A Report
on
COMPARISON OF PVC and HDPE GEOMEMBRANES (INTERFACE FRICTION PERFORMANCE)

for

PVC GEOMEMBRANE INSTITUTE.

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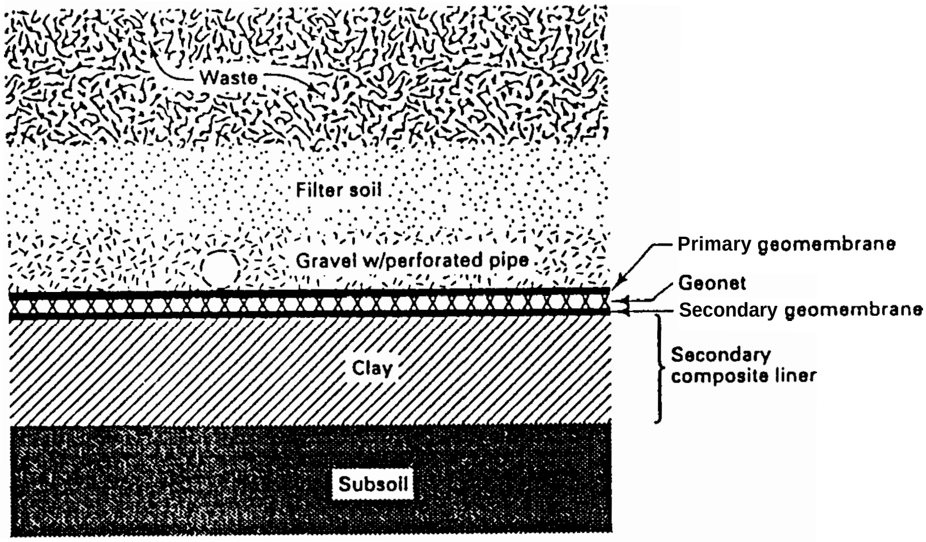
1.0 INTRODUCTION

Modem solid-waste landfills and hazardous landfills in the USA are required to have a low hydraulic conductivity liner and drainage system, consisting of geosynthetic materials (geomembranes, geotextiles, geonets and geocomposites) and compacted clay. **A** cross-section of a typical modem landfill, as shown in Figure 1.1, consists of several layers of soils and geosynthetic products. The stability of these 'slopes' is controlled by the shear strength of the various interfaces in such a composite liner. Critical interfaces include soil vs. geomembrane, soil vs. geotextile, geomembrane vs. geotextile and geomembrane vs. geonet. The strength of each of these interfaces has to be determined after careful, site-specific material testing (Koerner, 1994). The experience and confidence gained from these tests on different materials and soils is valuable to designers. Such data give the basis for better judgment in design. The importance of the evaluation of interface strength has been illustrated by the slope stability failure in Phase 1A of the construction of the Kettleman Landfill in California (Mitchell et al., 1990).

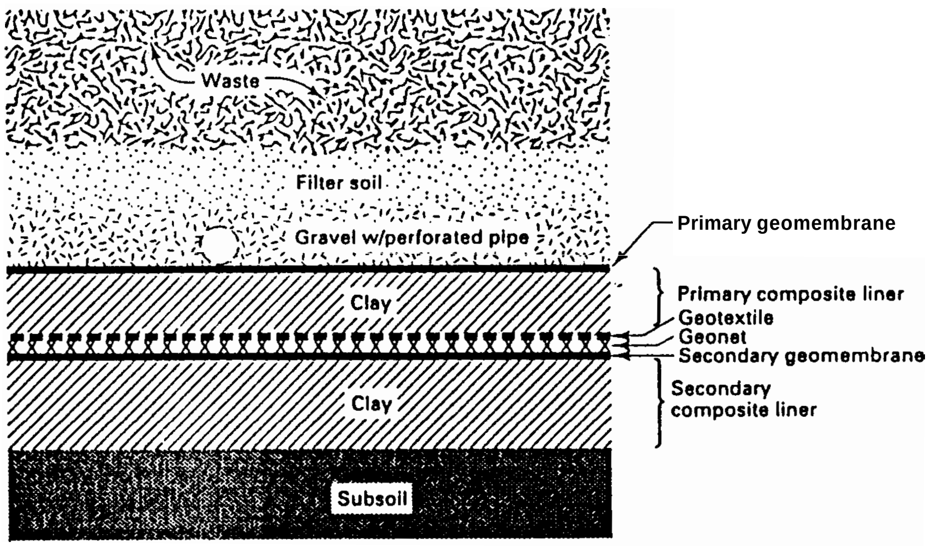
Geomembranes are critical components of modem landfill design, performing important functions moisture barriers in the containment system. Today, a variety of geomembranes are in use in current practice. The basic difference between them is the material and/or method of manufacture. The most commonly-used material types are (PVC) Poly Vinyl Chloride and (HDPE) High Density Poly-Ethylene. Based on a 1992 estimated total of 648 million sq. feet of geomembrane sales, HDPE accounts for 259 million sq. feet or 40 % of sales , while PVC accounts for 162 million sq. feet or 25 % of sales(Koerner, 1994). Very Low Density Poly-Ethylene (VLDPE), a Polyethylene product, which is more flexible than HDPE, accounts for 65 million sq. ft or 10 % of sales .

Geomembrane interface frictional failure has been identified as the cause of numerous geosynthetic-lined slope failures. As a result, the interface frictional strength of any geomembrane interface has to be determined with utmost care. It is recommended that wherever possible, the interface frictional strength for a geomembrane-soil combination be determined experimentally, without resorting to use of generalized values for similar soils from published data (Koerner, 1994). Direct shear, pullout and ring shear tests have been performed extensively, mainly on soil-geomembrane interfaces, to characterize their strengths (Koerner et al., 1986; Seed et al., 1988; O'Rourke et al., 1990; Takasumi et al, 1991; Stark and Poeppel, 1994)

There have been a limited number of testing programs that have attempted to draw a general comparison between HDPE and PVC geomembranes. O'Rourke (1990) reported that the higher the stiffness or hardness of the geomembrane, like HDPE, the lower the friction angle, as compared to a flexible membrane, like PVC. Martin et al. (1984) tested geotextile vs. geomembrane interface friction using a very soft, flexible geomembrane like Ethylene Propylene Diene Monomer (EPDM), a medium stiffness PVC geomembrane and a tough geomembrane like HDPE. They also concluded that the softer geomembranes, have greater friction angles than the tougher geomembranes.



a)



b)

Figure 1.1 Typical Cross-sections of Modem Landfills : a) without geotextiles b) with geotextiles

PVC geomembranes have unique interface friction behavior when compared to other geomembranes due to their flexibility. However, a systematic comparison between PVC and HDPE geomembranes is necessary to expand the existing knowledge-base. This testing program addressed this issue.

1.1 Poly Vinyl Chloride and High Density Poly Ethylene

Poly Vinyl Chloride and HDPE have different mechanical and physical properties as well as field applicability. However, depending on the specific application, both have been widely and successfully used in many applications. Some of the major differences between PVC and HDPE geomembranes are :

- Poly Vinyl Chloride geomembranes are flexible and relatively easy to handle, while HDPE geomembranes are tough and non-flexible;

- High Density Poly Ethylene geomembranes tend to exhibit a sharp peak in their stress-strain curve and therefore, tend to undergo a relatively abrupt failure whereas PVC undergoes a very large amount of elongation before failure; . (see Figure 1.2)

- The flexibility of PVC geomembranes is primarily due to additives such as plasticizers. The main concern regarding PVC geomembranes is their survivability, i.e., loss in strength and other properties due to leaching-out of plasticizer over time; and

- It is universally recognized that field seaming is potentially the most problematic aspect of a liner construction. Due to its flexibility, it is possible to do a majority of PVC seams under controlled factory-conditions because they can be folded easily. HDPE geomembranes, however, still need to be seamed in the field. **A** PVC liner may require as low as 20% of the field seams required by a HDPE liner (Peggs, 1992).

2.0 TESTING PROGRAM

For the proposed study, three different types of PVC membranes were compared with two types of HDPE membranes. These geomembranes were tested with sand, sandy loam and silty clay soils as well as a geotextile.

2.1 Materials

2.1.1 Geomembranes

In this study, in an attempt to include a variety of PVC and HDPE geomembranes presently available in the market, five different geomembranes were tested. The names and properties of the geomembranes used are shown in Table 2.1.

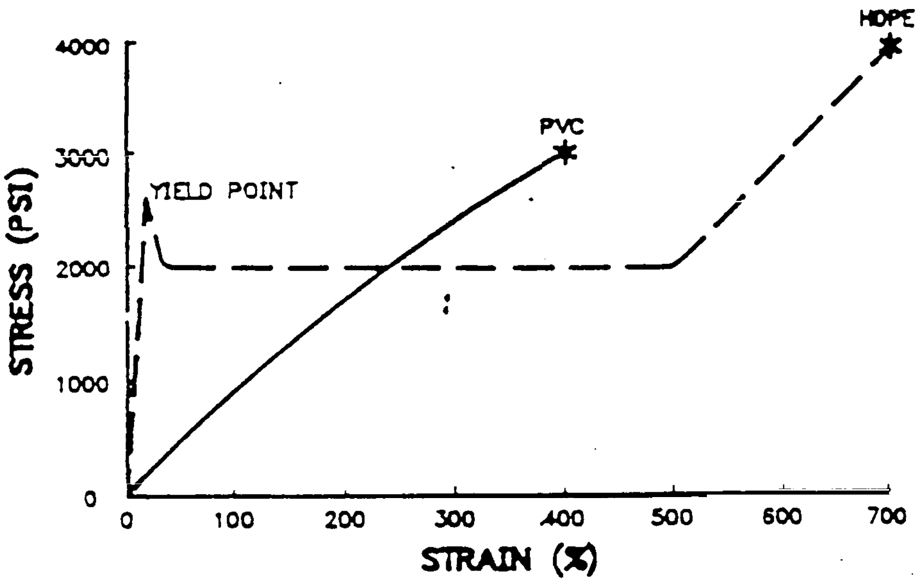


Figure 1.2 Schematic representation of Stress-Strain behaviour of **HDPE** and **PVC** (Peggs, 199

Table 2.1 Properties of Geomembranes used in the Testing Program

GEOMEMBRANE TYPE	*SMOOTH PVC*[1]	*TEXTURED PVC*[2]	*FILE-FINISH PVC*[3]	*SMOOTH HDPE*[4]	*TEXTURED HDPE*[5]
MANUFACTURER	Oxychem	**OxyChem**	**C.G.T. Ltd.** *	**GSE****	**GSE**
TRADE NAME	**Oxyflex**	**OxyGrip**	**Taffeta**	**GSEHD**	**GSEHDT**
GAUGE (mils)	30	30	30	60	60

* Canadian General Towers
** Gundle / SLT Environmental (Inc.) Company
1. Smooth PVC : Smooth, flexible PVC geomembrane
2. Textured PVC : PVC geomembrane, with extrusions of 4 - 6 mils on the surface, giving the rough texture. The textured surface was used as the interface
3. File-Finish PVC : Square grid etched onto one surface, with smooth PVC on the other surface. The surface with the file-finish was used as the interface.
4. Smooth HDPE : Smooth, tough, inflexible HDPE geomembrane
5. Textured HDPE : Co-extruded textured surface on one side and smooth HDPE on the other surface. The textured surface was used in the surface.

2.1.2 Soil

A typical landfill consists of soil-geomembrane interfaces involving a variety of soils. Most commonly, sand as a drainage layer and clay as a moisture barrier are used. However, when locally available soils are the only option, sandy loam and silty clay are used as substitutes. Hence, these soils were also included in this study. Figure 2.1 gives the grain size distribution of the soils.

2.1.2.1 Sand

Sand-Geomembrane interfaces are common at the boundary of a drainage layer and the next layer of moisture barrier. Testing for this interface was performed using sand with the following properties :

Grain size distribution :

D_{10} - 0.15 mm D_{50} - 0.29 mm D_{90} - 0.51 mm
C_u - 2.13 C_c - 0.919
Internal Friction : Angle of Internal Friction, from a Direct Shear Test = 32.3"

This sand can be described as uniform, fine sand. It was mixed with just enough water to simulate the average field wetness conditions (approximately 10%).

2.1.2.2 Sandy Loam

In many situations, the soils most suitable for a landfill may not be available on location. In such cases, liners are constructed with the available soil. One of the common soils found at sites is sandy loam. In such situations, sandy loam is used as an alternative to sands in the landfill. The soil used for testing in this program can be described as well graded sandy loam. In this soil, there was a significant amount of organic matter, including plant root fibers and remains of insects. The natural water content of the soil was 41.8 % . Testing was done at the same water content.

The requirements of a material to be used as drainage material in a waste containment system are as follows (USEPA, 1989) :

- Hydraulic conductivity must be greater than 10^{-2} cm / s ;
- Rounded to sub-rounded material, to avoid damage to the adjacent geosynthetics ;
- Well graded material ; and
- Maximum particle size of 3 / 8 inch (9.5 mm) .

The properties of the sandy loam used in this study were :

Grain size distribution characteristics :

D_{10} - 0.10 mm	D_{50} - 0.53 mm	D_{90} - 4.2 mm
C_u - 9.0	C_c - 0.69	

Based on the USEPA requirements above for a drainage material, the sandy loam tested satisfies the requirements for use as a drainage material. The hydraulic conductivity requirement needs to be verified, but it is strongly believed that it will be complied, based on its grain size distribution.

2.1.2.3 Silty Clay

Locally available soil is generally preferred for the compacted clay layer in a landfill liner. In such cases, the criteria for selecting the soil are(Daniel, 1993) :

- % dry weight passing the #200 sieve > = 39 % - 50 %
- % dry weight retained on the # 4 sieve <= 20 % - 50 %
- PI (ASTM D 4318) > = 7 % - 10%
- Maximum grain size : 25 mm - 50 mm

Grain size distribution characteristics :

D_{10} - < 0.075 mm	D_{50} - 0.12 mm	D_{90} - 4.3 mm
C_u - 23.17	C_c - 1.03	

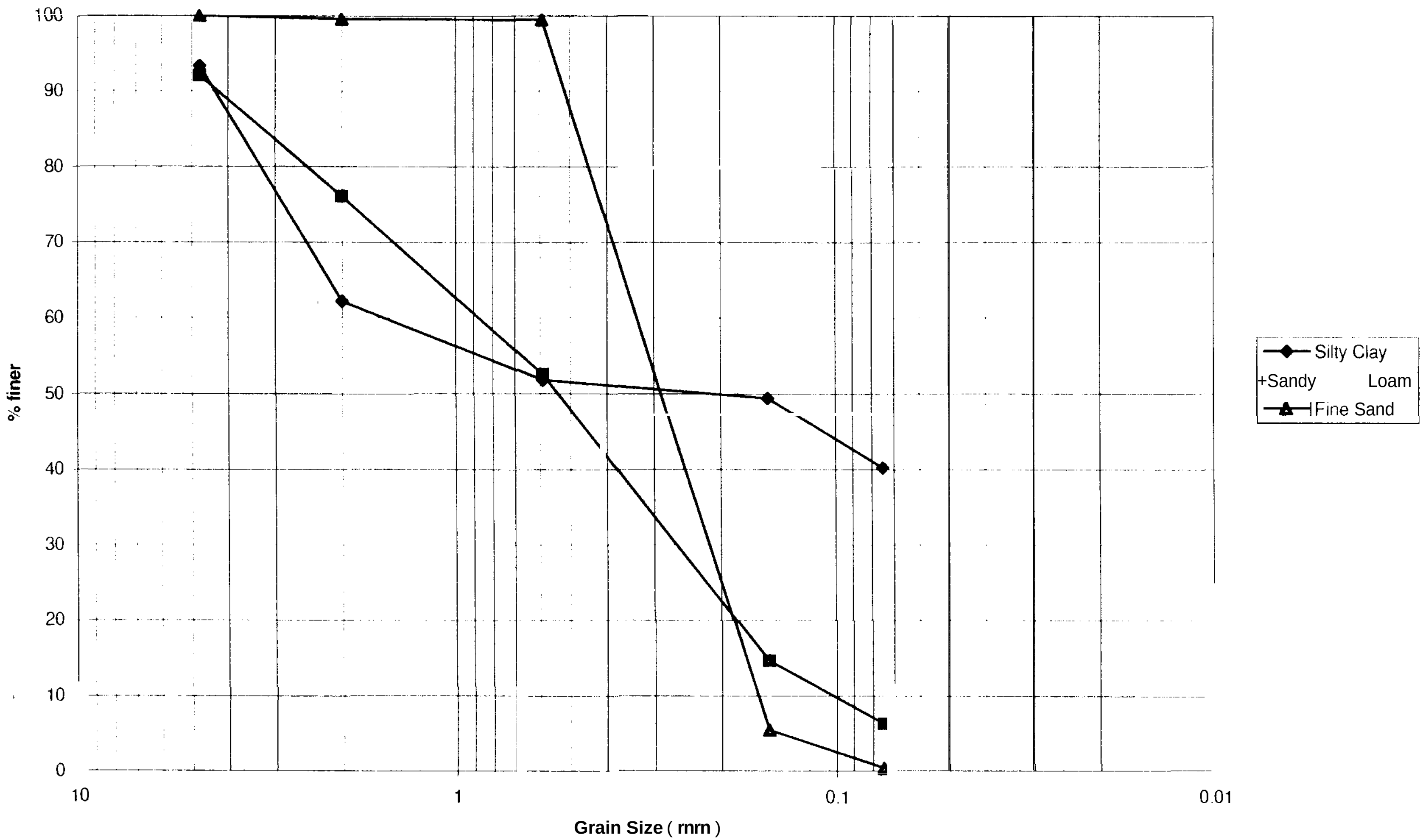


Figure2.3 Grain size distribution of Soils used in the Testing Program

Atterberg's Limits (on Material passing the # 40 sieve) :

PL = 12.97 % LL = 30.02 % PI = 17.05 %

The silty clay used for the study satisfies all of the above requirements. Hence, it was used as representative of soils that can be used as a compacted clay layer in a landfill.

2.1.3 Geotextile

Geotextiles are used in the landfill liner as a filter layer to prevent the loss of fines from the clay layer, as well as a cushioning layer for the geomembrane against the drainage layer placed above it. The geotextile-geomembrane interface is one of the most critical for the slope design. The geotextile used in this testing program was a non-woven, staple-filament geotextile, with one side rougher than the other. The rougher surface was used as the interface as that would provide better frictional properties.

2.2 Equipment

The equipment used for this testing program was a large direct shear box (30.5 cm x 30.5 cm), designed and built at Syracuse University. It consisted of a split box, with the top box being 30.5 cm x 30.5 cm x 5.1 cm. The bottom box was 30.5 cm x 46 cm x 5.1 cm. The longer length of the bottom box provides a constant area of contact during the entire travel of the bottom box, to a maximum of 76 mm (25 % strain). The top box was held in place while the bottom box rested on wheels and could be moved, relative to the top box. Both boxes had clamps at both their ends, to allow for clamping of geotextile (top box) or geomembrane (bottom box). Normal stress was applied through a yoke that rested on the top box after the two boxes were set in place. Stress was applied by a set of pneumatic pistons, with a maximum capacity of upto 250 kPa. Shear stress applied when the bottom box was displaced was measured by a load cell with a capacity of 2200 kg. The horizontal and vertical displacements are measured by Linear Variable Displacement Transducers (LVDT) with an accuracy of 0.025 mm.

2.3 Procedure

For all the tests, the bottom box was filled with compacted silty clay at a dry density of 2081 kg/m^3 and at an optimum moisture content of 9.78 %. The dry silty clay was crushed using a jaw-crusher and sieved in a #40 sieve. It was then mixed with water to get the optimum moisture content. The clay was then placed in the bottom box in three layers and compacted using a wooden tamper. After the soil was placed in the bottom box, the top was levelled using a straight edge and covered with plastic wrap until the membrane was placed, to avoid loss of moisture. At the beginning of each test, a fresh sample of geomembrane, cut to the dimensions 330mm x 460mm (13" x 18"), was placed on top of the compacted clay in the bottom box. The bottom box was moved to the starting position. The top box was then placed on top of it. For soil interfaces, the soil (mixed with the appropriate amount of water to simulate field moisture conditions) was placed in the top box in three layers and compacted. On an average, the height of the soil in the top box was 20 mm above the geomembrane. After soil was placed in the top box, it was raised slightly and tightened in this position, to ensure full contact between the geomembrane and the soil.

For tests with geotextile interfaces, the geotextile was clamped to both ends of the top box. To ensure that the geotextile did not tear out of the clamping before the interface failed, holes were made at the ends of the geotextile and the clamping screws were inserted through them and tightened.

The loading plate was placed on top of the soil or geotextile in the top box, along with the loading ball. The loading yoke was lowered so that it sat exactly on the ball. Pressure was increased to the calculated level, to exert the required amount of normal stress for each run of the test. The load cell and vertical and horizontal LVDTs were reset to zero. The exerted normal stress was allowed to settle fully on the interface for about five minutes. Testing was performed at a displacement rate of 1 mm (0.04") per minute and data was collected to a maximum displacement of 64mm (2.5"). Shear force was exerted on the interface by pulling the bottom box relative to the top box. The gear system controlling the motion of the bottom box is automated through a computer. Data collection was also done using a computerized data acquisition system.

3.0 RESULTS

A total of 101 tests were conducted on the 20 interfaces (five different geomembranes against three different soils and one geotextile). Initially, tests were repeated to verify their reproducability. Since good reproducability was observed in the initial tests, subsequent tests were not repeated (See Figure 3.1).

3.1 Sand vs. Smooth Poly Vinyl Chloride Geomembrane

The stress vs. displacement data generated from the tests on smooth PVC geomembrane vs. sand interface at various normal stresses is shown in Figure 3.2(a). The interface friction values derived from these tests are shown in Figure 3.2(b).

The stress-strain behaviour of the PVC vs. Fine sand is shown in Figure 3.2(a). After a displacement of 20 mm, the stress remained constant at a particular value, which was determined to be the peak shear stress.

It can be said that the test conditions in this program were a better representation of the field conditions than a steel plate or wooden base. Displacement occured not only between the membrane and sand but also between the geomembrane and the base. The measured displacement was, however, the one between the sand and geornembrane, because displacement measured is that of the bottom box motion relative to the top box motion.

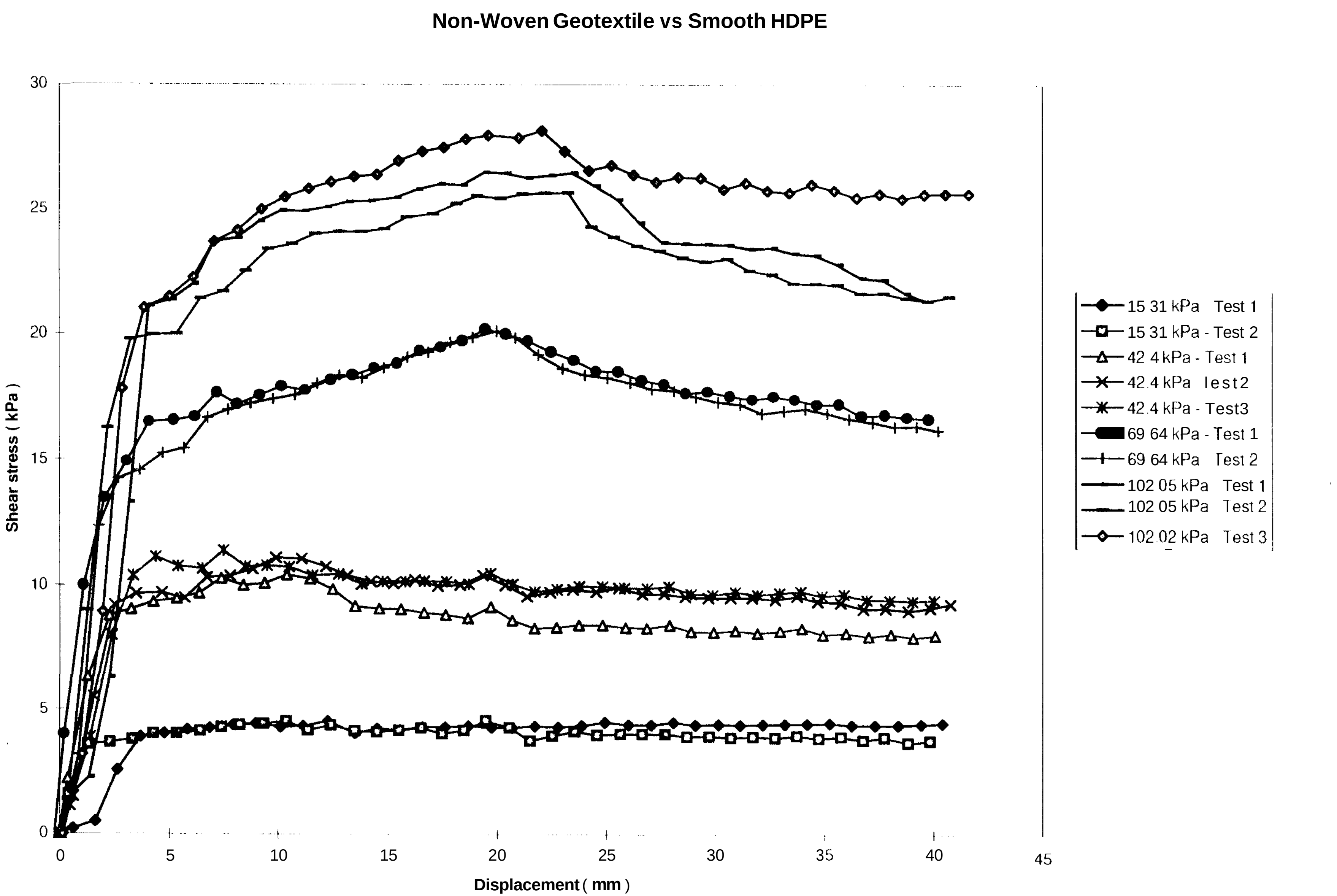
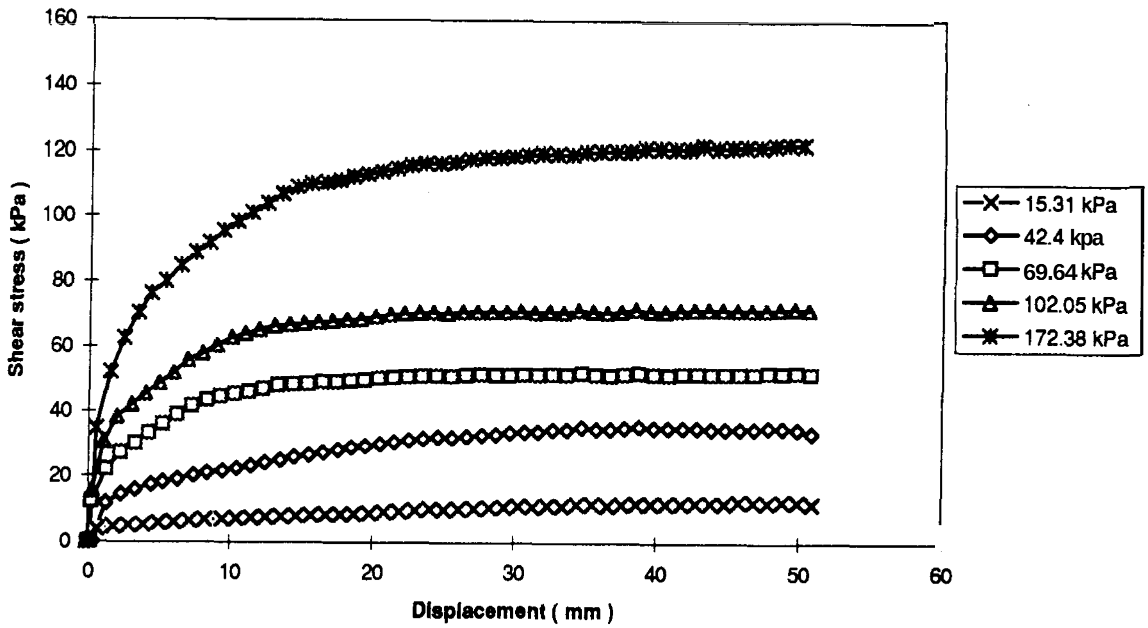
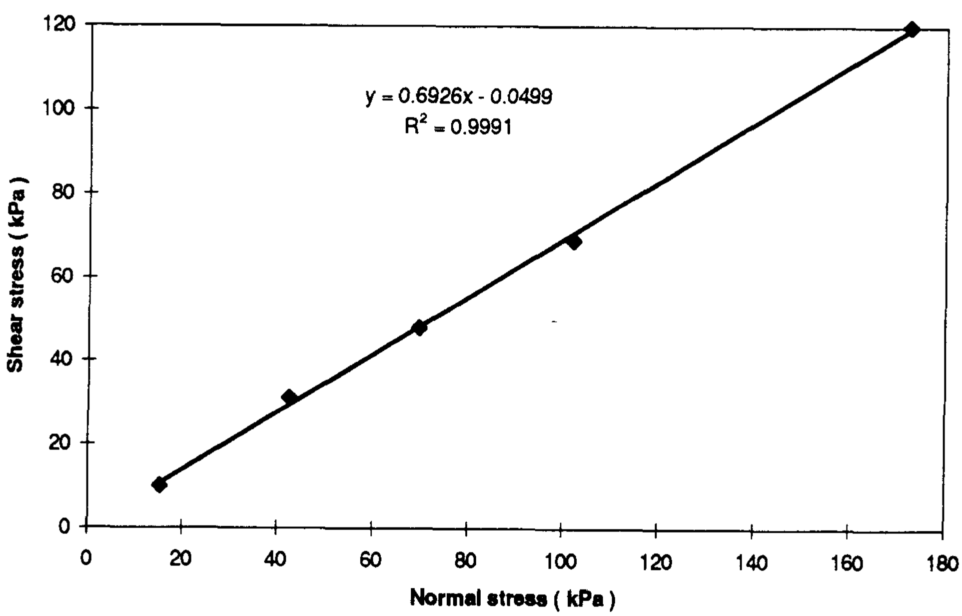


Figure 3.1 Reproducibility of Test Data

Shear stress vs Displacement



Failure envelope



δ(peak & 10%)=34.7°

Figure 3.2 Fine Sand vs Smooth PVC : a) Shear stress vs Displacement b) Friction angle

Similarly, the stress measured was that between the geomembrane and the soil as well, because those were the only two materials in contact as the top box moved relative to the bottom box.

The high value of R^2 for the graph of the failure envelope (Figure 3.2(b)) indicates that the ϕ value for this interface was not affected by the confining stress level, although it may be different for much lower confining stresses (less than 10 kPa).

3.2 Sand vs. the Other Geomembranes

The relationships for fine sand vs. smooth HDPE interface are shown in Figures 3.3 (a) and (b). The same relationships, stress vs. displacement and interface friction angle, for sand vs. the rest of the geomembranes in the testing program, are given in Appendix A. Stretching was observed in the File-finish PVC interface at higher normal stresses (greater than 100 kPa). Strain softening behaviour was noticed with HDPE. Textured HDPE exhibited peak values at higher displacements (about 35 mm). However, textured PVC did not reveal a clear trend in its stretching.

3.3 Influence of Soil Type

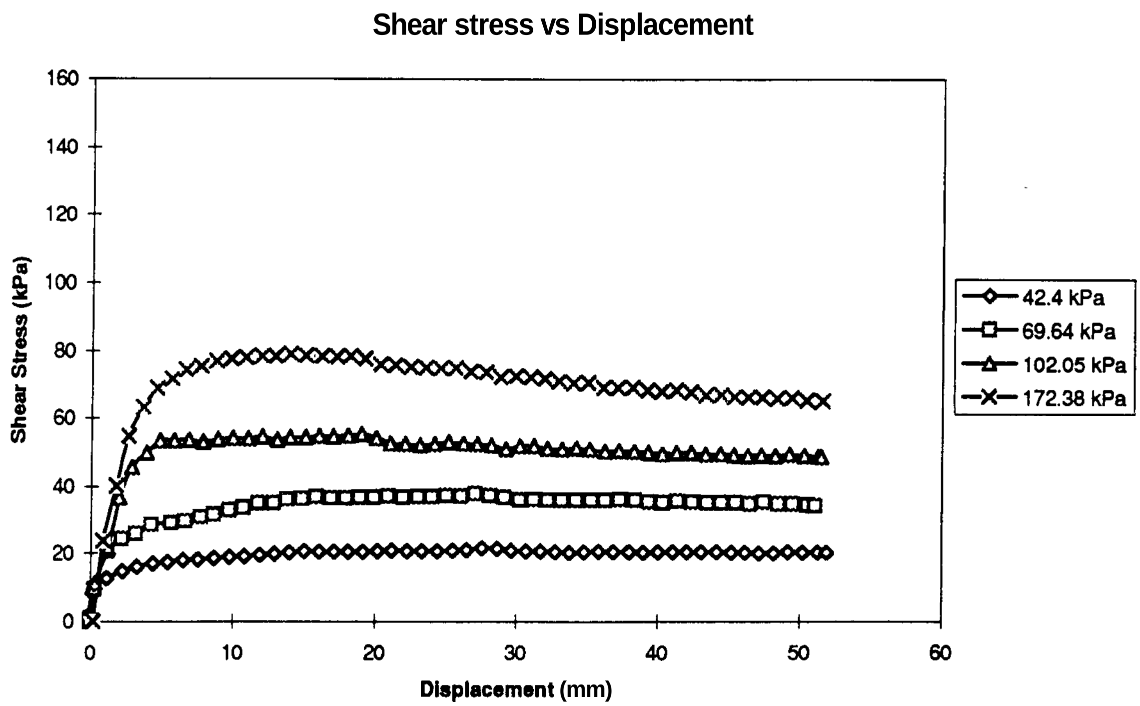
The study of the variation of interface friction values of the same geomembranes with soil type shows considerable difference in the stress-strain behaviour as well as friction angle values. Figures 3.4 and 3.5 give relationships of smooth PVC interfaces against sandy loam and silty clay respectively. Figures showing these relationships for interfaces with other geomembranes are given in Appendix B (Sandy Loam) and Appendix D (Silty Clay).

3.4 Geomembrane vs. Geotextile

The relationships for the smooth PVC vs. geotextile interface are shown in Figure 3.6. Interface friction values of the other geotextile-geomembrane interfaces are given in Appendix D.

4.0 SUMMARY OF RESULTS

The results of the testing program are summarized in Tables 4.1 and 4.2. The interface friction angles based on stress obtained at about 10 % strain (25.4 mm) from the stress displacement curves are given in Table 4.1. Table 4.2 gives the interface friction angles based on the peak stress obtained from the stress-displacement graphs. In the case of HDPE and textured-HDPE membranes, the stress-displacement response of the interface is such that after reaching peak stress, further shearing to a larger strain causes stabilization of the stress (remains constant ; see Figure 3.3). Hence, the shear stress at 10% strain for the rigid membranes (HDPE and HDT) is less than at the peak. However, for the flexible membranes (PVCs), due to their stretching during the tests, the strength at higher strain is greater than at lower strain (see Figure 3.4). This was observed with all PVC interfaces with all the other interface materials except with fine sand.



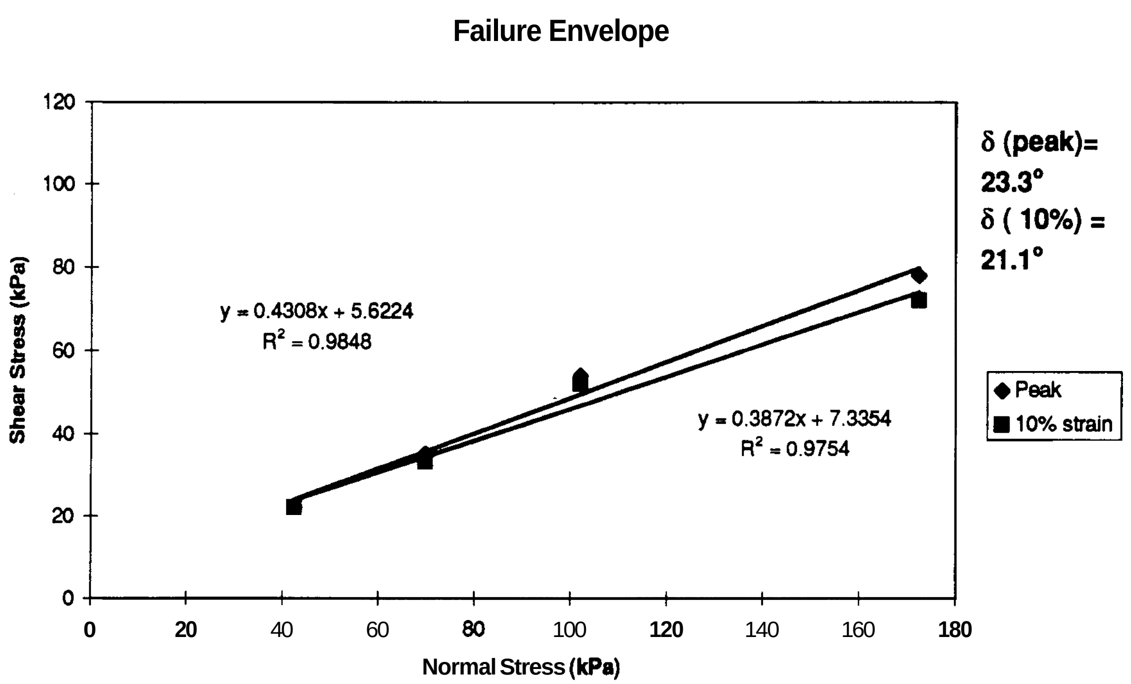
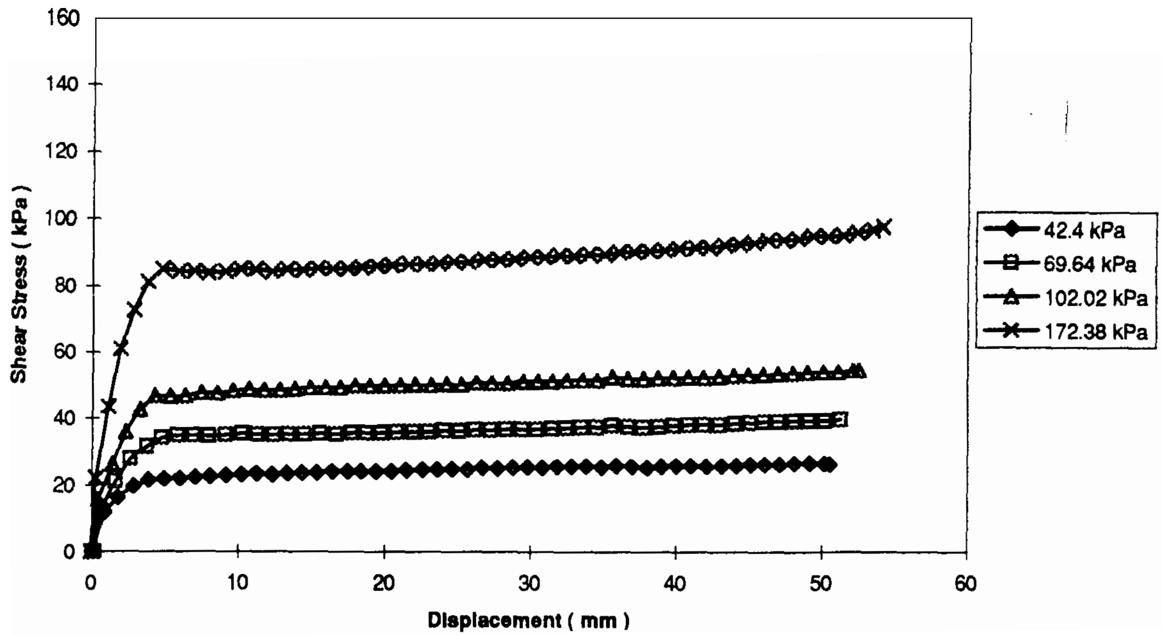


Figure 3.3 Fine Sand vs Smooth HDPE a) Shear vs Displacement b) Friction Angle

Shear Stress vs Displacement



Failure Envelope

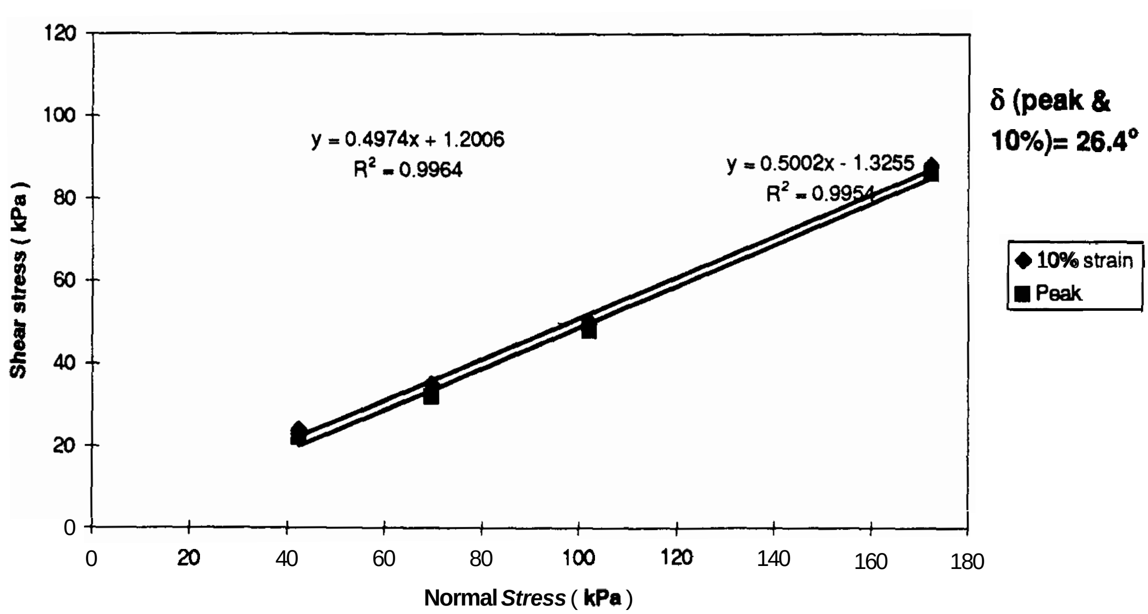
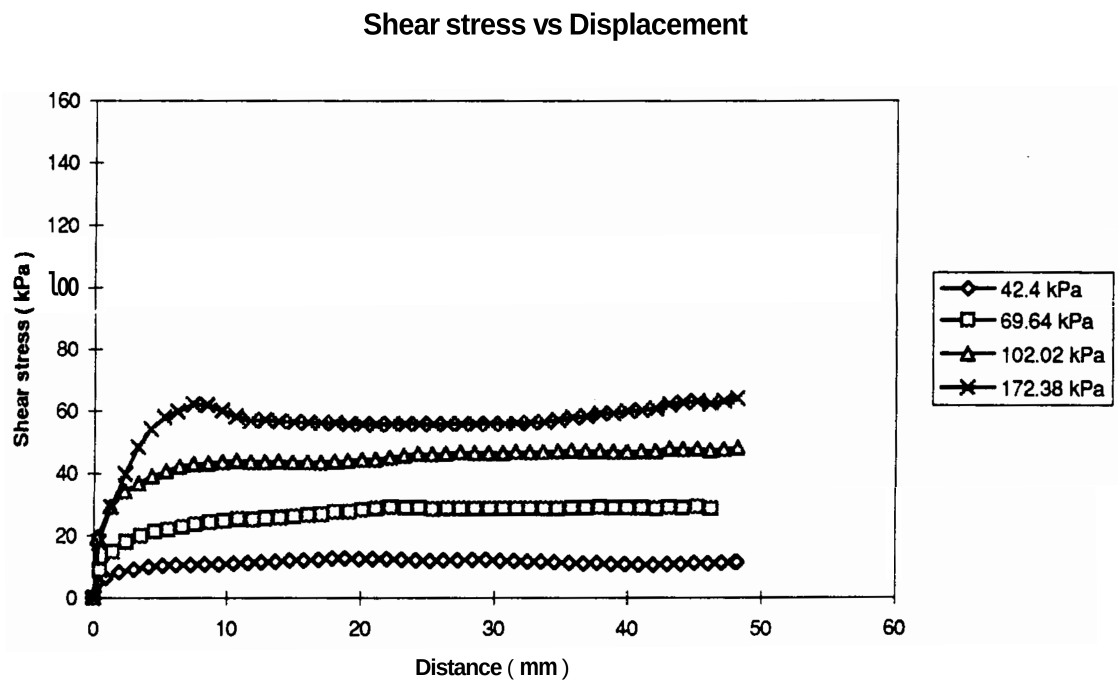


Figure 3.4 Sandy Loam vs. Smooth PVC a) Stress vs. Displacement b) Friction Angle



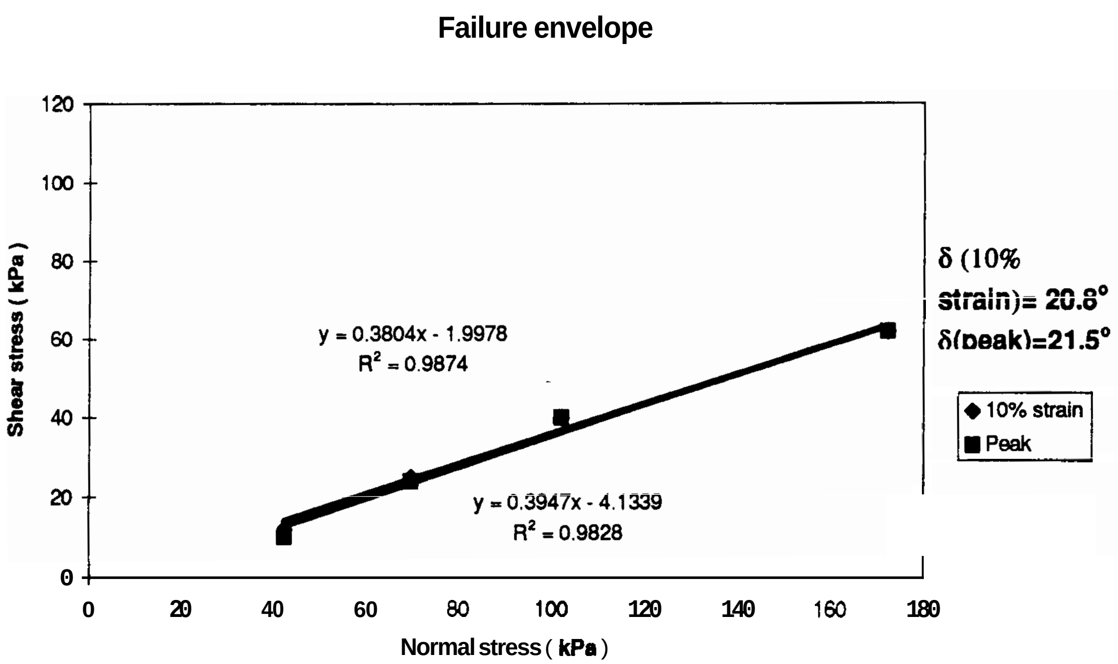


Figure 3.5 Silty Clay vs. Smooth PVC a) Stress vs. Displacement b) Friction angle

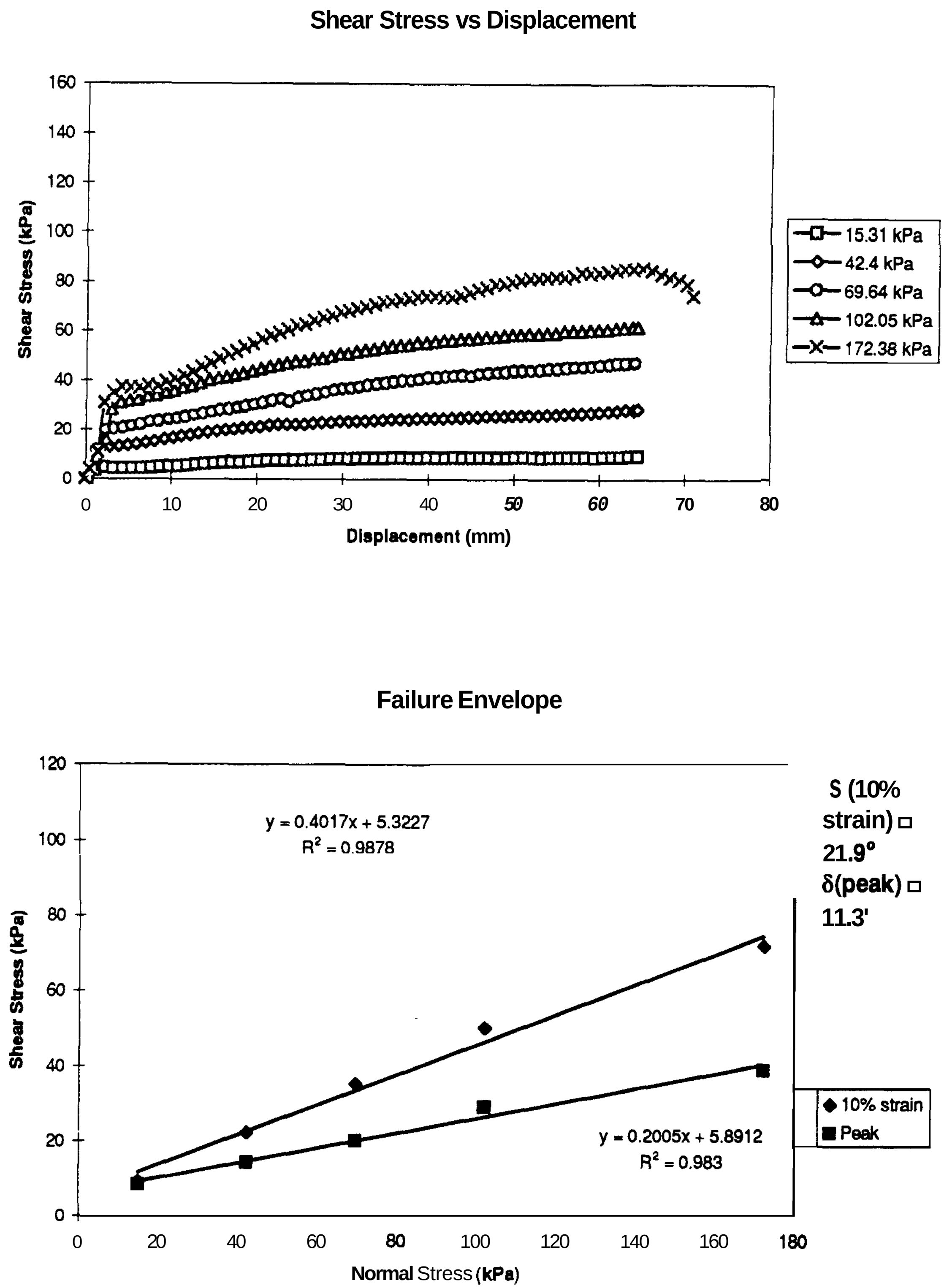


Figure 3.6 Non-Wovemn Geotextile vs. Smooth PVC a)Stress vs. Displacement b) Friction Angle

For this reason, the friction angle for the interfaces were calculated at both the peak stress and the stress at 10 % strain. It can be readily seen, comparing Tables 4.1 and 4.2, that the interface angle for PVC membranes at initial peak (yield stress for the interface) is much lower than at higher strain. However, the yield point of the interface does not represent a failure condition. This is because further shearing causes an increase in strength and not a decrease, whereas further shearing in HDPE causes reduced strength.Therefore, under field conditions, if the PVC membranes are stressed beyond the yield stress for the interface, the material stretches under the load without any loss of strength or material damage.

Table 4.1 Interface Friction Angle values (degree)obtained for various interfaces tested (at 10 % strain)

	Fine Sand	Sandy Loam	Silty Clay	Non-woven Geotextile
30 mil Smooth PVC (at 10 % strain)	34.7	26.4	20.8	21.9
30 mil textured PVC (at 10 % strain)	35.3	21.1	26.4	19.6
30 mil File-finish PVC (at 10 % strain)	30.9	28.1	26.0	17.3
60 mil Smooth HDPE (at 10 % strain)	21.1	18.2	17.0	14.2
60 mil Textured HDPE (at 10 % strain)	36.6	33.8	41.8	17.4

Table 4.2 Interface Friction Angle values (degree)obtained for various interfaces tested (at Peak Stress)

	Fine Sand	Sandy Loam	Silty Clay	Non-woven Geotextile
30 mil Smooth PVC (Peak stress)	34.7	26.4	21.5	11.3
30 mil textured PVC (Peak stress)	35.3	19.9	22.9	13.2
30 mil File-finish PVC (Peak stress)	30.9	28.1	27.7	11.4
60 mil Smooth HDPE (Peak stress)	23.6	25.2	25.8	15.1
60 mil Textured HDPE (Peak stress)	36.6	33.8	41.8	17.4

5.0 DISCUSSION

5.1 Failure Modes

The failure of an interface can take place in any of the following ways :

(i) By shear failure at the pre-determined horizontal interface between the interface material (soil or geotextile) and the geomembrane.(This was clearly the failure mode for the tough and rigid HDPE geomembranes);

(ii) When the entire interface slides over the base material.(In this testing program, the base was of compacted silty clay, but it could have been a steel or wooden plate. This behaviour is typical of PVC interfaces, where the flexibility of the geomembrane is so high that after initial failure of the interface, the continued increase in the shear stress causes failure with respect to the base. This facilitates the stretching of the sample. This was the main reason why frictional strength of PVC interfaces could not be characterized by a peak failure stress. Instead, interface friction angles had to be calculated based on stress at a particular strain.); and

(iii) Failure within the interface material.(This was always observed in all the interfaces with soils - fine sand, silty clay and sandy loam. After the interface fails, further shearing causes failure to occur within the soils layer because the internal friction of the soil is reached. This is manifested in the form of a thin layer of about 2 mm of soil left on the top surface of the membrane as shearing is continued to higher strain).

5.2 General Observations

- Considerable stretching of all PVC membranes was observed.
- Wrinkles were observed to have formed in the PVC membranes with Sandy loam due to the large grain-size of sandy loam.
- Geotextiles experienced stretching with textured membranes, both HDPE and PVC.
- Both textured HDPE and textured PVC had significant amount of soil embedded in the membrane at the end of the test.

5.3 Comparison with existing knowledge

In current practice, HDPE geomembranes often compete with PVC geomembranes, as landfill covers. Although research involving PVC geomembranes is considerably less than that involving HDPE geomembranes, all testing programs involving PVC and HDPE membranes have shown that PVC membranes are more efficient than smooth HDPE membranes in their frictional behavior.

Martin et al. (1984) tested PVC, Chloro-Sulphonated Poly-Ethylene (CSPE), Ethylene Propylene Diene Monomer (EPDM) and HDPE geomembranes against sand, clay and geotextiles, using a 10 cm x 10 cm shear box. Based on the results of their tests, they concluded that :

- PVC geomembranes are exceptional in that their adhesion to soil tends to be greater than the cohesion of the soil itself;
- The more flexible the Geomembrane, the higher the friction angle;
- The stiffer the geotextile, the lower the friction angle; and
- The geotextile-geomembrane interface has the lowest friction angle in a liner system and is therefore considered the most critical.

Akber et al. (1985) tested PVC geomembranes against uniform sands (passing one sieve and retained on the next standard sieve) in a 152.4 mm (6") square shear box. Soil was placed in the bottom box. The same soil was placed in the top box and the geomembrane was wrapped around it. They concluded that :

- Interface friction angle increases with particle size;
- When the geomembrane surface is tough, it does not follow the asperities of the soil surface. A flexible membrane like PVC can conform to the asperities of soil particles, thereby increasing effective area of contact. Hence, friction angle in the case of flexible membranes is higher.

Williams and Houlihan (1987) tested PVC and HDPE membranes against sand and clay soils in a 30.5 cm x 46 cm direct shear box. The base material was compacted soil (the same soil as in the interface). The geomembrane was tested in both the fixed (anchored) and free state. They observed that since PVC has lower elastic modulus than HDPE, soil particles get embedded in the surface, causing higher shear stress to be mobilized. Even with clay soil, they observed the adhesion to be higher with PVC than HDPE.

Druschel and O'Rourke (1991) conducted experiments on HDPE, PVC and specially manufactured Epoxy membranes against sandy soils, using a 60 mm square shear box. The results of the testing program included :

- Friction angle with PVC was higher than with smooth HDPE; and
- A relation between a measure of surface hardness of the membrane (called Shore D hardness) and the ratio of interface friction angle to the internal friction angle of the sand ($6 / \phi$) was established, which showed the highest value of $6 / \phi = 0.8$ for PVC and a decreasing trend for other geomembranes.

Lauwers (1991) conducted tests on PVC membranes and PVC geocomposites (with polyester geotextiles) against Ottawa sand, concrete sand, glacial till, lean clay and fresh concrete. Test details, regarding the placement of the materials and the clamping conditions, were not reported. The interface friction angles for PVC geocomposites were found to be consistently greater than those for the geomembrane by 5 - 10 degrees.

Takasumi et al. (1991) conducted a review of the available test procedures for interface friction testing of geosynthetics. They concluded, among other things, that "interface friction efficiency ($6 / \phi$) is higher for a soft polymer (eg. PVC) than a hard polymer (eg. HDPE)".

Nataraj et al. (1995) conducted tests on nine geotextiles and six geomembranes against two cohesionless soils and one cohesive soil. Tests were performed on 62.5 mm and 100 mm square shear box, to test the effect of sample size on the interface friction. The geomembrane or geotextile was glued to a wooden box and placed in the lower box, while the soil was compacted and placed in the top box. They inferred that "flexible geomembranes (PVC and CPE) provide higher interface friction angle than rigid (HDPE) geomembranes".

Vaid and Rinne (1995) conducted experiments on HDPE (20 and 100 mils) and PVC (20 and 30 mils) geomembrane against an angular and a rounded quartz sand. Tests were performed using a ring shear device. The soil sample was an annular cylinder, with inner and outer dimensions of 44.5 and 70.0 mm respectively, confined within a bottom and a top confining ring.This test allowed for large, continuous uni-directional strains to be applied and is considered the best method for estimating residual strength. Surface roughness characteristics were also measured for the geomembranes, using a profilometer. Vaid and Rinne concluded that :

- Interface friction angle of soil with PVC membranes is close to the internal friction angle of the soil because the failure in this case occurs within the soil.
- The waviness of the shearing plane (base) does not effect interface friction values.
  PVC geomembranes do not show a clear peak or residual stress-displacement behaviour.

Although all these testing programs seem to arrive at similar conclusions, generalisations must be made with caution. It is to be noted that the conditions of the testing programs reviewed were quite varied. Some of the test details, that were missing or differed significantly were :

- Stress-displacement behaviour of the tests are not reported. This makes it difficult to know how the peak stress was determined, the stress at failure, if the geomembrane has undergone extension before failure etc.
- The range of confining stresses was different. The failure envelope for interface friction with geosynthetics tends to be curved near the lower confining stresses and more linear at the higher confining stresses. Hence, interface friction angles from a testing program are specific to the range of confining stresses at which the tests have been performed.
- The base material used also influences the kind of failure mechanism (Section 4.1). If the base material allows sliding along that interface (eg. when the base material is soil), then failure is likely to occur at that interface rather than the interface that is tested.

Base fixity can be achieved by using a steel plate or gluing the geomembrane to a woode block in the base.

6.0 CONCLUSIONS

The following are the conclusions of this study (refer to Table 2.2 for values) :

- The relatively large particles of the sand and the sandy loam get embedded in the flexible surface of the PVC membranes, giving additional friction. This is not observed with silty clay, however, because the particles of silty clay are too small to cause effective embedment in the PVC surface. Hence, smooth PVC had a lesser angle of internal friction than smooth HDPE with silty clay.
- Textured HDPE was found to have a higher interface friction angle than smooth PVC in all cases except with the geotextile. This is believed to be due to reduction in contact area since the rough side of the geotextile and the rough surface of the geomembrane are in contact at texture projections.
- Textured geomembranes give better interface friction values than their corresponding smooth membranes.
- The file-finish in the PVC had no useful influence on the strength of the interface in the case of the sand interface. This is probably due to the incompatibility of the grain size of the sand particles with the size of the file-grid. It is felt that the size of the file-finish grid was too fine for sand particles to be embedded within it and caused improvement in frictional characteristics of the interface. At the same time, interface friction angle was higher or nearly the same for file finish PVC against the sandy loam and silty clay. This was due to the fact that these soils have a greater portion of finer particles than the sand. This leads us to the conclusion that File-Finish PVC improves frictional characteristics with only specific types of soils, depending on the particle size and the size of the file-finish grid.
- Similarly, textured PVC does not always give a higher interface friction angle than smooth PVC. With large particle sizes (like sand and sandy loam), interface friction is improved, while with smaller particles and with the geotextile, interface friction is reduced. This is probably due to the rolling of the smaller particles around the smooth edges of the texturing projections. This confiis the fact that interface friction is very specific to the soil as well as the membrane.
- The stress strain behaviour of PVC is much different from that of HDPE. Even after reaching yield stress of the interface, PVC interfaces will not fail but maintain stability by stretching of the membrane material without loss of strength or material damage.

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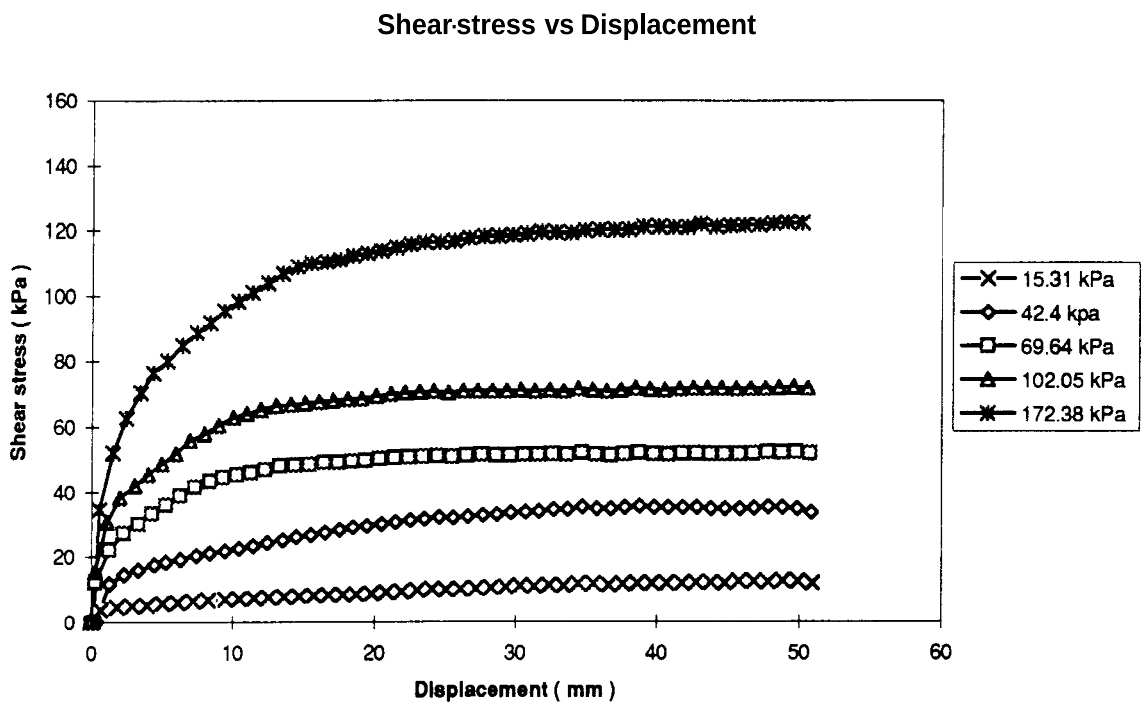
APPENDIX A

FINE SAND vs. VARIOUS GEOMEMBRANES



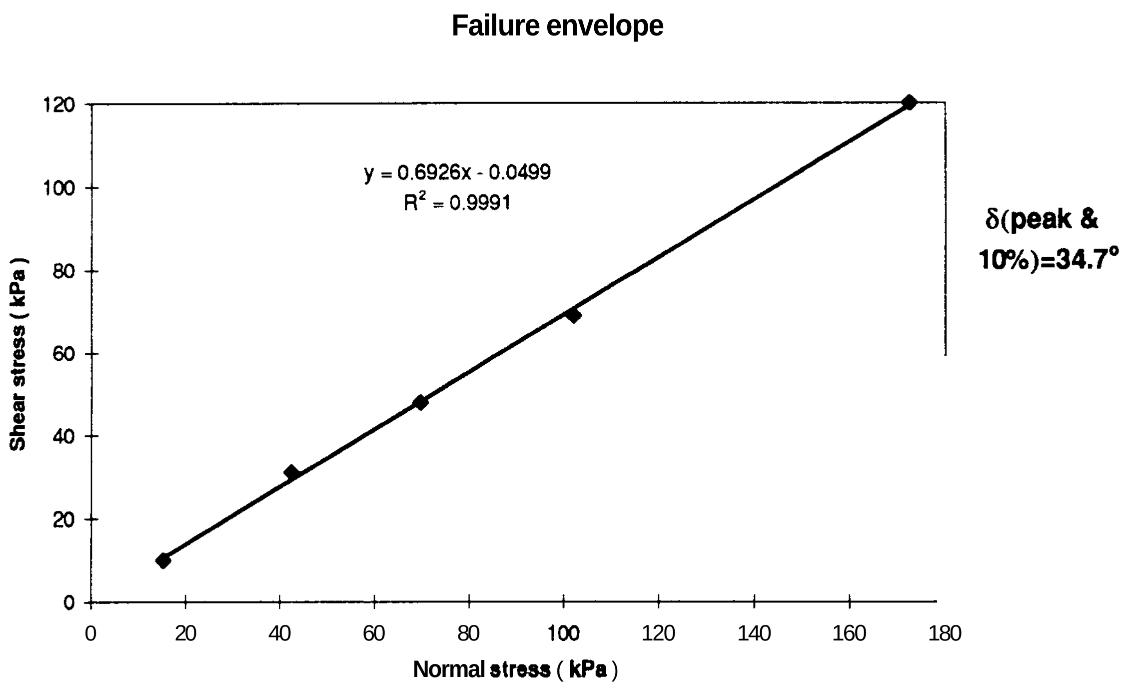
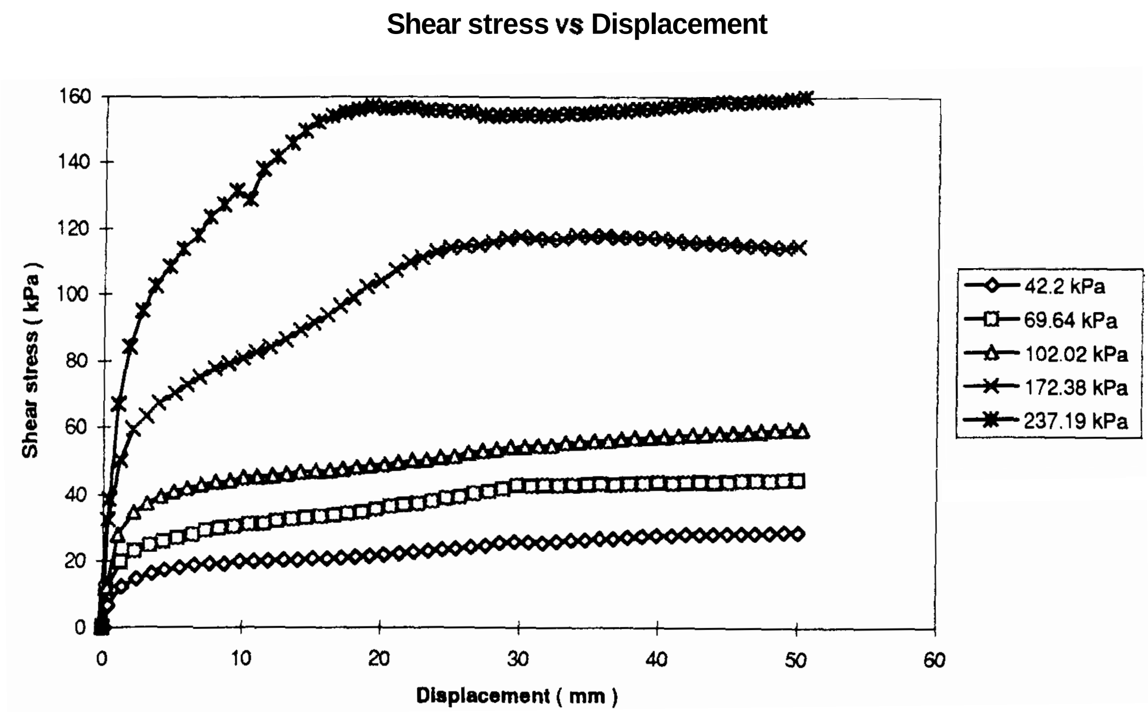


Figure A1. Sand vs. Smooth HDPE a) Stress vs. Displacement b) Friction Angle



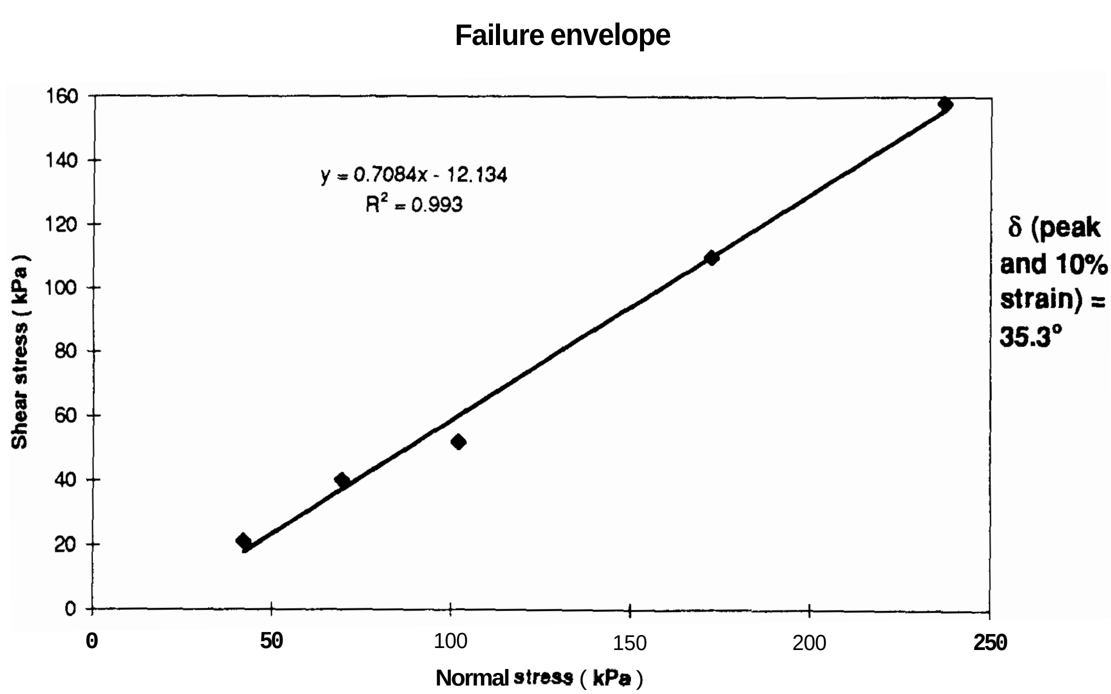
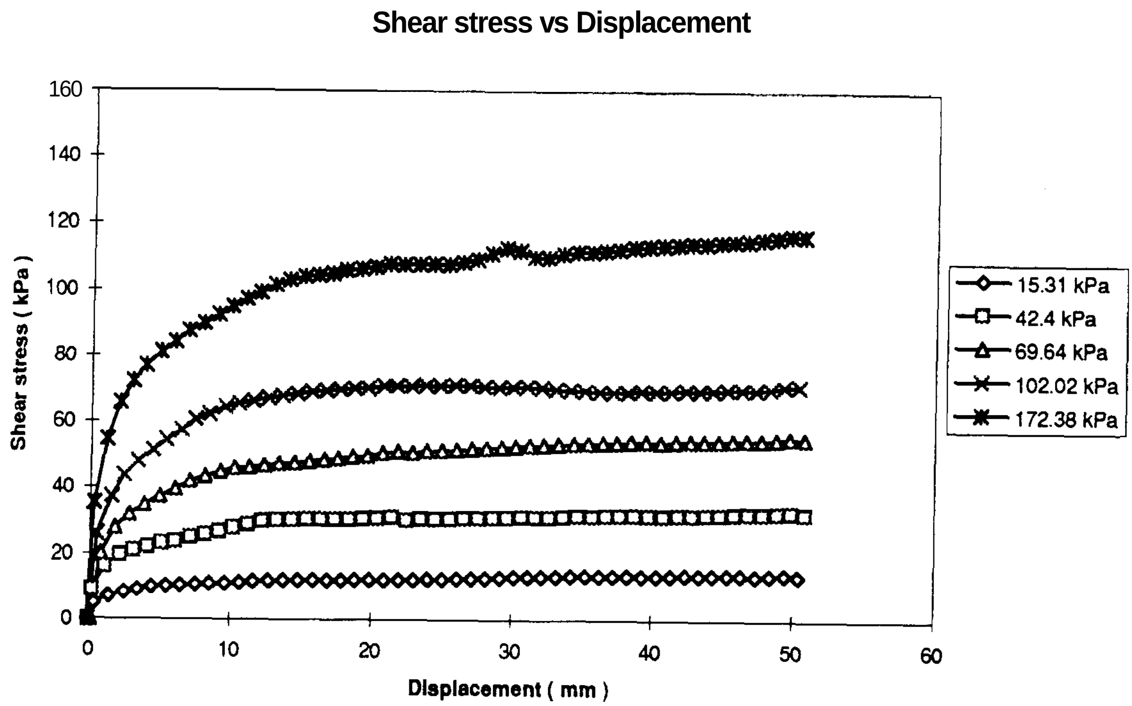


Figure A2. Fine Sand vs. Textured PVC a) Stress vs. Displacement b) Friction Angle



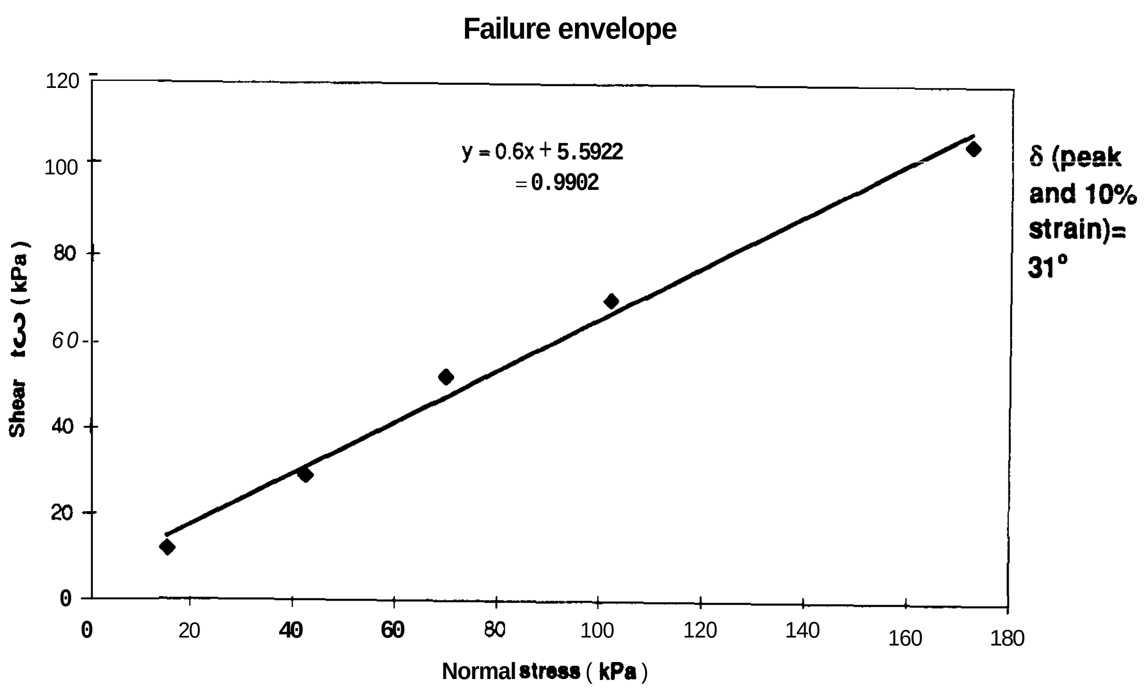
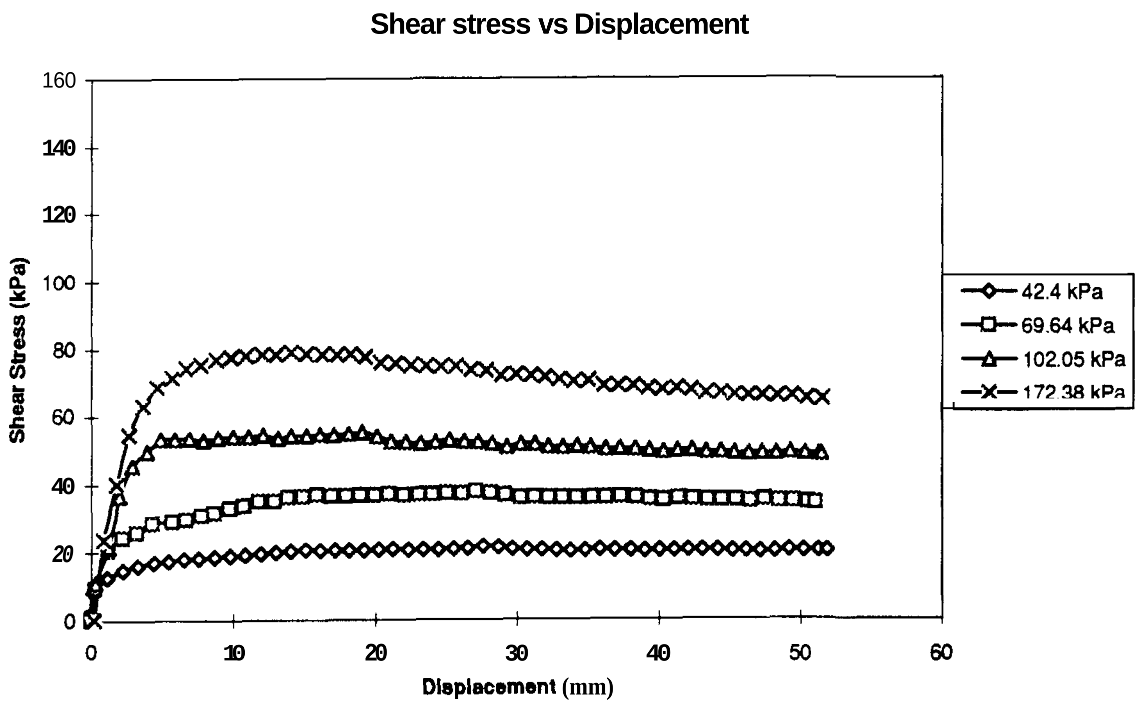


Figure A3. Fine Sand vs. File-Finish PVC a) Stress vs. Displacement b) Friction Angle



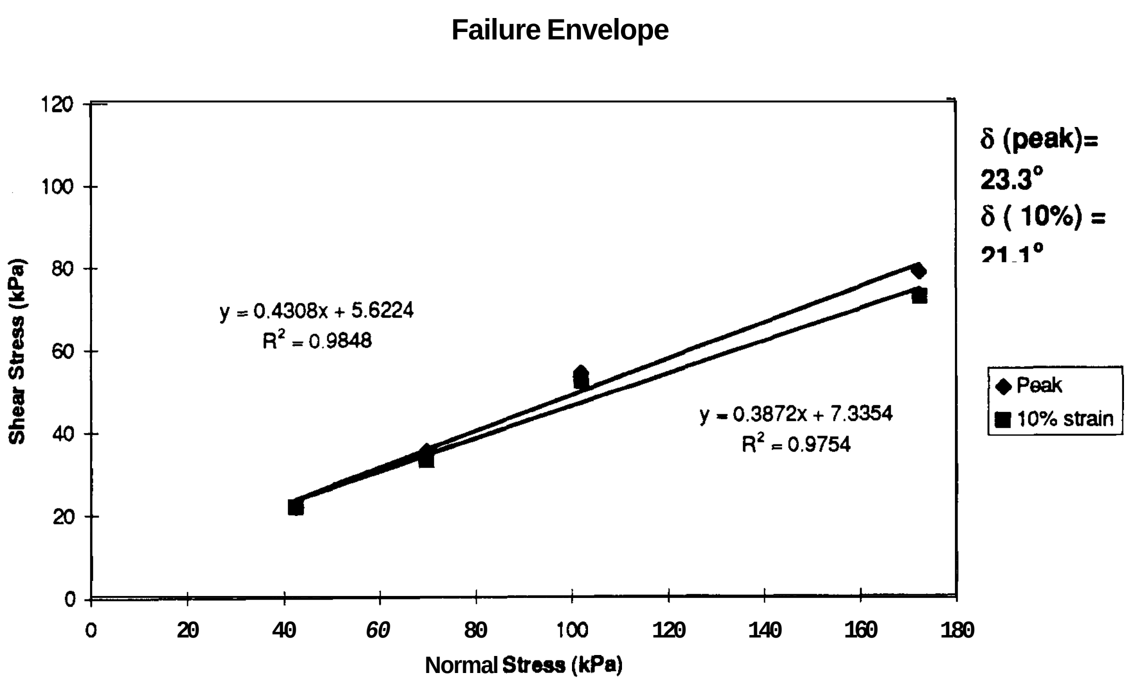
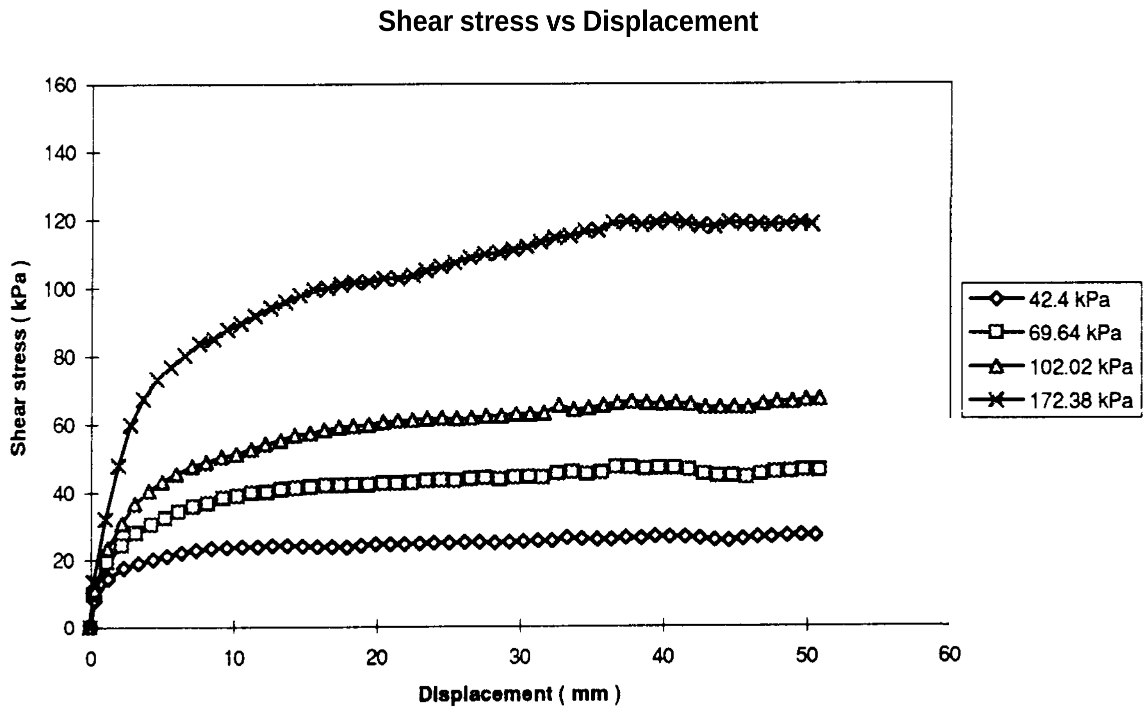


Figure A4. Fine Sand Smooth HDPE a) Stress vs. Displacement b) Friction Angle



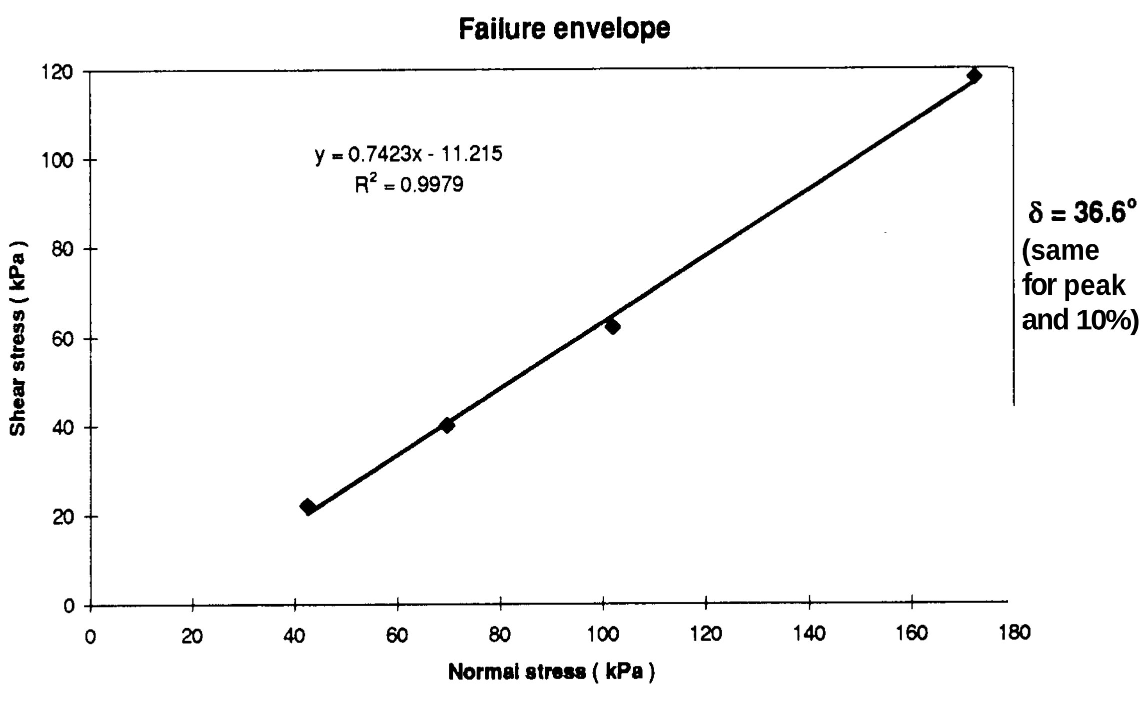
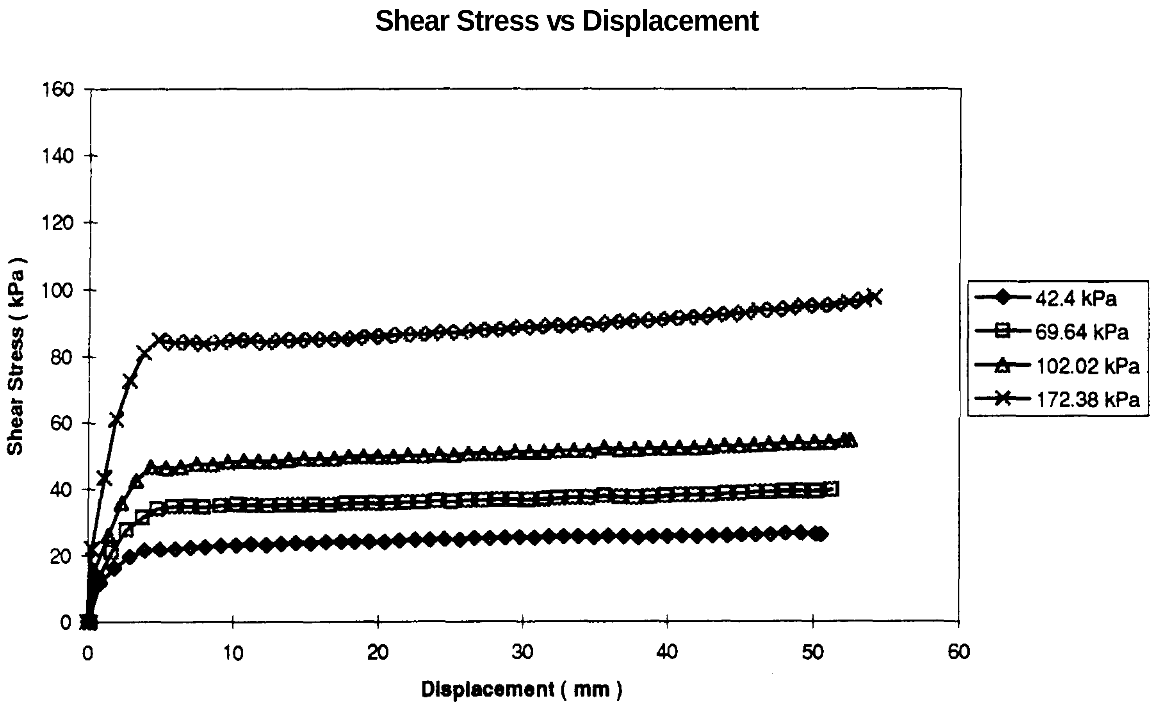


Figure A5. Fine Sand vs. Textured HDPE a) Stress vs. Displacement b) Friction Angle

APPENDIX B

SANDY LOAM vs. VARIOUS GEOMEMBRANES



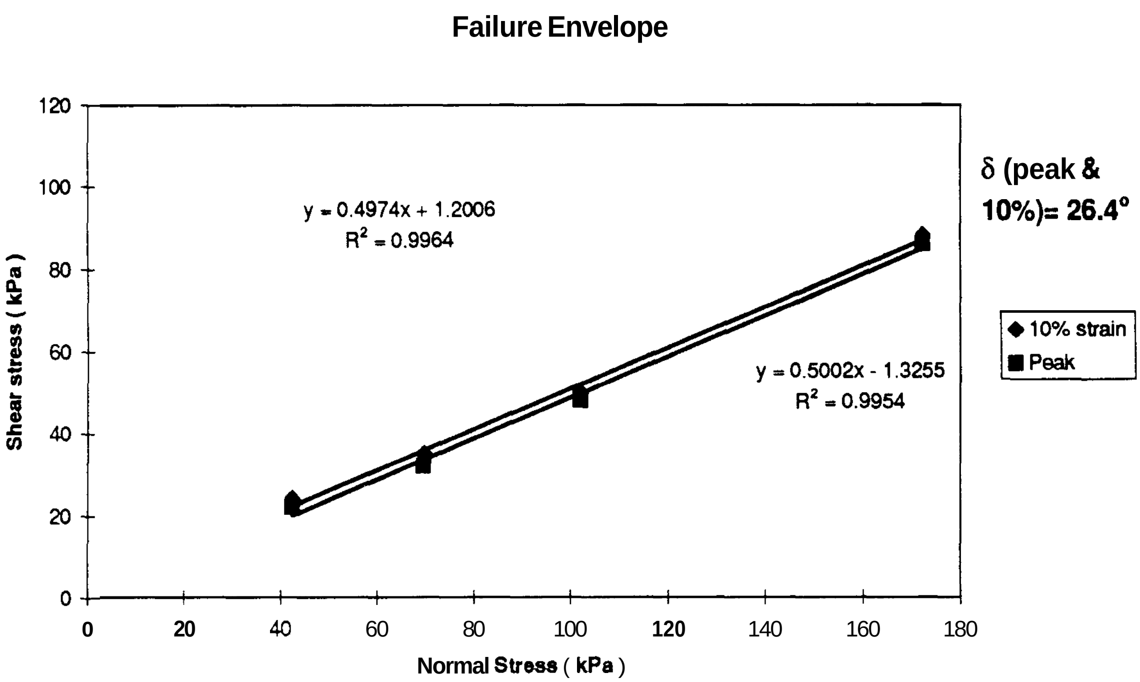
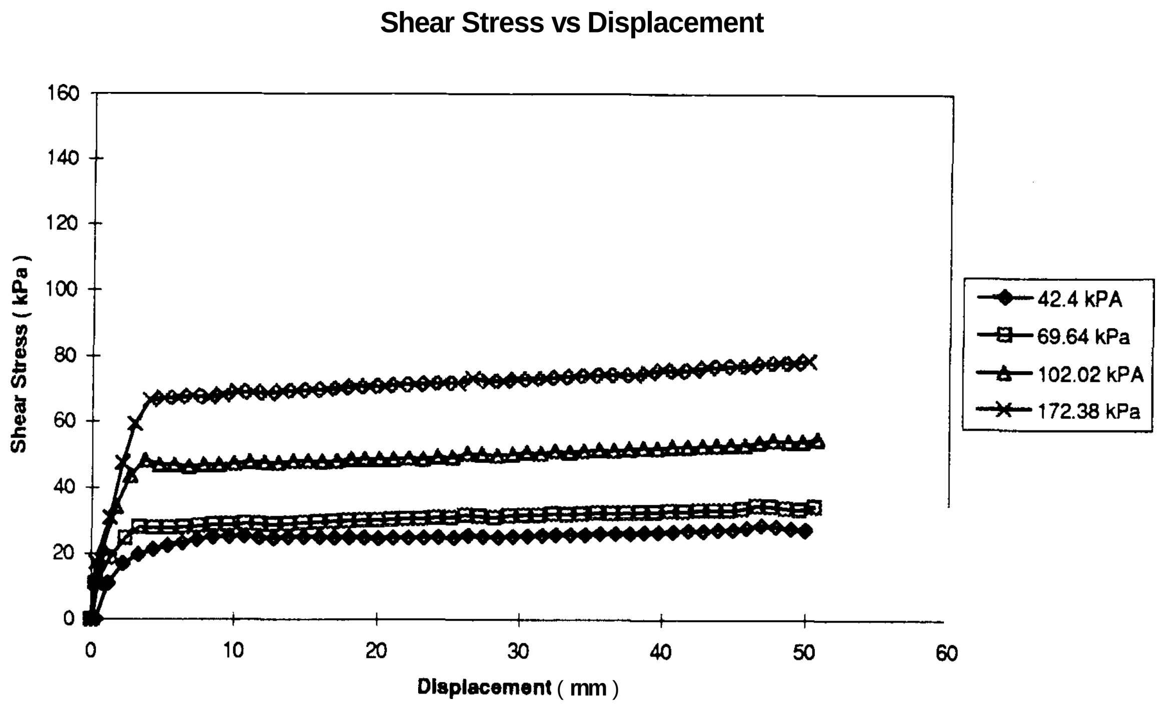


Figure B1. Sandy Loam vs. Smooth PVC a) Stress vs. Displacement b) Friction **Angle**



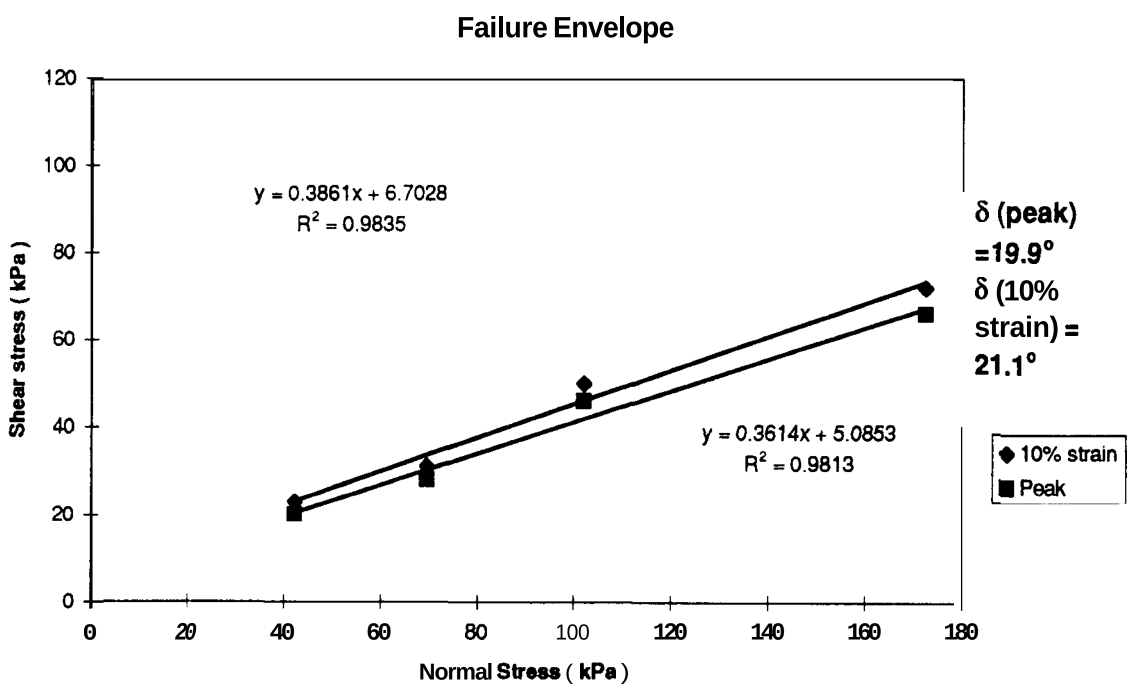
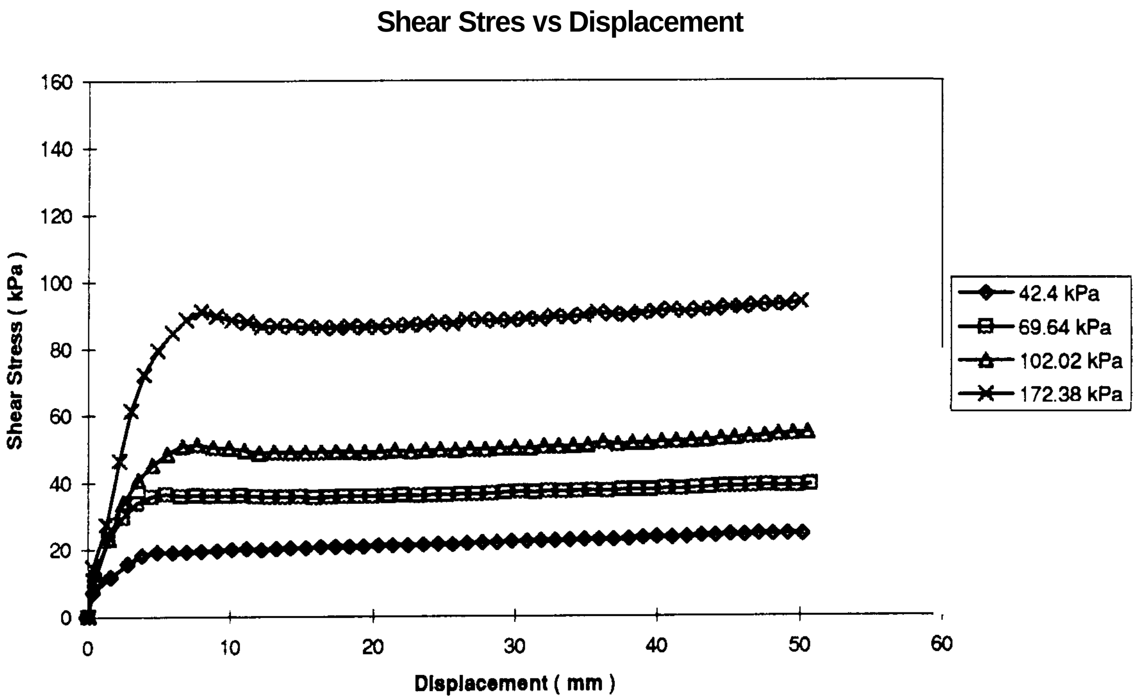


Figure B2. Sandy Loam vs. Textured PVC a) Stress vs Displacement b) Friction Angle



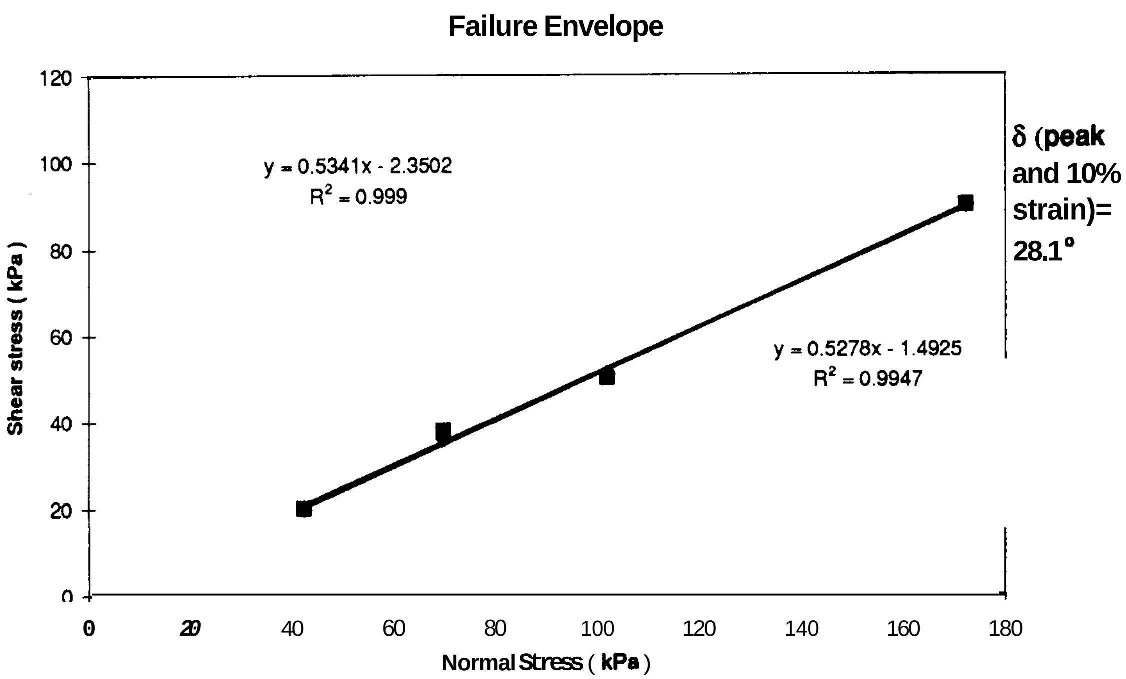
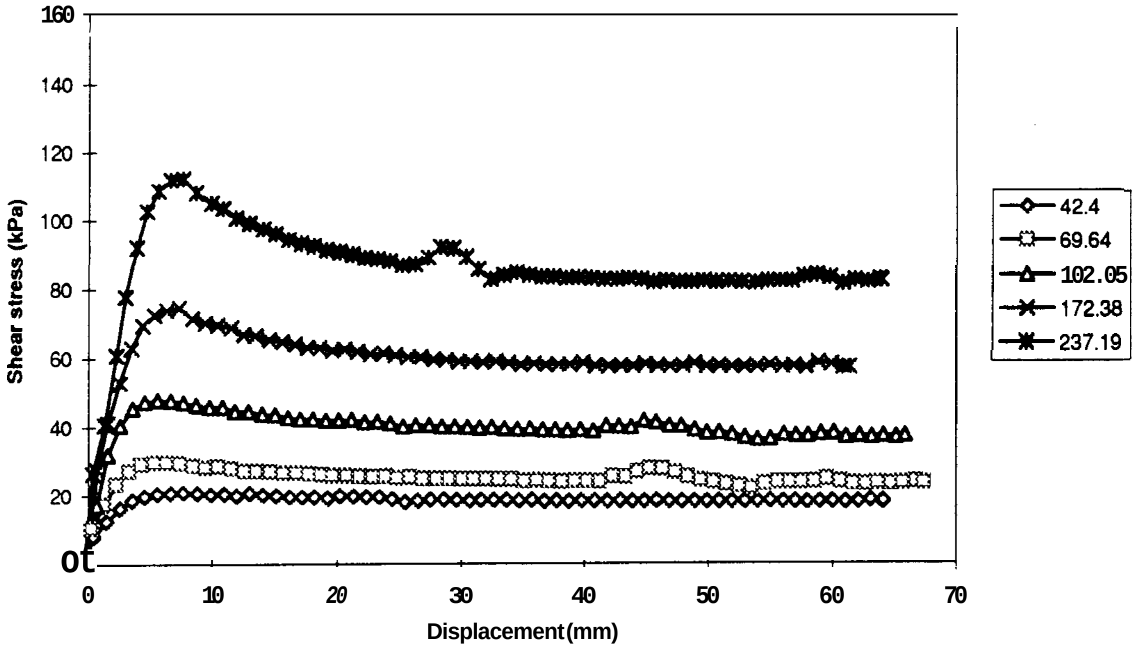


Figure B3. Sandy Loam vs. File-finish PVC a) Stress vs. Displacement b) Friction Angle

Shear Stress vs Displacement



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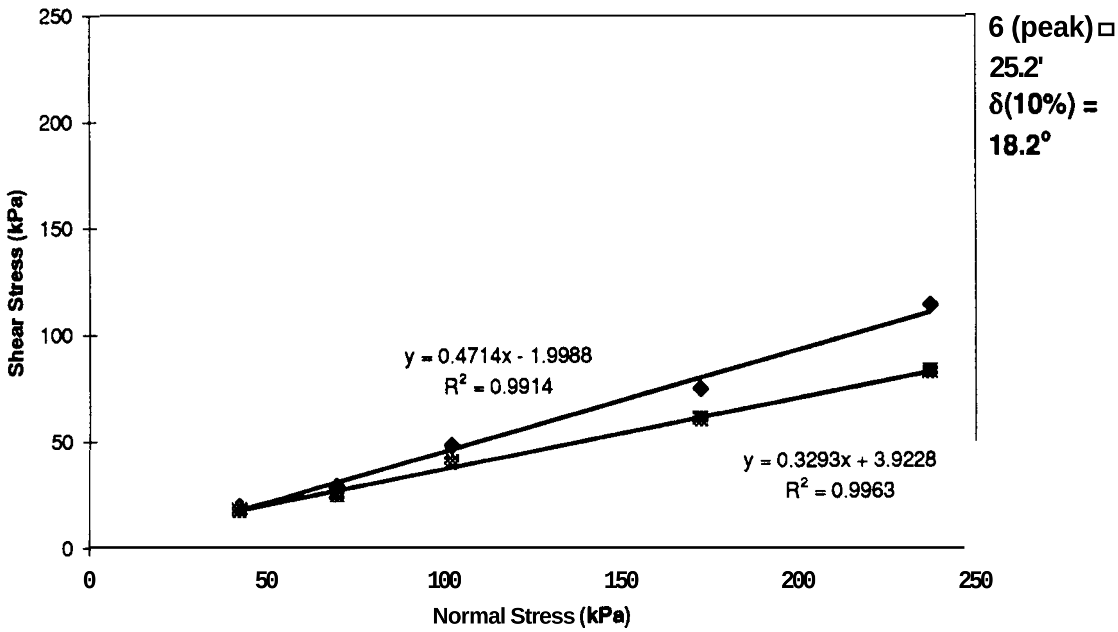
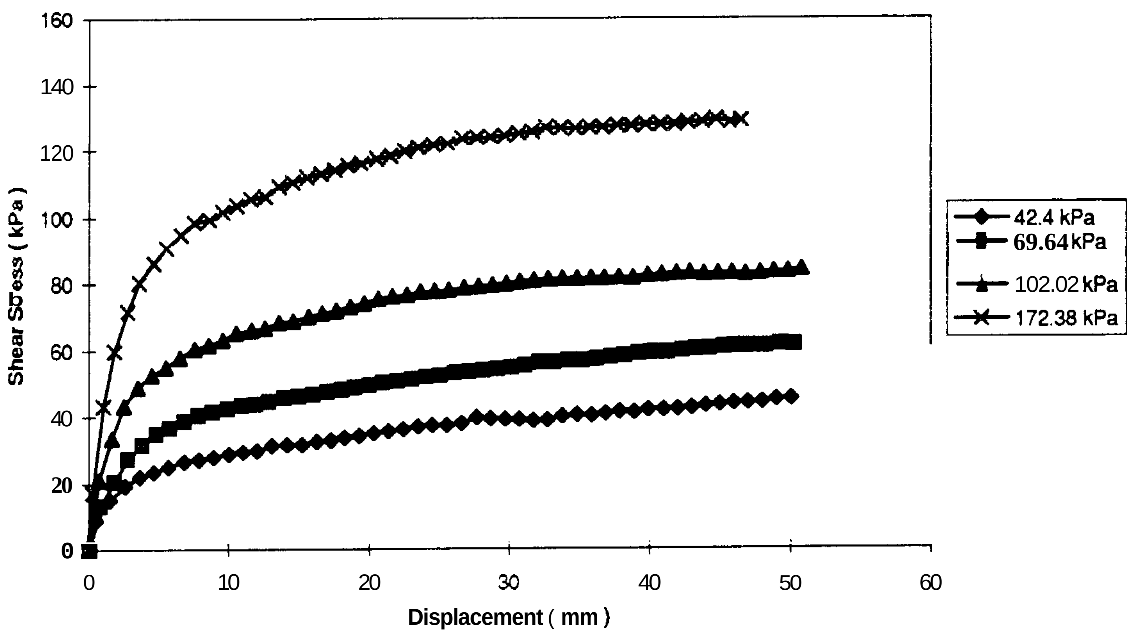


Figure B4. Sandy Loam vs. HDPE a) Stress vs. Displacement b) Friction Angle

Shear stress vs Displacement



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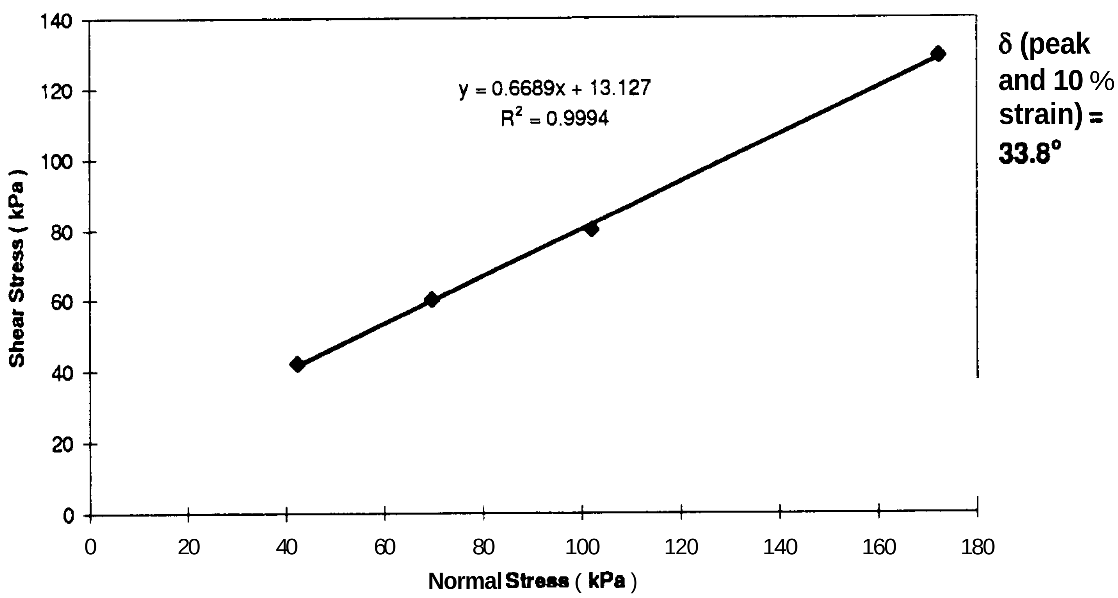
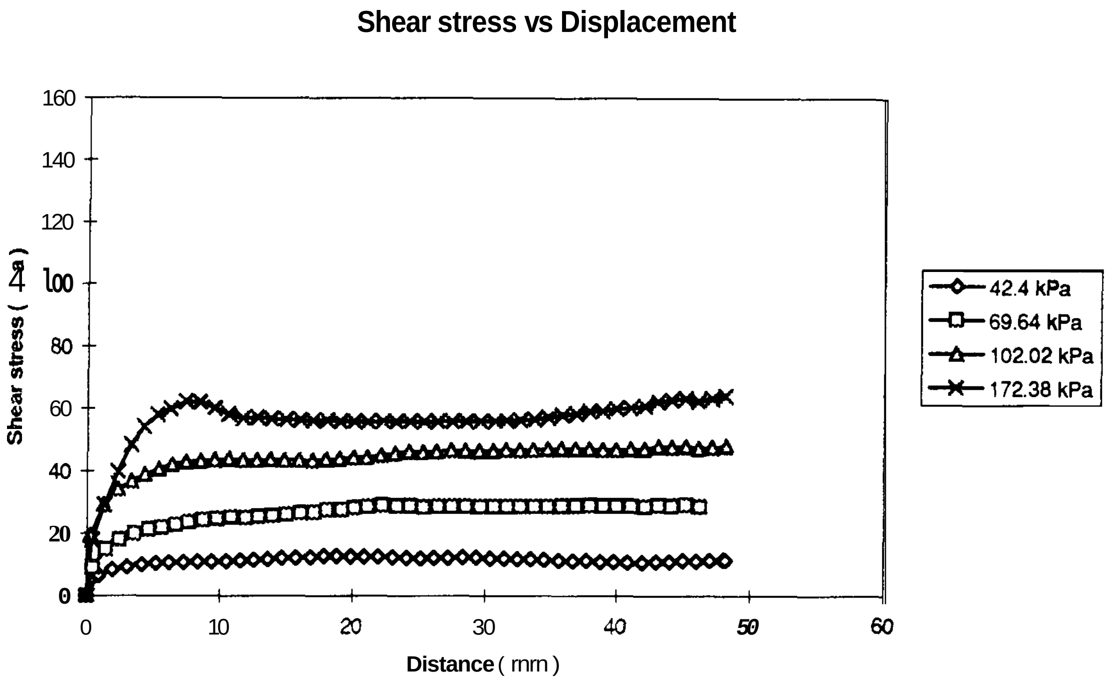


Figure B5. Sandy Loam vs. Textured HDPE a) Stress vs. Displacement b) Friction Angle

APPENDIX C

SILTY CLAY vs. VARIOUS GEOMEMBRANES



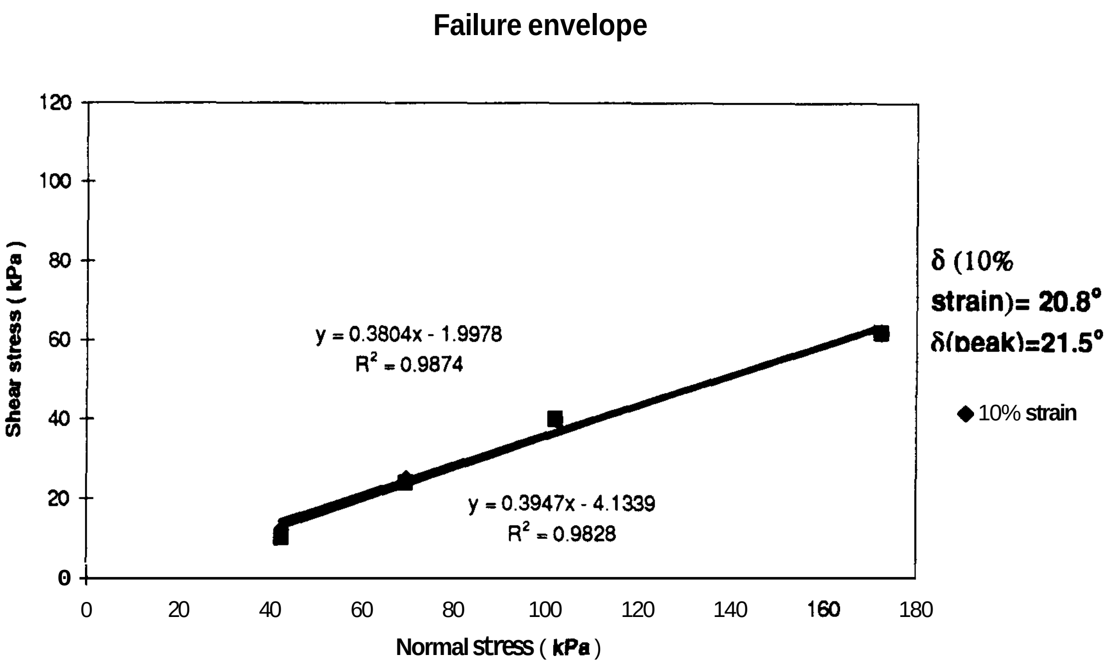
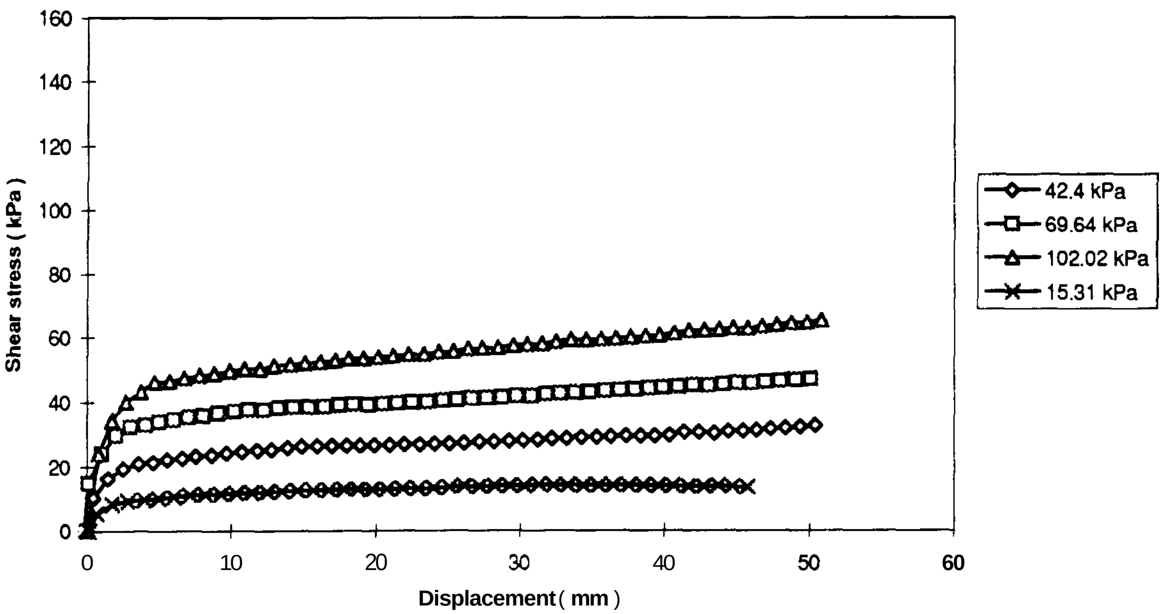


Figure C1. Silty Clay vs. Smooth PVC a) Stress vs. Displacement b) Friction Angle

Shear Stress vs Displacement



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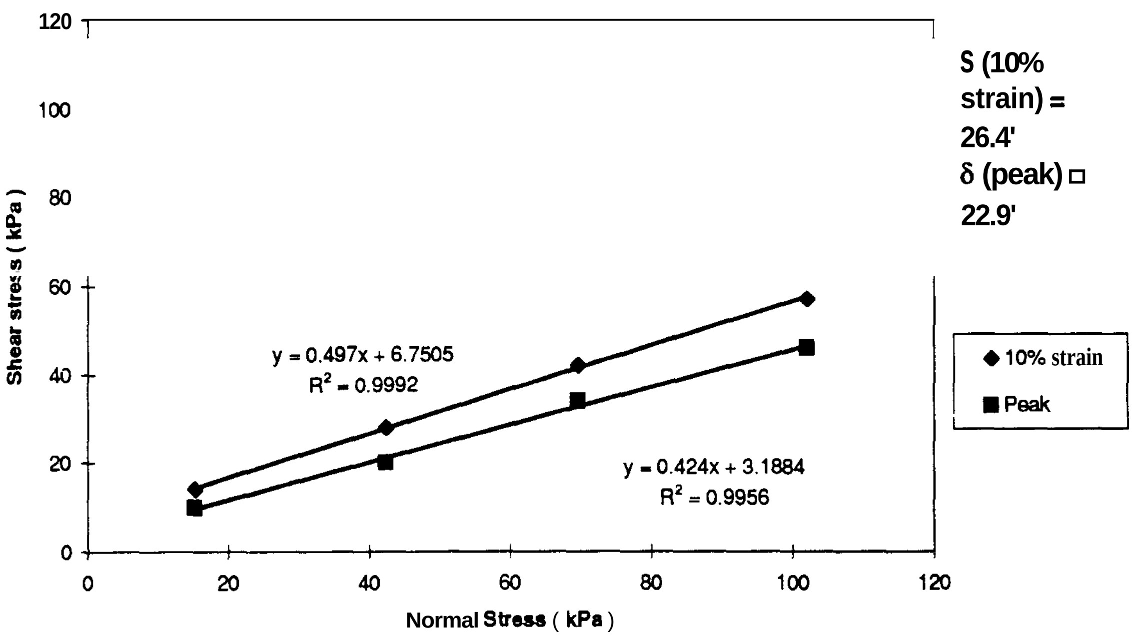
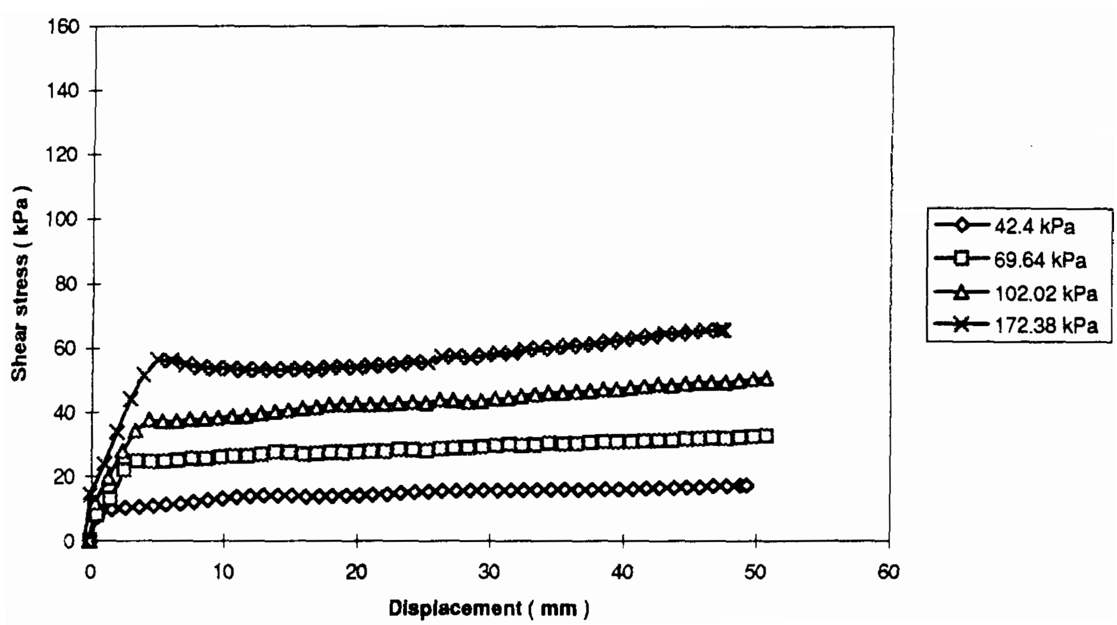


Figure C2. Silty Clay vs. Textured PVC a) Stress vs Displacement b) Friction Angle

Shear Stress vs Displacement



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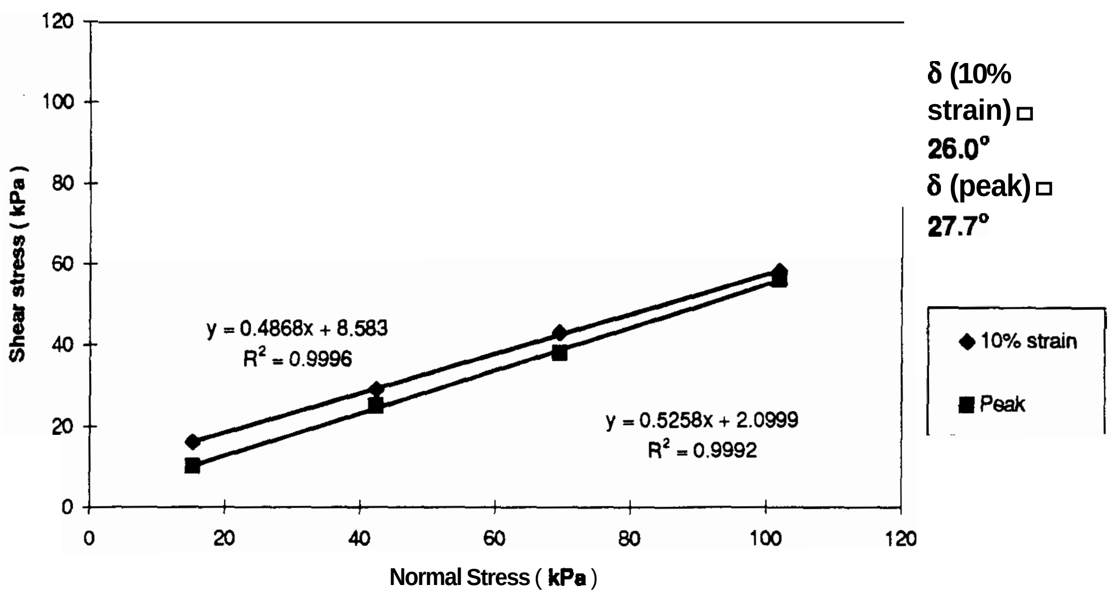
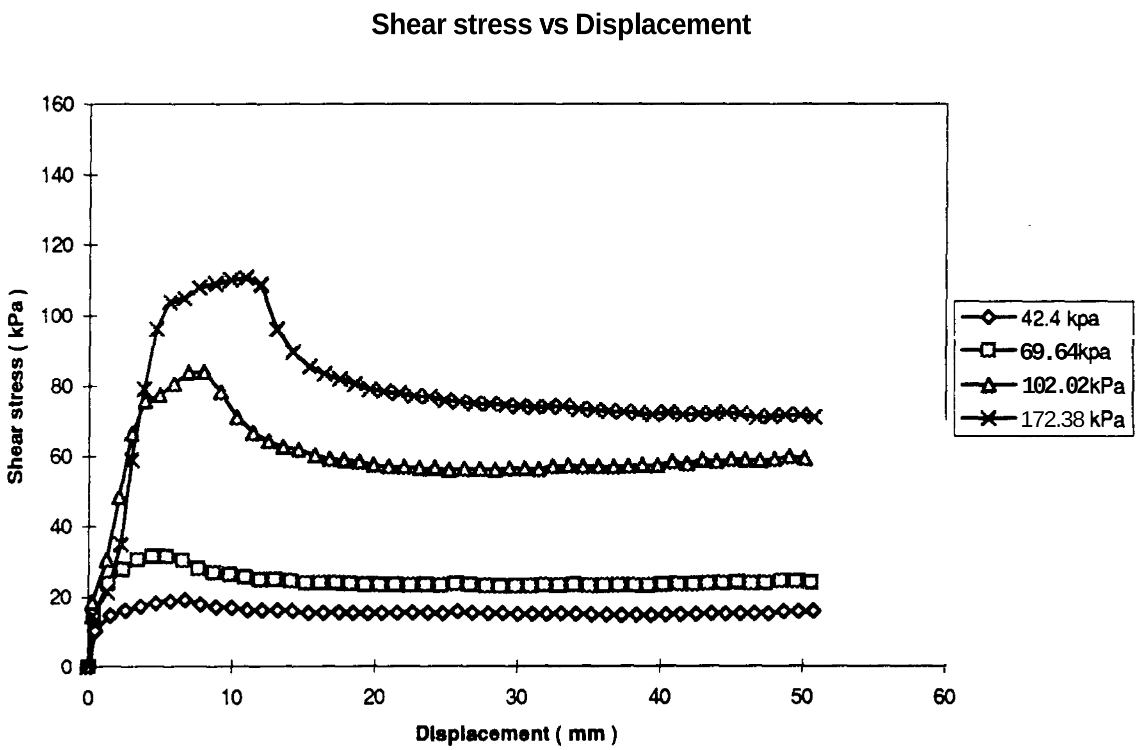


FigureC3. Silty Clay vs. File Finish PVC a) Stress vs. Displacement b) Friction Angle



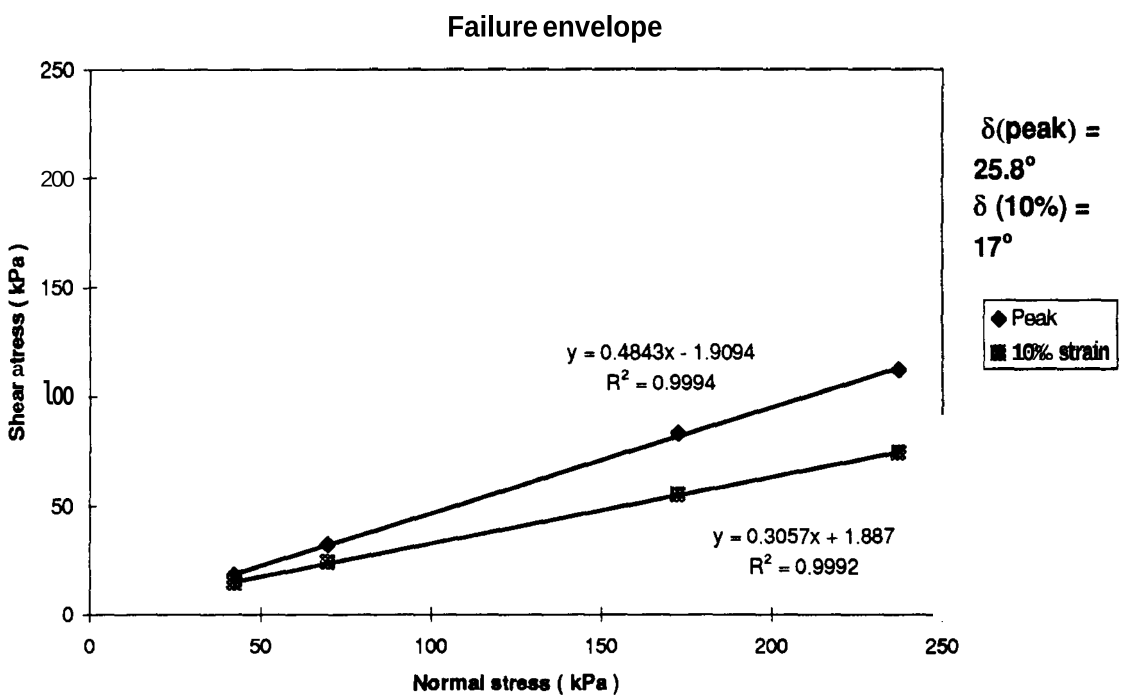
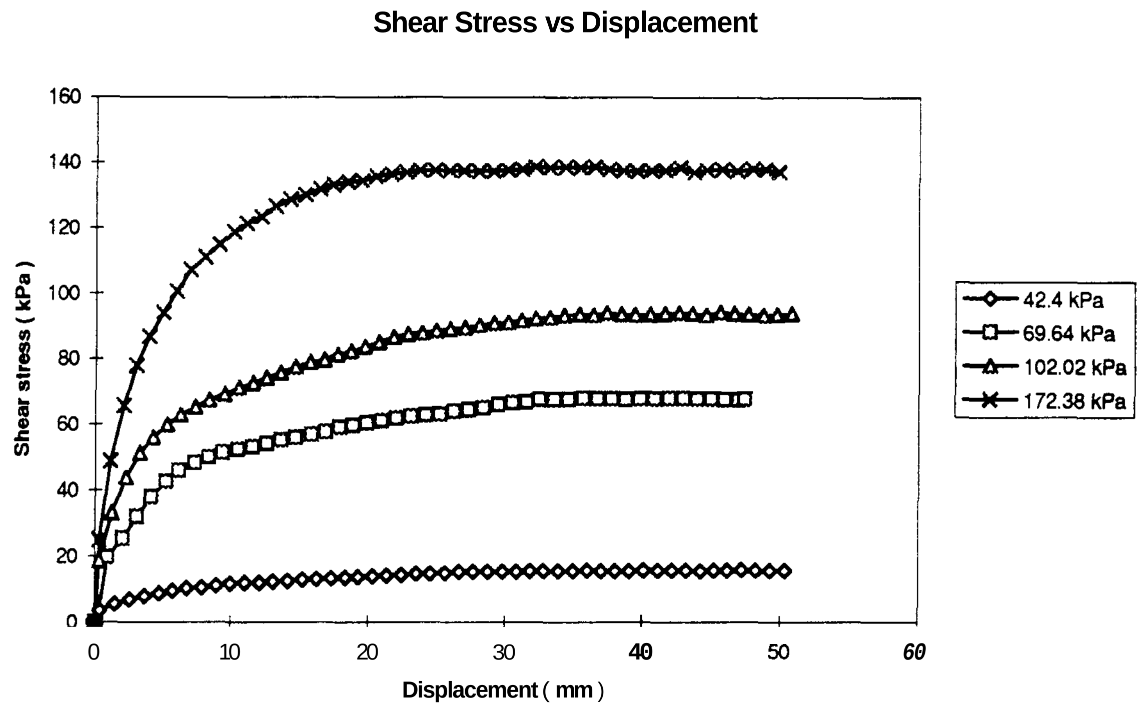


Figure C4. Silty Clay vs. Smooth HDPE a) Stress vs Displacement b) Friction Angle



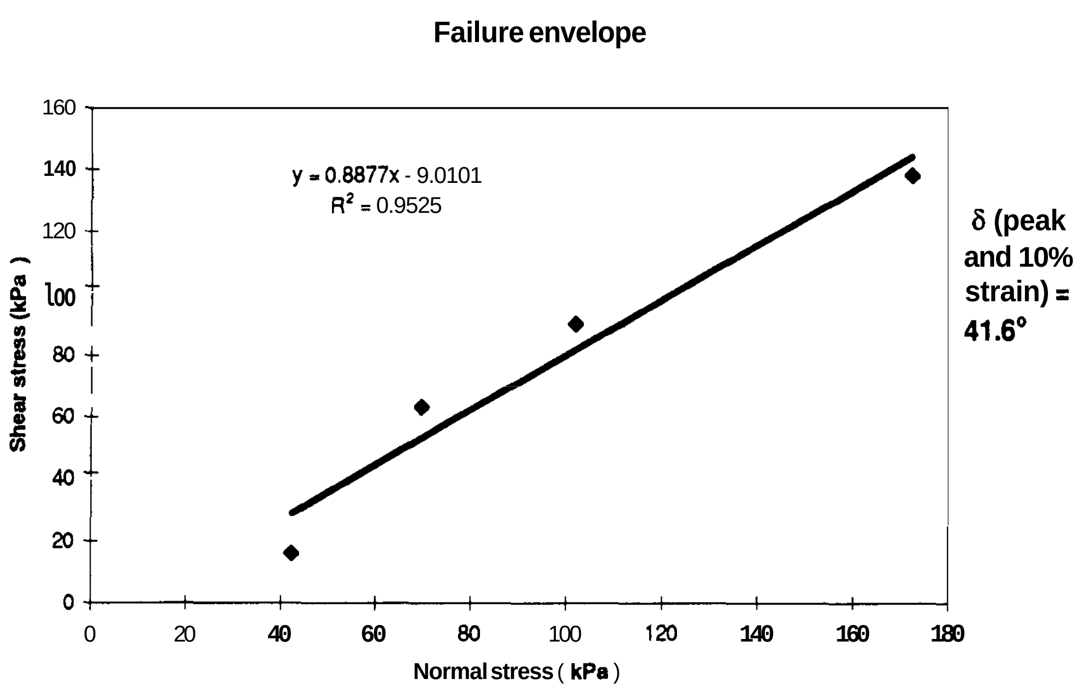


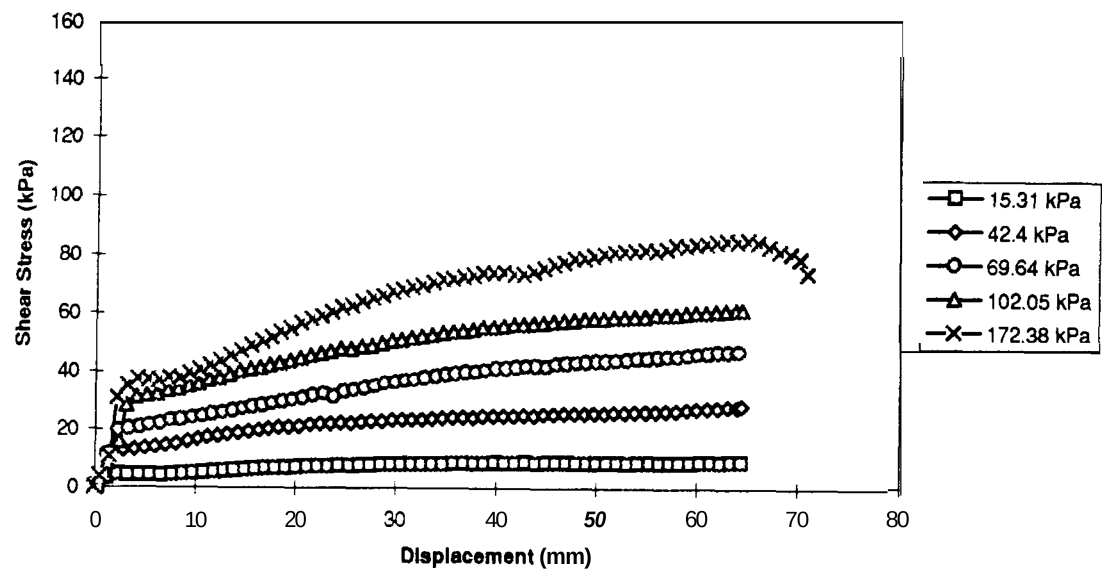
Figure C5. Silty Clay vs. Textured HDPE a) Stress vs. Displacement b) Friction Angle

APPENDIX D

NON-WOVEN GEOTEXTILE vs.

VARIOUS GEOMEMBRANES

Shear Stress vs Displacement



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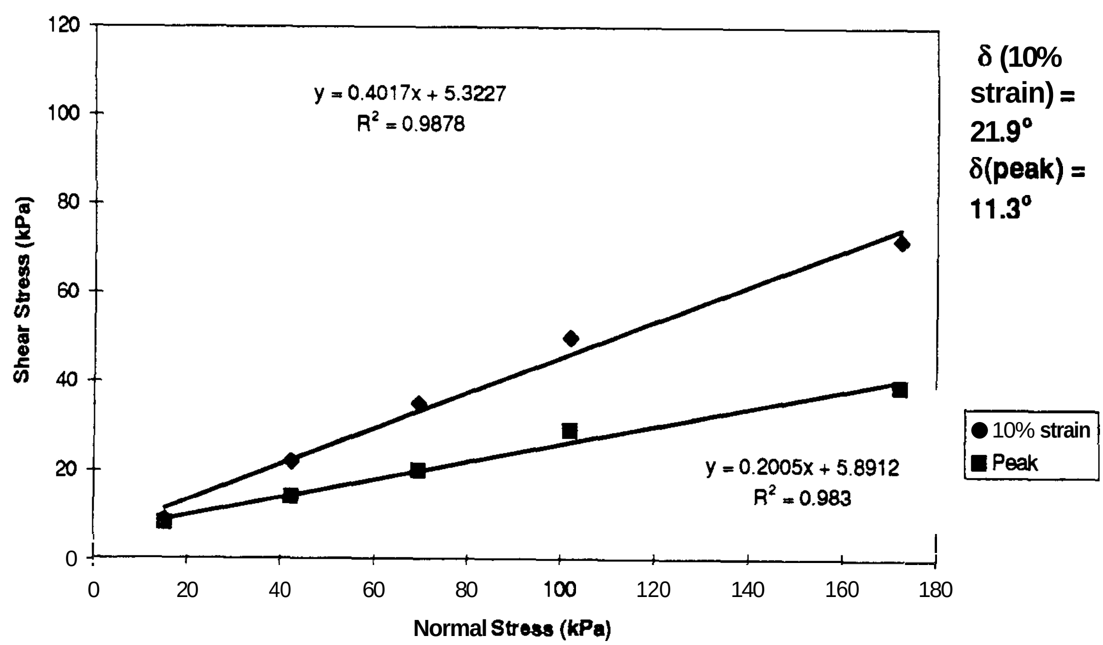
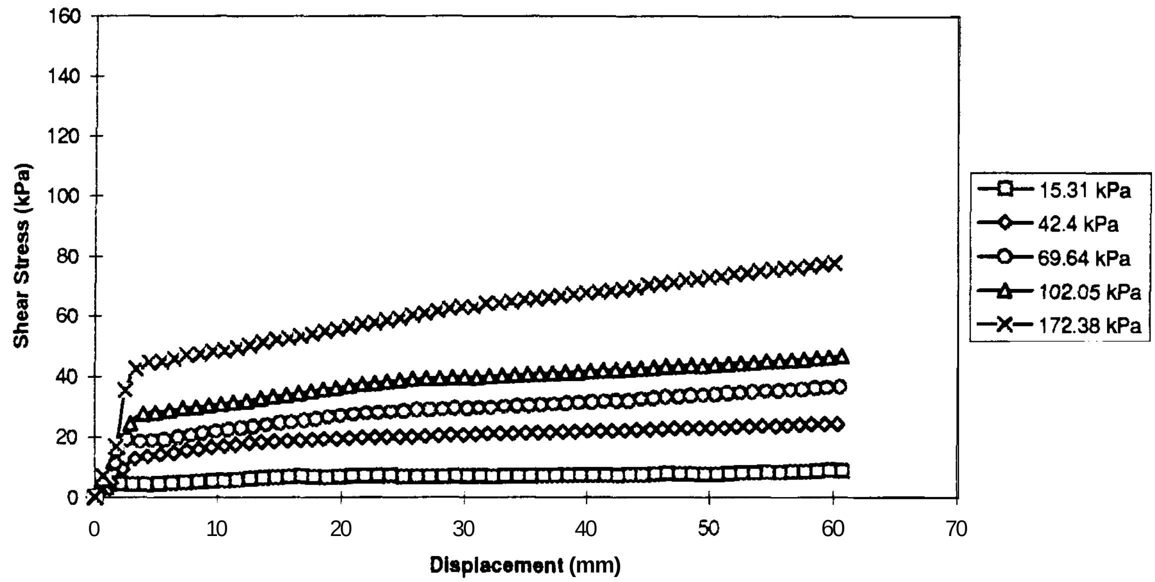


Figure D1. Non-Woven Geotextile vs. Smooth PVC a) Stress vs Displacement b) Friction Angle

Shear Stress vs Displacement



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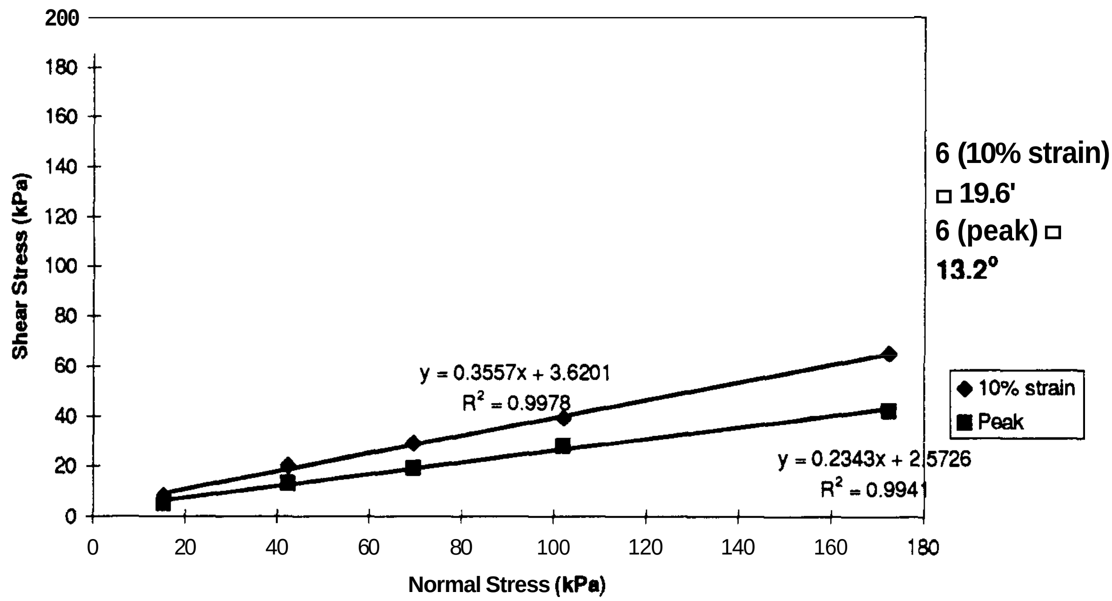
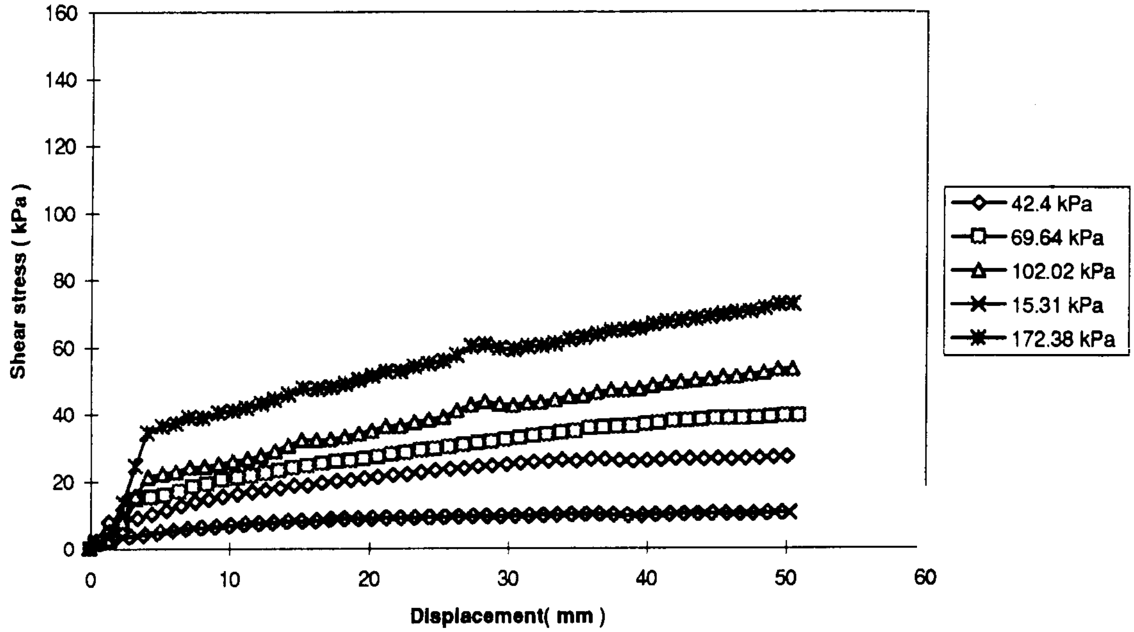


Figure D2. Non-Woven Geotextile vs. Textured PVC a) Stress vs. Displacement b) Friction Angle

Shear stress vs Diplacement



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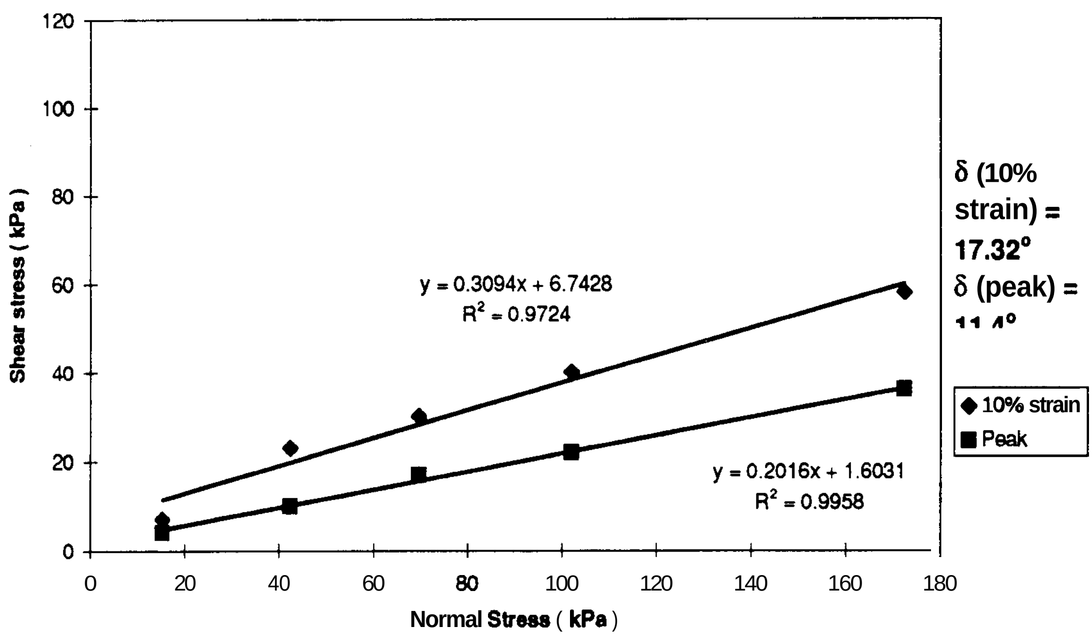
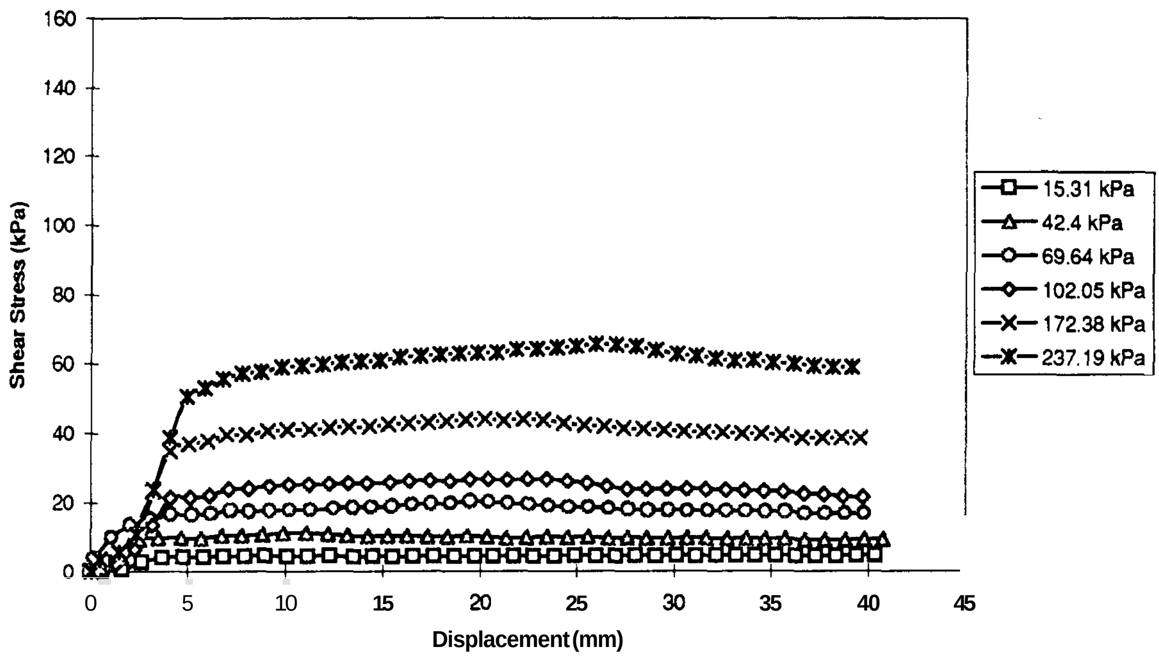


Figure D3. Non-Woven Geotextile vs. File-finish PVC a) Stress vs Displacement **b)** Friction Angle

Shear Stress vs Displacement



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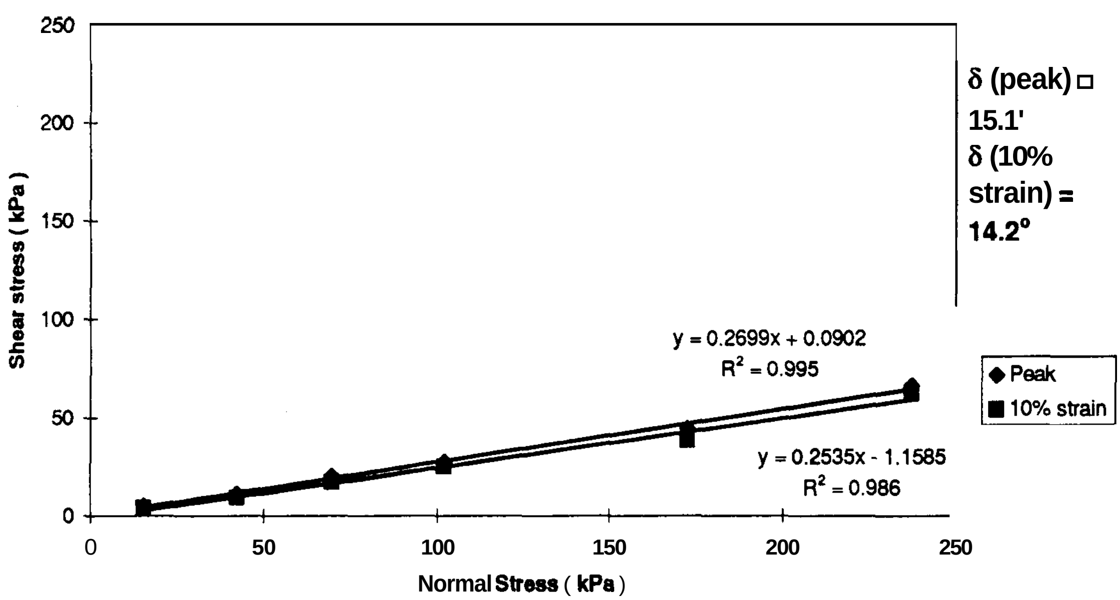
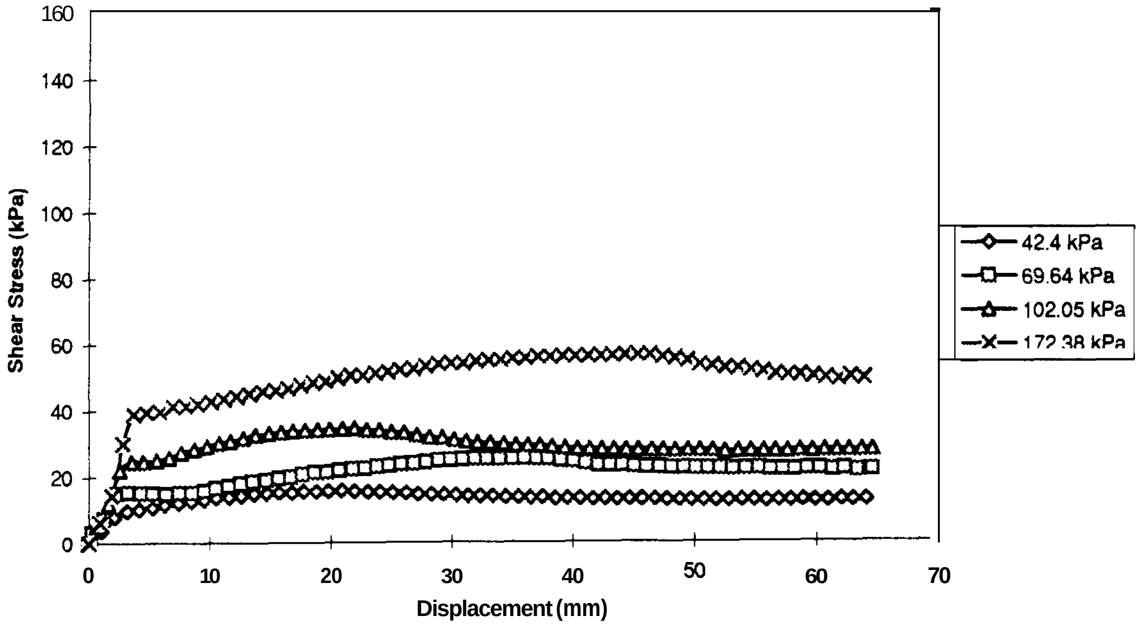


Figure D4. Non-Woven Geotextile vs. Smooth HDPE a) Stress vs. Displacement b) Friction Angle

Shear Stress vs Displacement



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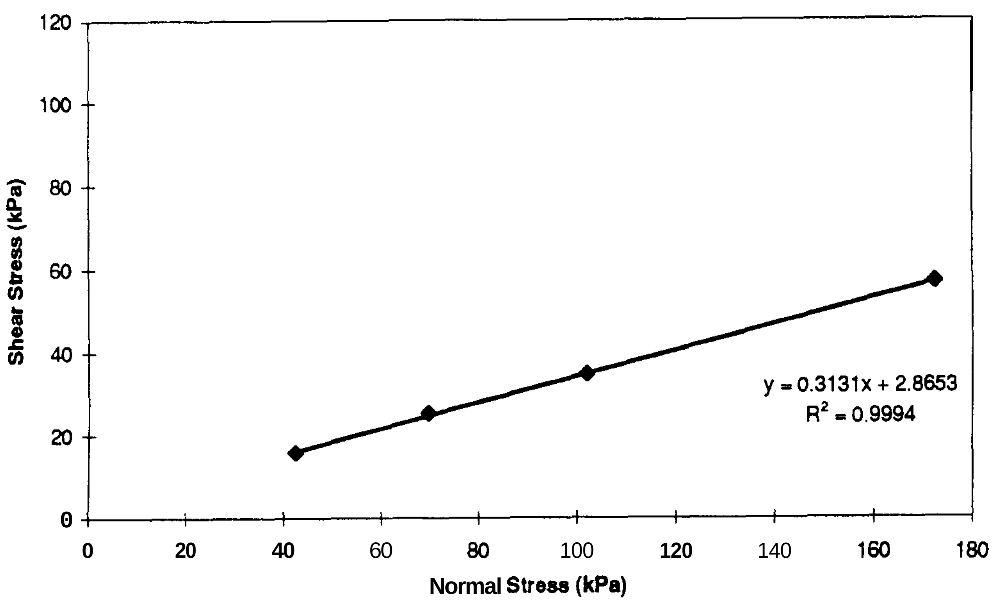

δ (peak and 10% strain) = 17.4°

Figure D5. Non-Woven Geotextile vs. Textured HDPE a) Stress vs Displacement b) Friction Angle