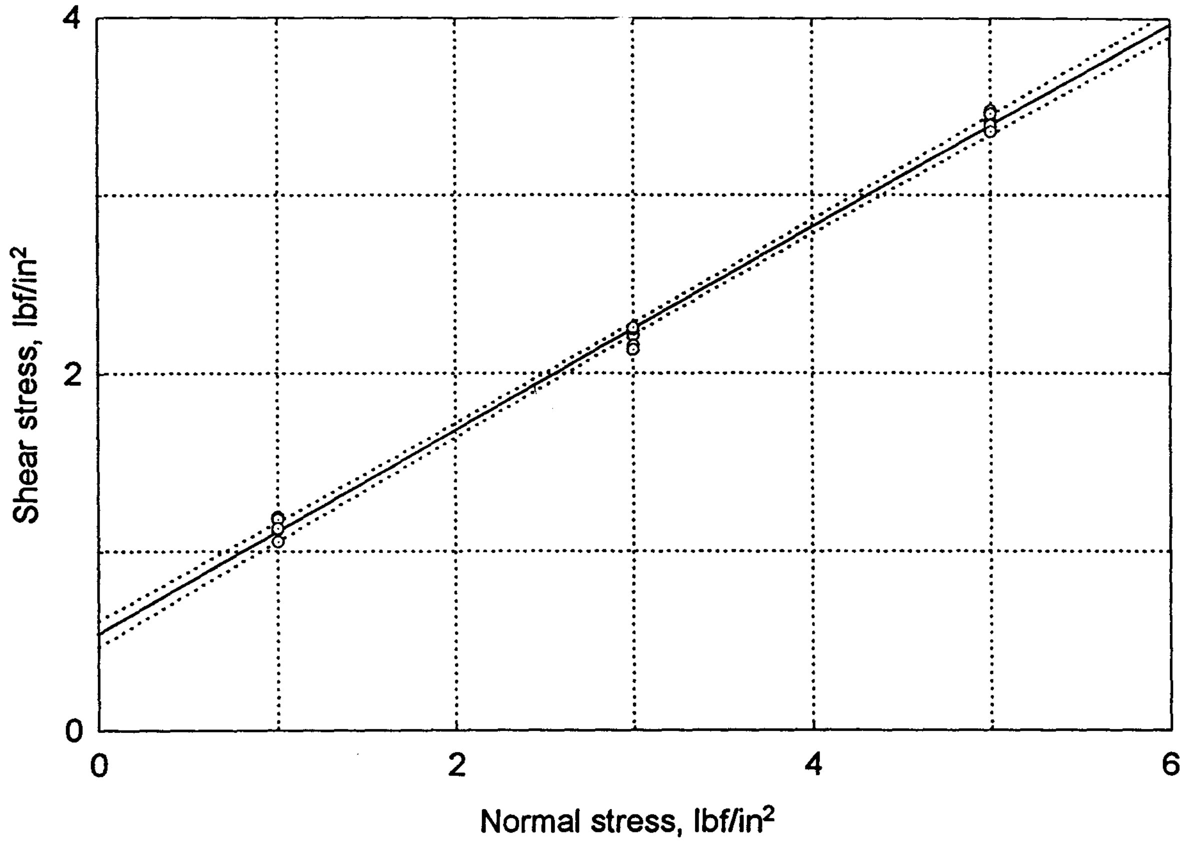


Best fit straight line with 95% confidence intervals:

Shear strength = Cohesion + [Normal stress x *tan* ϕ]

Shear strength = (1.23 ± 0.21) + [Normal stress x (1.09 ± 0.06)]

Figure 12. - Geomembrane direct shear tests: soil-on-soil—peak shear strength; Mohr-Coulomb model.

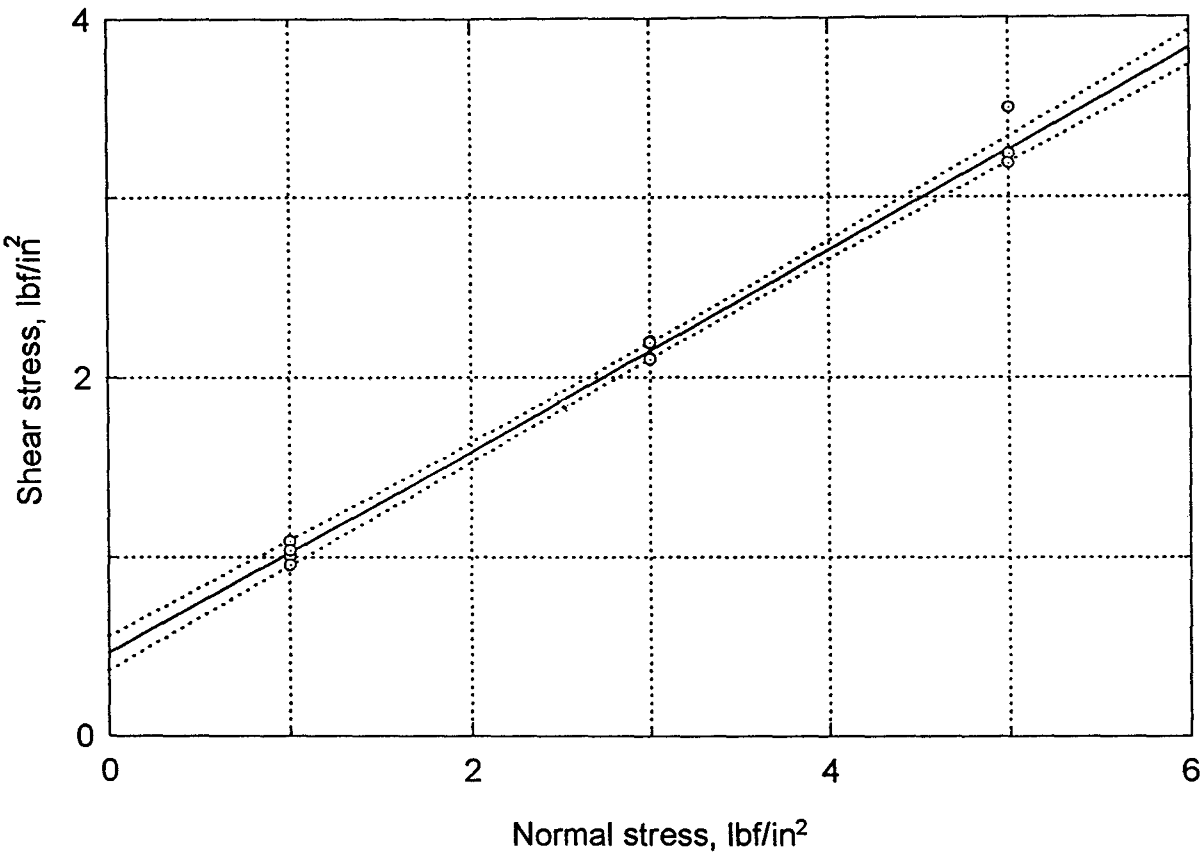


Best fit straight line with 95% confidence intervals:

Shear strength = Cohesion + [Normal stress x *tan* ϕ]

Shear strength = (0.54 ± 0.07) + [Normal stress x (0.57 ± 0.02)]

Figure 13. - Geomembrane direct shear tests: soil-on-PVC—peak shear strength; Mohr-Coulomb model.

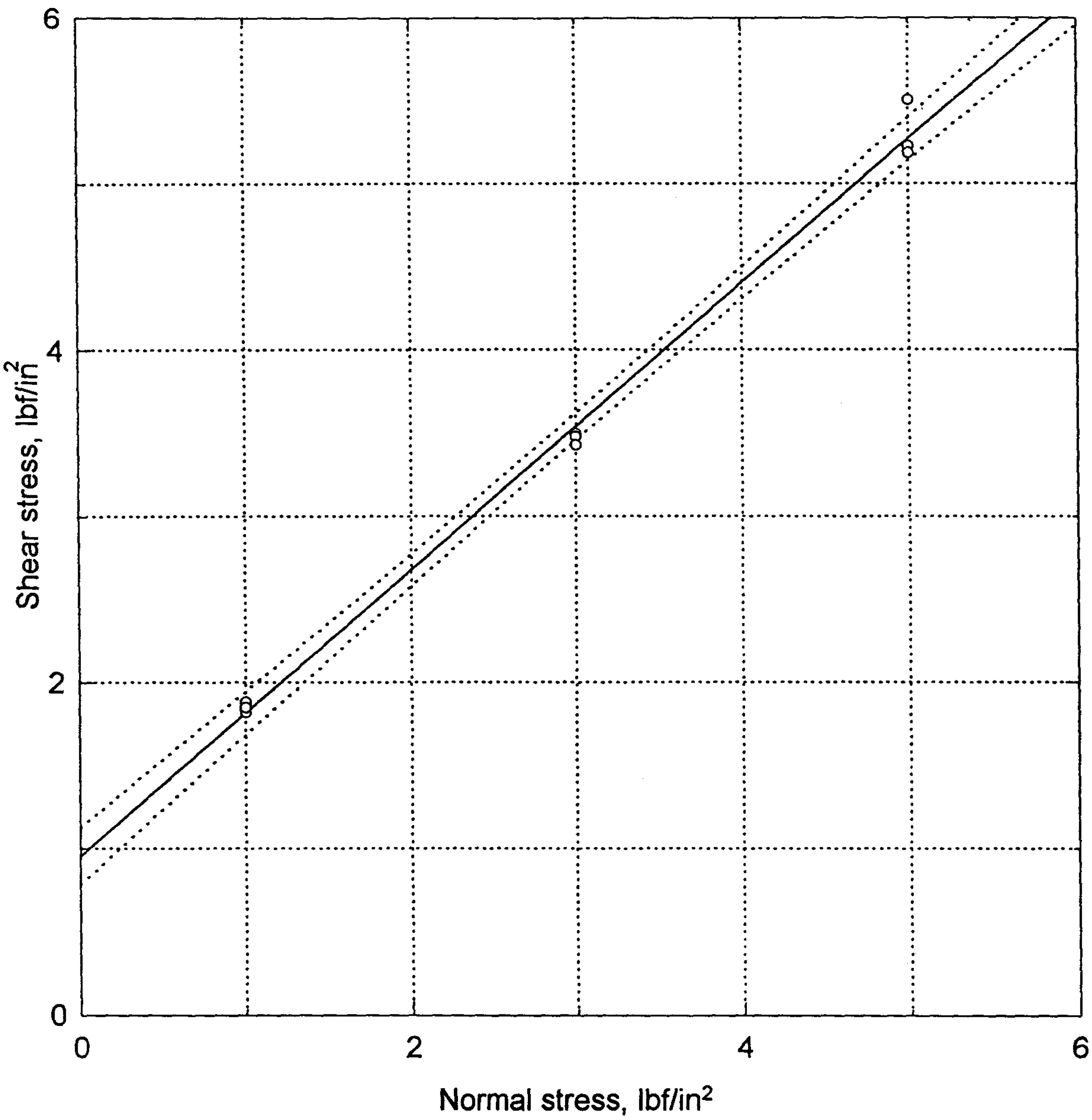


Best fit straight line with 95% confidence intervals:

Shear strength = Cohesion + [Normal stress x *tan* ϕ]

Shear strength = (0.46 ± 0.10) + [Normal stress x (0.56 ± 0.03)]

Figure 14. - Geomembrane direct shear tests: soil-on-VLDPE—peak shear strength; Mohr-Coulomb model.

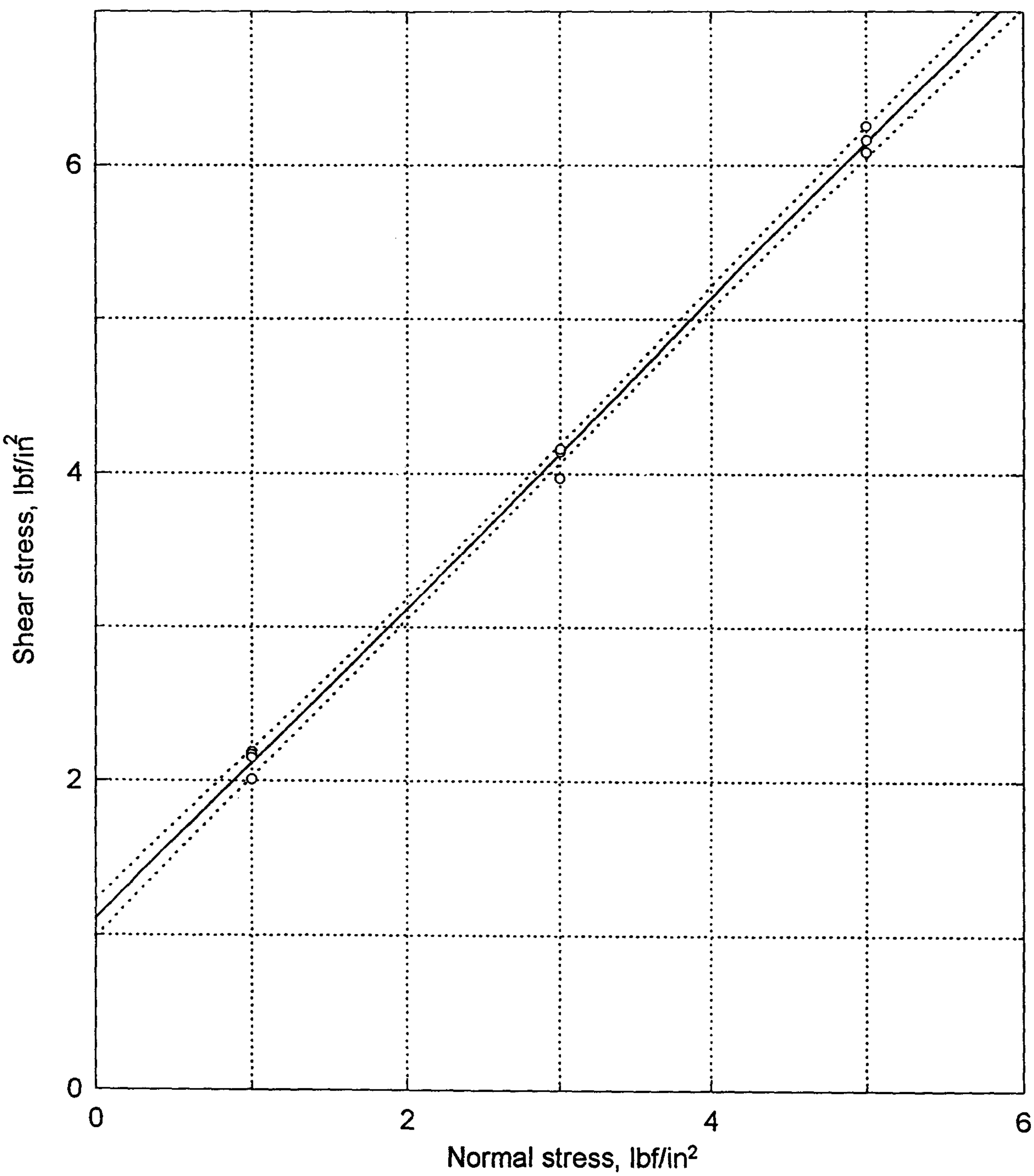


Best fit straight line with 95% confidence intervals:

Shear strength = Cohesion + [Normal stress x *tan* ϕ]

Shear strength = (0.95 ± 0.18) + [Normal stress x (0.86 ± 0.54)]

Figure 15. - Geomembrane direct shear tests: soil-on-geotextile/PVC composite—peak shear strength; Mohr-Coulomb model.

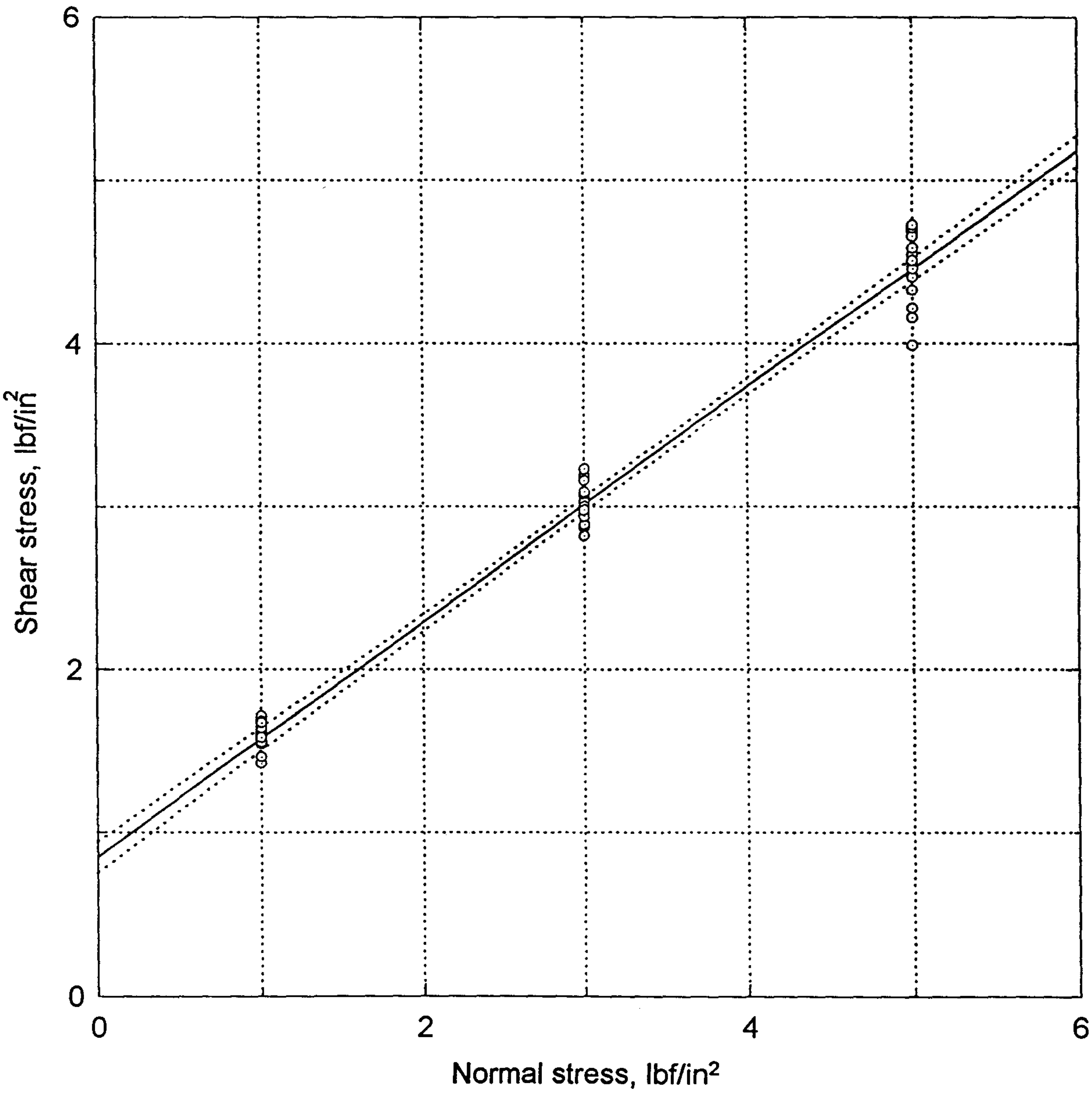


Best fit straight with 95% confidence intervals:

Shear strength = Cohesion + [Normal stress x *tan* ϕ]

Shear strength = (1.11 ± 0.13) + [Normal stress x (1.01 ± 0.04)]

Figure 16. - Geomembrane direct shear tests: soil-on-texturized HDPE—peak shear strength; Mohr-Coulomb model.

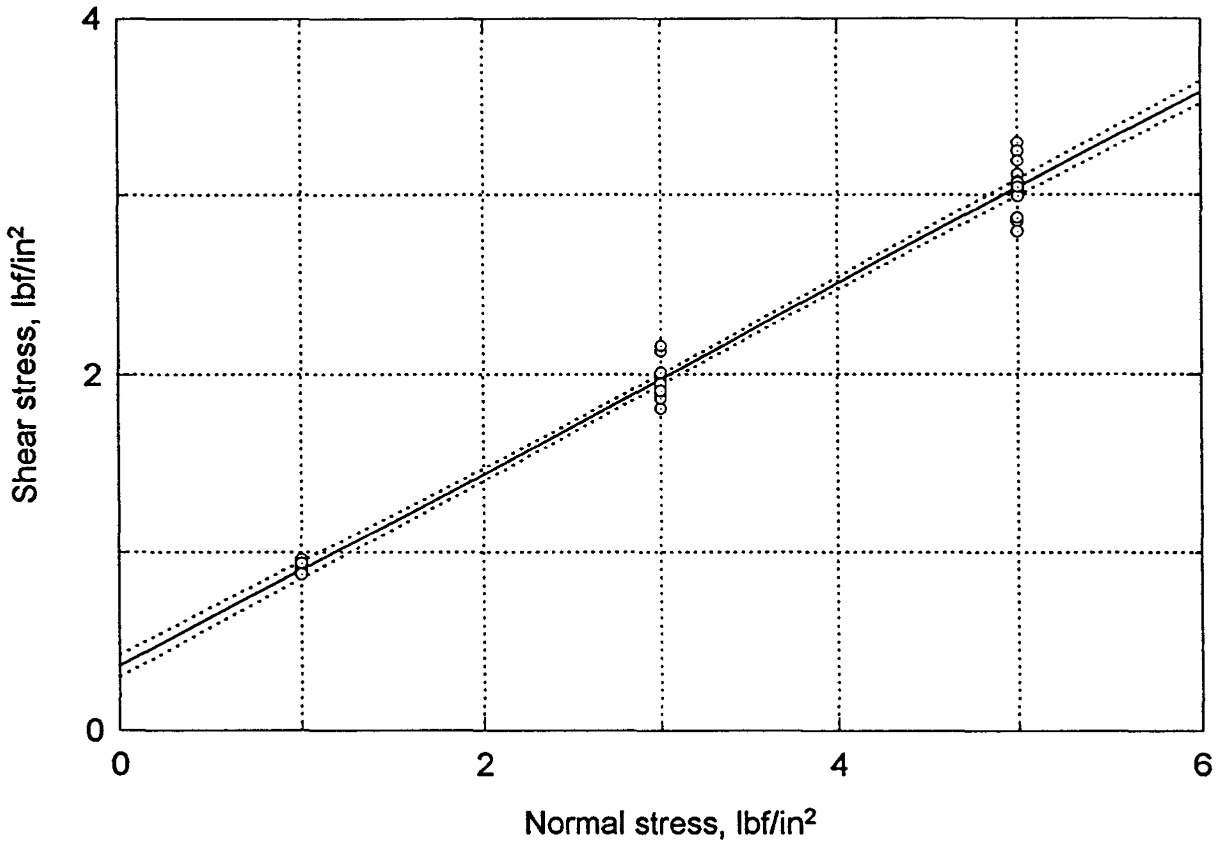


Best fit straight line with 95% confidence intervals:

Shear strength = Cohesion + [Normal stress x *tan* ϕ]

Shear strength = (0.85 ± 0.10) + [Normal stress x (0.72 ± 0.03)]

Figure 17. - Geomembrane direct shear tests: soil-on-soil—post-peak shear strength; Mohr-Coulomb model.

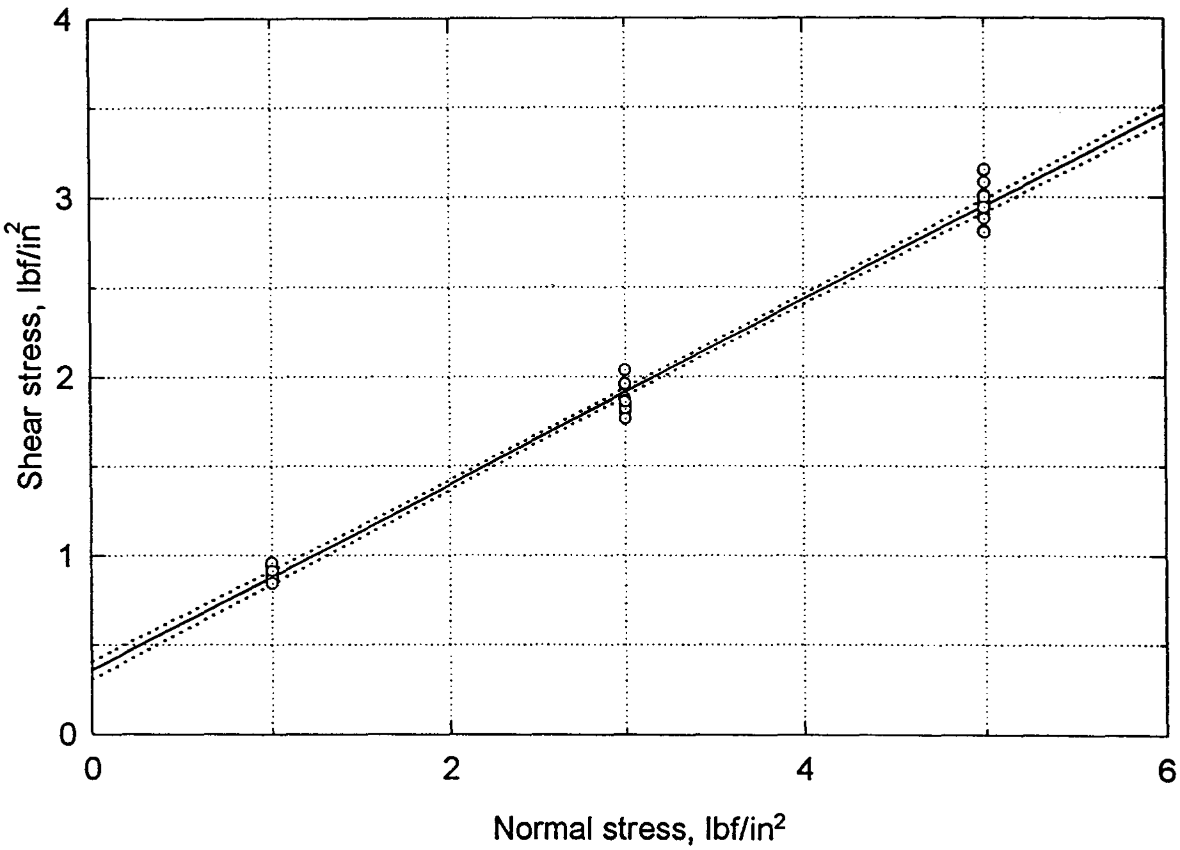


Best fit straight line with 95% confidence intervals.

Shear strength = Cohesion + [Normal stress x *tan* ϕ]

Shear strength = (0.37 ± 0.06) + [Normal stress x (0.54 ± 0.02)]

Figure 18. - Geomembrane direct shear tests: soil-on-PVC—post-peak shear strength; Mohr-Coulomb model.

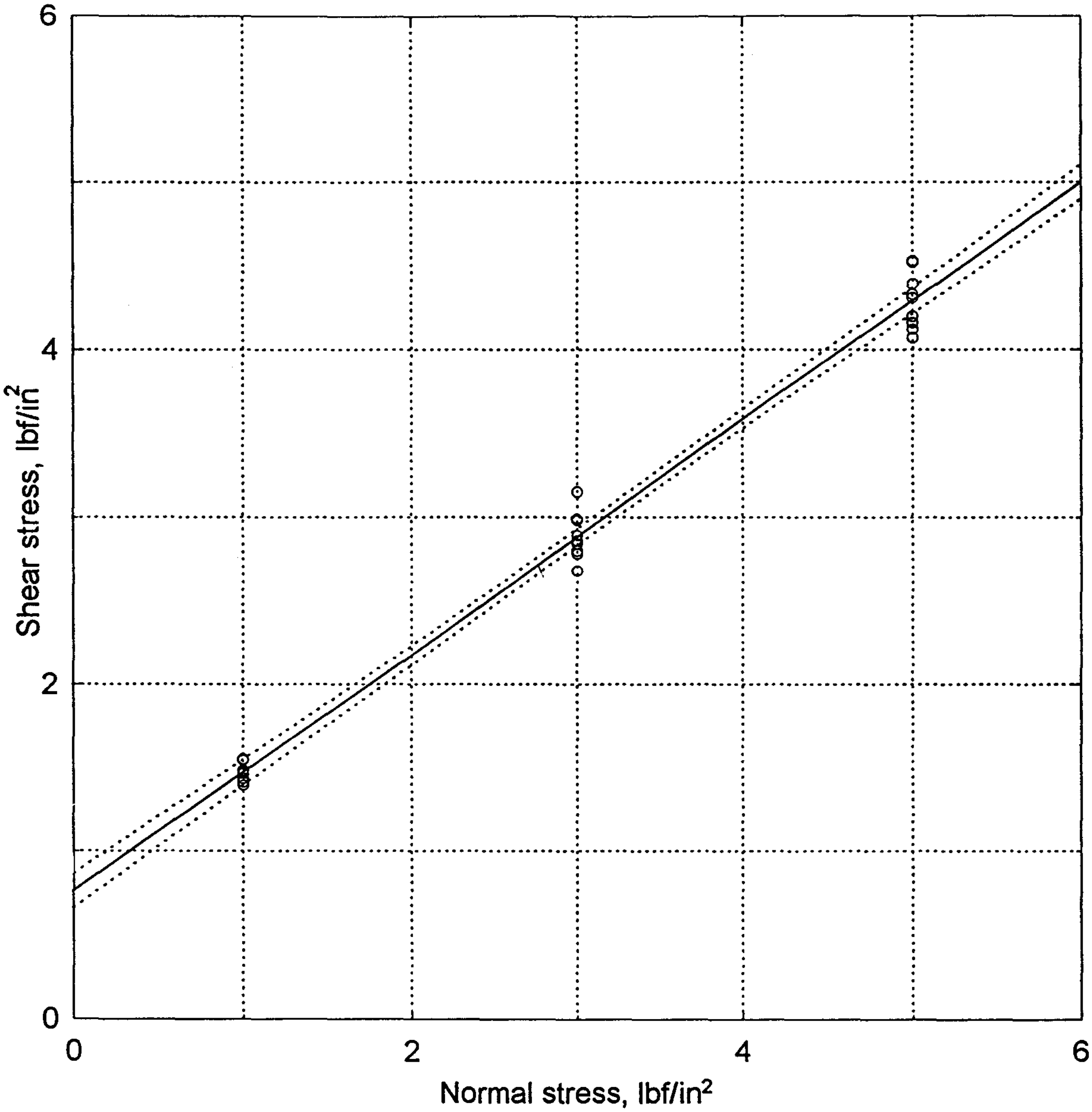


Best fit straight line with 95% confidence intervals:

Shear strength = Cohesion + [Normal stress x *tan* ϕ]

Shear strength = (0.36 ± 0.05) + [Normal stress x (0.52 ± 0.01)]

Figure 19. - Geomembrane direct shear tests: soil-on-VLDPE—post-peak shear strength; Mohr-Coulomb model.

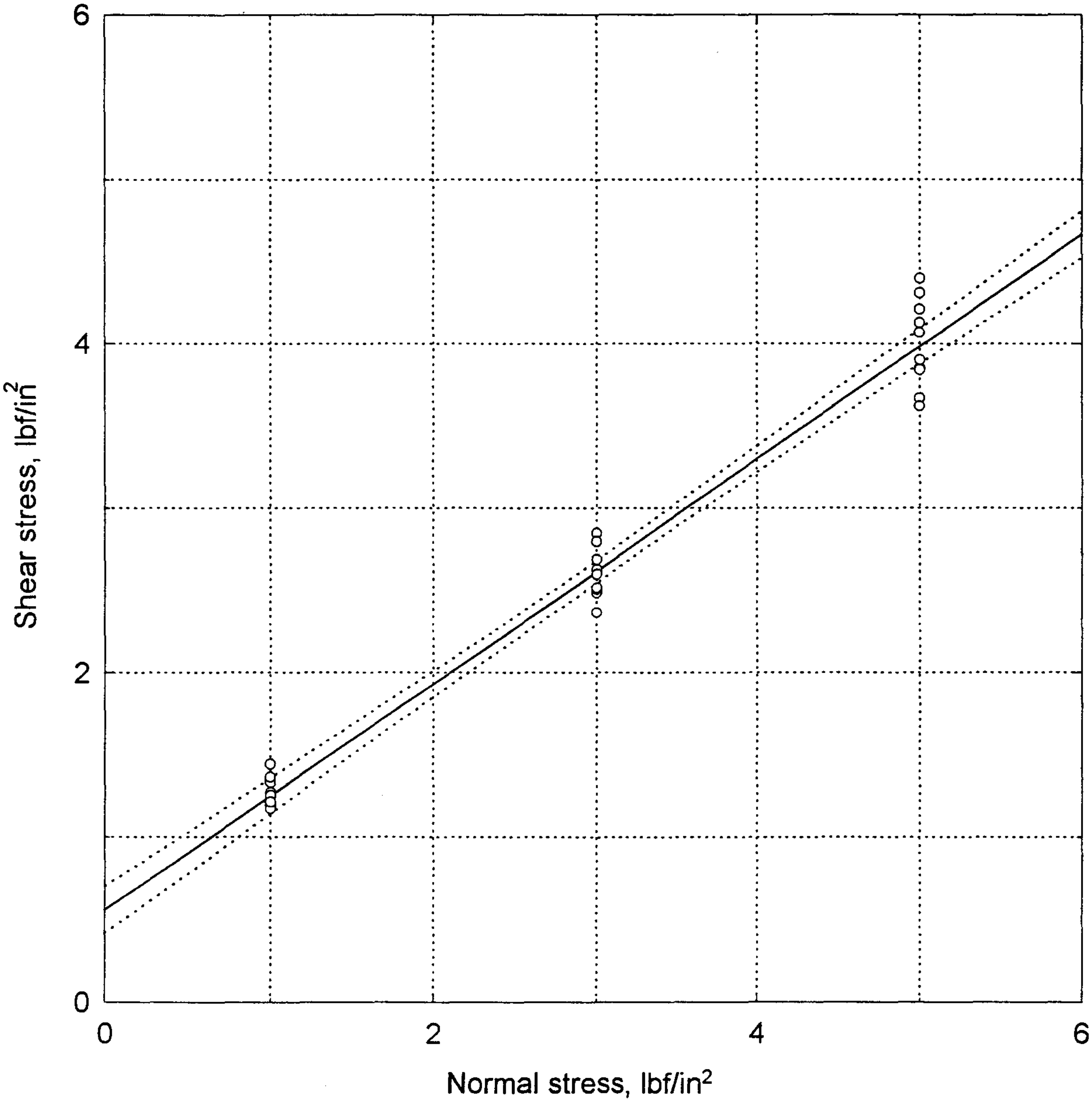


Best fit straight line with 95% confidence intervals:

Shear strength = Cohesion + [Normal stress x *tan* ϕ]

Shear strength = (0.76 ± 0.11) + [Normal stress x (0.71 ± 0.03)]

Figure 20. - Geomembrane direct shear tests: soil-on-geotextile/PVC composite—post-peak shear strength; Mohr-Coulomb model.



Best fit straight line with 95% confidence intervals:

Shear strength = Cohesion + [Normal stress x *tan* ϕ]

Shear strength = (0.56 ± 0.14) + [Normal stress x (0.68 ± 0.04)]

Figure 21. - Geomembrane direct shear tests: soil-on-texturized HDPE—post-peak shear strength; Mohr-Coulomb model.

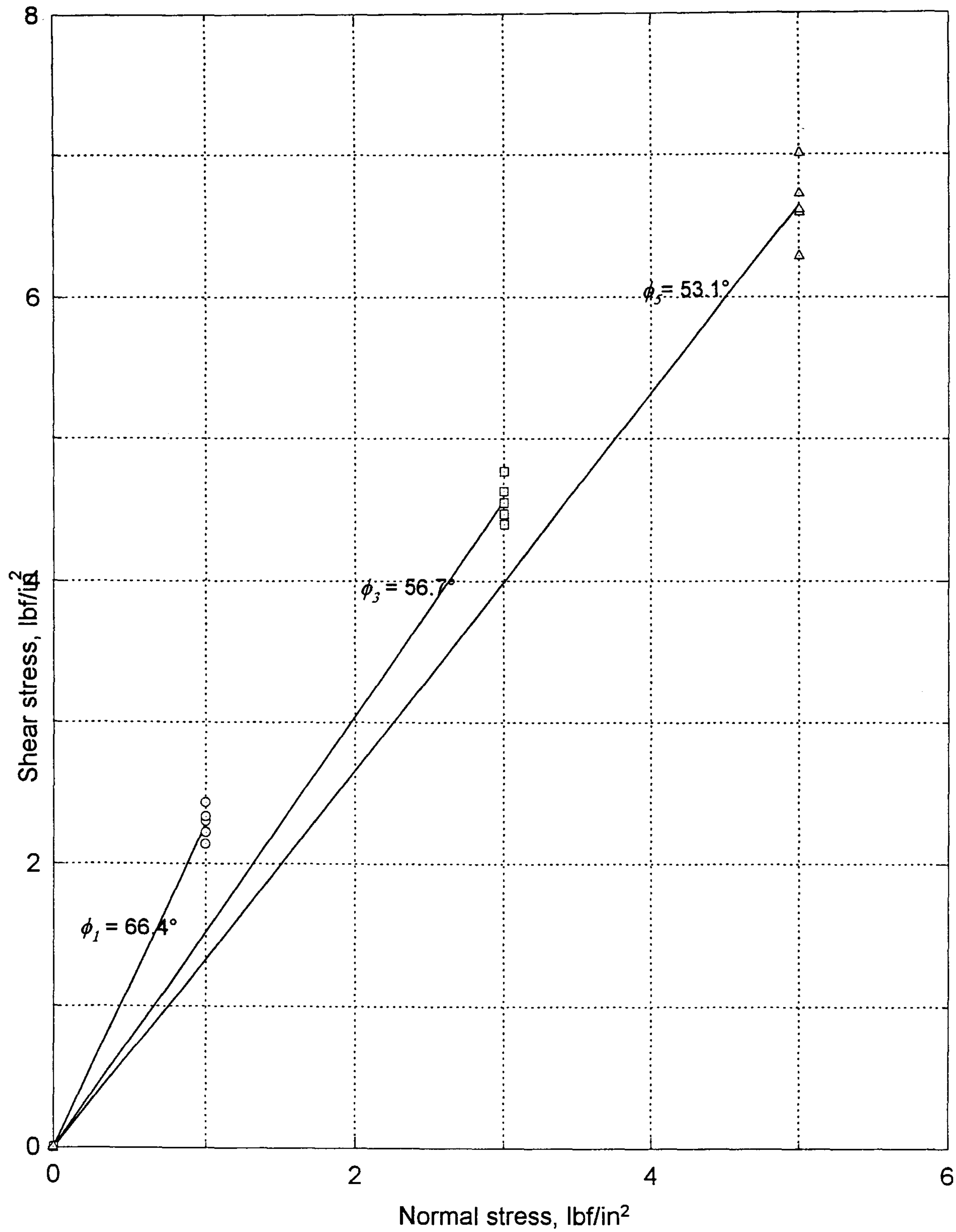


Figure 22. - Geomembrane direct shear tests: soil-on-soil—peak shear strength—one-point model.

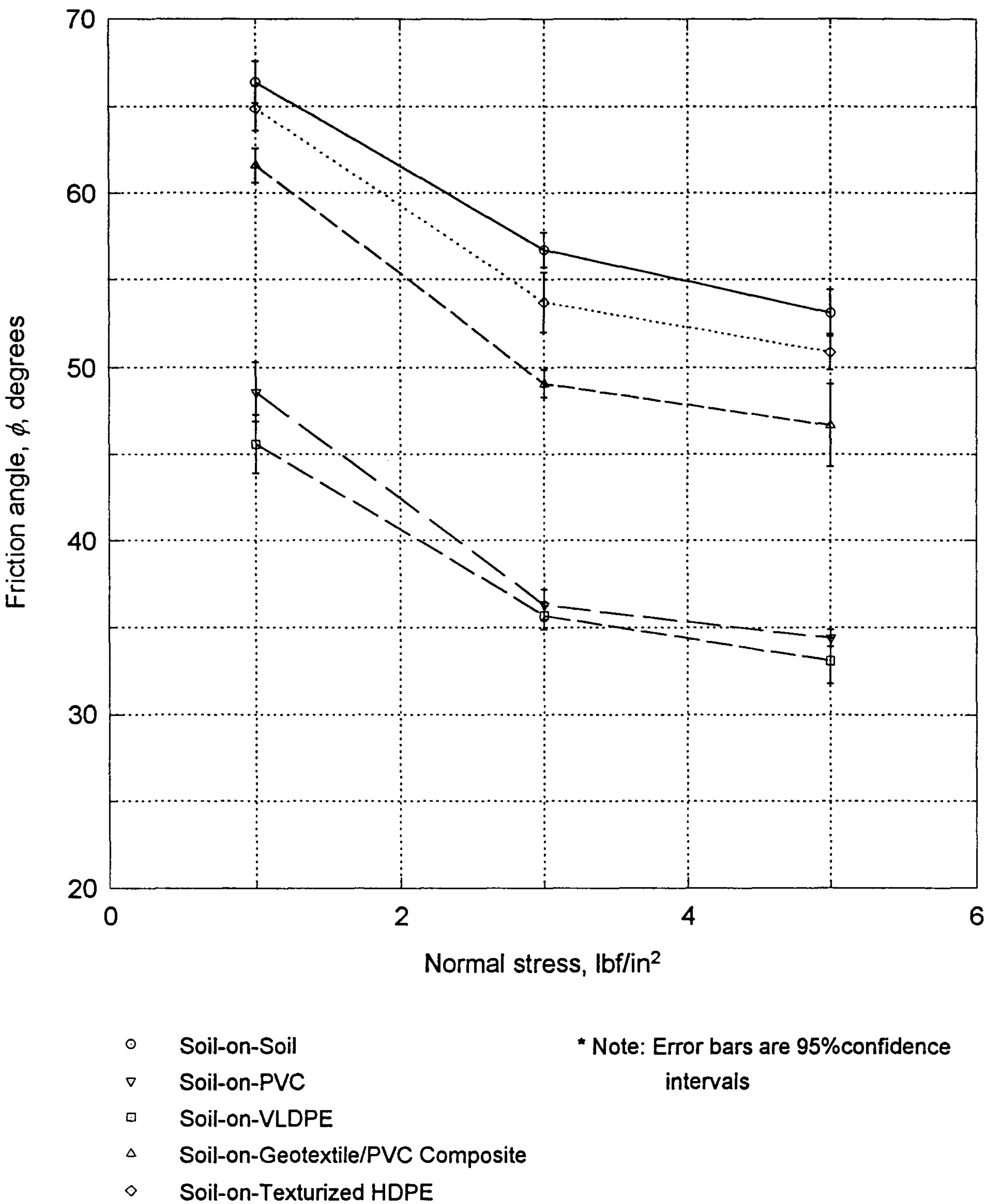


Figure 23. - Geomembrane direct shear tests: normal stress versus friction angle—one-point model—peak shear strength.

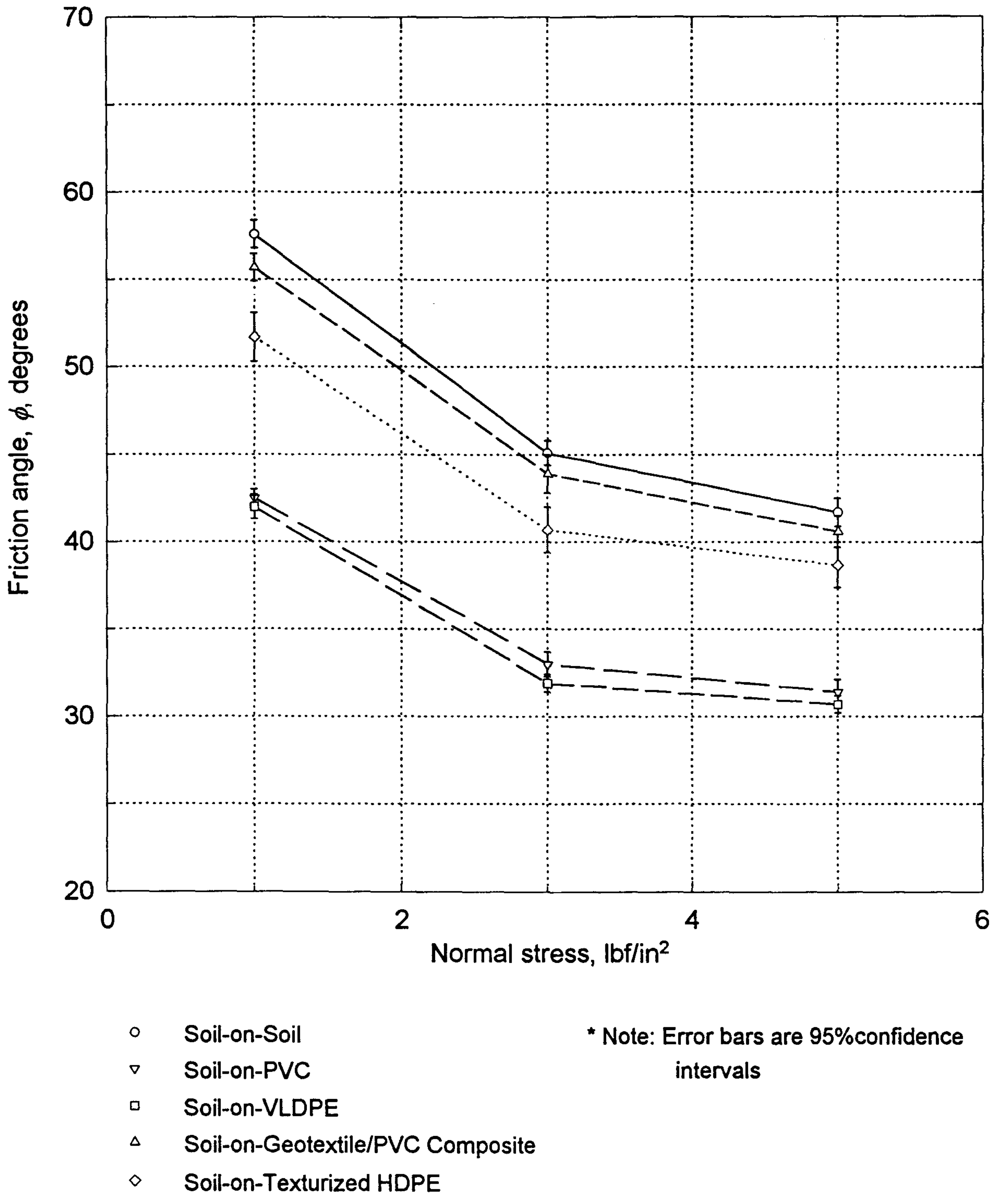


Figure 24. - Geomembrane direct shear tests: normal stress versus friction angle—one-point model—post-peak shear strength.

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.