Geosynthetic interface testing at low normal stresses: design implications

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ABSTRACT: The economic benefits associated with incorporating geosynthetics in landfill cover systems are leading to their increased use. Consideration of slope stability is often critical for cover design as geosynthetics introduce planes of weakness. In many cases, it is the shear strengths available at the geosynthetic/geosynthetic interfaces that control the safe angle of these slopes both during and after construction. Repeatability shear strength testing for both smooth and textured LDPE geomembranes against a polypropylene geotextile has been undertaken to assess variability of results. A standard large shear box has been used to measure shear strength at values of low normal stress suitable for capping systems. This has revealed a high degree of variability in the shear strength test data. Possible reasons for the variability have been investigated, and guidance is provided on the test procedure. The results demonstrate that care must be taken when interpreting test data for use in design. If the degree of possible variation in measured shear strength is not appreciated, inappropriate values could be used in design and this could lead to failure.

1 INTRODUCTION

Landfill closure often involves the construction of engineered cover systems. The use of geosynthetic materials in cover systems is on the increase due to economic benefits associated with their use. New and improved materials are continually being developed. The role of the capping system is to ensure that there are no uncontrolled emissions of gas and liquid into the environment, to minimise ingress of fluid into the landfill and to provide conditions for the establishment of vegetation as part of re-habilitation and re-use of the site. These requirements result in cover systems comprising of a number of geosynthetics (e.g. geomembrane, geotextile, geonet, geocomposite) and soils (e.g. low permeability and drainage materials). Each interface between adjacent materials (i.e. geosynthetic/geosynthetic or geosynthetic/soil) is a potential plane of slippage. Site specific testing should always be undertaken to obtain shear strength information for each interface, and hence to enable the critical plane to be used in design. This paper focuses on issues related to assessment of cover system stability.

As shown in Figure 1, capping systems typically incorporate about one metre of cover soil above the geosynthetic materials. The normal stresses at the geosynthetic interfaces are therefore low (i.e. approximately 20kPa), and hence the shear strengths of these interfaces are also low. In addition, small changes in shear strength have a significant effect on stability. If stability of the capping system is to be ensured, without resorting to the adoption of over-conservative designs, the interface shear strengths must be accurately determined and the possible variation in strength quantified. The presence of low shear strength interfaces has been an important factor in slope stability failures in the past (e.g. Mitchell *et al*. 1990). Failures will continue to occur until the issues identified above are addressed.

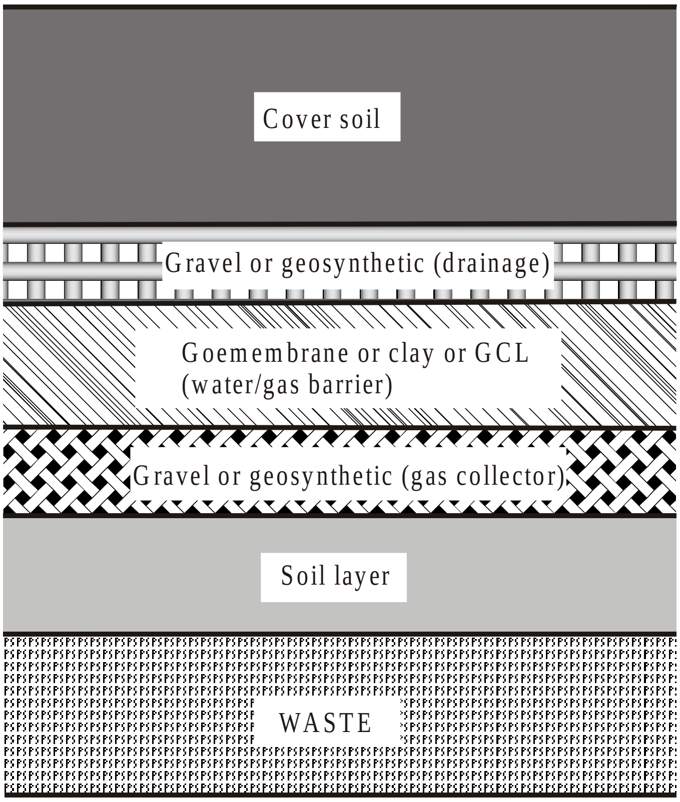


Fig 1 A Typical Final Cover System

This paper presents the results of repeatability tests carried out in a shear box at low normal stresses, on both smooth and textured Low Density Polyethylene (LDPE) geomembrane against a needle punched non-woven Polypropylene (PP) geotextile. The test procedure followed the draft European Standard (prEN ISO 12957-1:1997).

2 TESTING PROGRAMME

2.1 *Material description*

Materials used in this test programme were selected as being typical for cover system construction. Both smooth and textured (by impingement method) 1mm thick LDPE geomembranes were used. In the UK, LDPE geomembranes are routinely used in cover systems. The average asperity height was 0.95 mm ± 0.2 mm, for the textured geomembrane. An 80 g/m^2 non-woven stable fibre needle-punched polypropylene geotextile was selected as being representative of geotextiles typically used in caps. In order to reduce the number of variables, and hence variability of results, the repeatability test materials were restricted to geomembrane and geotextile (i.e. no cover soils were involved). Both geosynthetics were sheared parallel to the roll direction, which based on present site place-ment practices, means that the shearing direction was parallel to the cover system slope. One side of each of the geosynthetics was selected for testing, and all tests were carried out on these sides. Samples were stored for a minimum of 24 hours in a room with the temperature controlled at 20 ± 2 ^{o}C.

2.2 *Equipment*

A large direct shear apparatus with an upper box plan area of 300mm x 300mm and a bottom box area of 300mm x 400mm was used for these tests. The design of the shear device is based on a fixed top box (i.e. the upper box can not move vertically or rotate). This design is used worldwide for routine geosynthetic interface shear strength assessment, and is in accordance with the commonly referenced national test standards (e.g. BS 6906, ASTM D5321). This apparatus can be used for testing at normal stresses of between 5 kPa and 600 kPa. The use of this equipment in the range of normal stresses relevant for cover systems requires an assessment of the achievable accuracy and reproducibility of results.

Normal stress was applied using a pneumatically operated piston reacting against the body of the shear device, and acting through a rigid load platen with the same plan area as the top box. The normal stress can be controlled to a resolution of 0.2kPa and is recorded throughout each test. A displacement transducer is used to measure vertical displacement of the sample during application of normal stress and during shearing.

2.3 *Test procedure*

The following test set up was used in all tests. Nylon spacer blocks were placed in the bottom box such that the top surface of the upper spacer was flush with the top of the box. The upper surface of the top block was covered with a high friction coating in order to ensure that the overlying geomembrane did not stretch. A geomembrane sample with a shear area of 300mm x 400mm was clamped to the leading edge of the bottom box using bolts acting through a spreader bar. The geotextile sample, with a shear area of 300mm x 300mm, was clamped to the leading edge of the top box using a similar system. In all tests the geotextile was attached to the top box and the geomembrane to the bottom as this configuration produces results most representative of field conditions (Jones, Dixon 2000).

The upper box was brought into contact with the lower box, and then raised by 1mm to ensure that a shear force was not generated between the top and bottom boxes. Due to the top box being fixed, this gap was maintained throughout the test. Nylon spacer blocks were placed in the top box in order to transfer the normal stress to the interface. The lower surface of the bottom block was covered with a high friction coating in order to ensure that the underlying geotextile did not stretch.

Tests were conducted at normal stresses of 10, 20 & 30 kPa, and each test was conducted using virgin samples of geosynthetics. Normal stress was applied and held for 10 to 15 minutes before shearing the interface at a rate of 3mm per minute. The temperature during testing was maintained at $20 \pm 2\,^{o}C$. A minimum shear displacement of 90mm was achieved in all tests. One operator carried out all the tests, thus eliminating variations in the test procedure caused by different operating techniques.

A summary of the testing program is given in Table 1. The main series of tests was conducted in order to quantify the variation in data resulting from a carefully controlled test procedure, and with the number of variables minimised. A minimum of 11 tests was carried out at each normal stress for both the smooth and textured geomembranes. Following completion of the tests, the wide range of values obtained prompted a second series of tests with special conditions. The aim of the investigation was to assess possible causes of the scattering. For each of the types of geomembrane, two conditions were investigated separately. For the smooth material the effect of scoring the surface and of wetting the surface were assessed. In order to investigate the affect of possible variations in the surface friction of the geomembrane caused by damage during manufacturing and sample preparation, a pattern of shallow scratches was made across the geomembrane surface. The same regular pattern was used in each of the tests. The influence of moisture on shear strength was assessed by wiping the surface of the geomembrane with a wet cloth prior to covering it with the geotextile.

Table 1. Testing Programme

Interface	Condition	Normal stress (kPa)	No. of Tests
Smgm/gt	Normal	10	13
Smgm/gt	Normal	20	11
Smgm/gt	Normal	30	11
Smgm/gt	Scratched	10, 20, 30	6 (2 each)
Smgm/gt	Damp Wipe	10, 20, 30	6 (2 each)
Txgm/gt	Normal	10	13
Txgm/gt	Normal	20	12
Txgm/gt	Normal	30	11
Txgm/gt	Preload	10, 20, 30	6 (2 each)
Txgm/gt	Rub	10, 20, 30	6 (2 each)

For the textured geomembrane tests, conditions of pre-loading and geotextile damage were investigated. The effect of pre-loading the interface before shearing was assessed as it was anticipated that activities such as dropping the nylon spacer blocks into the top box, or accidentally increasing the normal stress above the test stress during test set-up, might have increased the entanglement between the geotextile fibres and the geomembrane asperities. The normal stress was increased by 20 kPa above the test normal stress value and held for 10 minutes before reducing it back to the test value and shearing the interface. To investigate possible damage to the geotextile during sample preparation (i.e. fibres might be pulled out or broken), the geotextile was dragged across the surface of a separate piece of textured membrane, in the direction of shearing and under zero normal stress, prior to clamping it in the shear box. Six tests were conducted for each of the conditions investigated (i.e. two tests were carried out at each normal stress).

3 RESULTS

3.1 *Repeatability tests*

Shear stress vs. displacement plots from each of the first series of tests (i.e. the repeatability tests) on smooth geomembrane/ geotextile and textured geomembrane/geotextile are shown in Figures 2 and 3 respectively. Figures 4 and 5 are shear stress vs. normal stress plots showing peak and large displacement shear strengths respectively from the repeatability tests on smooth geomembrane/ geotextiles. Also shown are the mean regression line for shear strengths, and the 95% confidence limits for all data (outer limits) and the mean (inner limits). Figures 6 and 7 are shear stress vs. normal stress plots showing the peak and large displacement shear strength data respectively from the repeatability tests on textured geomembrane/geotextile. Again, the mean regression line and 95% confidence limits are included. It could be argued that the failure envelopes are non-linear, however for ease of analysis, best-fit straight lines have been used to help describe the data. This leads to negligible errors within the tested range of normal stresses (10 kP to 30 kPa).

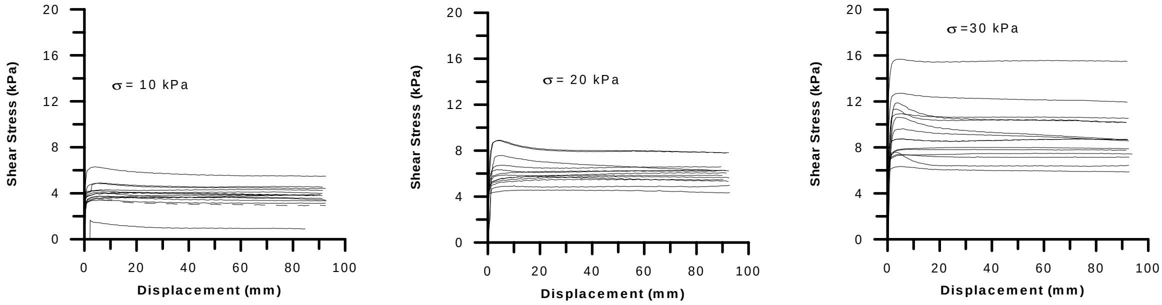


Figure 2. Shear stress vs. displacement: smooth geomembrane/geotextile

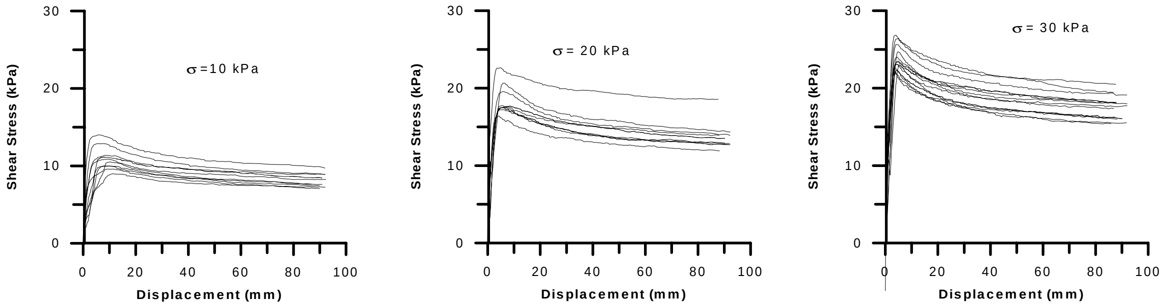


Figure 3. Shear stress vs. displacement: textured geomem brane/geotextile

3.2 *Special condition tests*

Figures 8 and 9 are shear stress vs. normal stress plots showing the peak and large displacement shear strength data respectively from the special condition tests on smooth geomembrane/geotextile. In order to aid interpretation of the second series of tests, the mean line and both sets of confidence limits from the repeatability tests have been reproduced. Figures 10 and 11 are shear stress vs. normal stress plots showing the peak and large displacement shear strength data respectively from the special condition tests on textured geomembrane/geotextile. The mean line and both sets of confidence limits from the repeatability tests have again been reproduced.

4 DISCUSSION

4.1 Factors influencing variability

Figures 2 and 3 show consistent shear stress vs. displacement relationships for the two interfaces investigated, with both demonstrating a degree of strain softening behaviour that becomes more marked with increasing normal stress, and for the textured geomembrane. In the large majority of the smooth geomembrane/geotextile tests it appears that residual conditions have been established. However, Figure 3 suggests that the textured geomembrane/geotextile tests have undergone

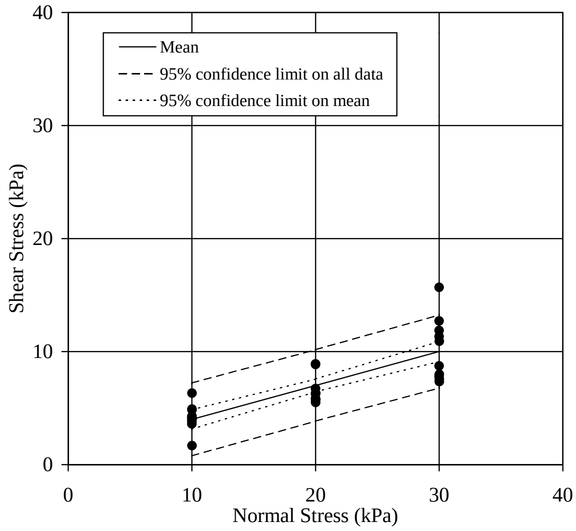


Figure 4. Smooth geomembrane/geotextile: Residual shear strength

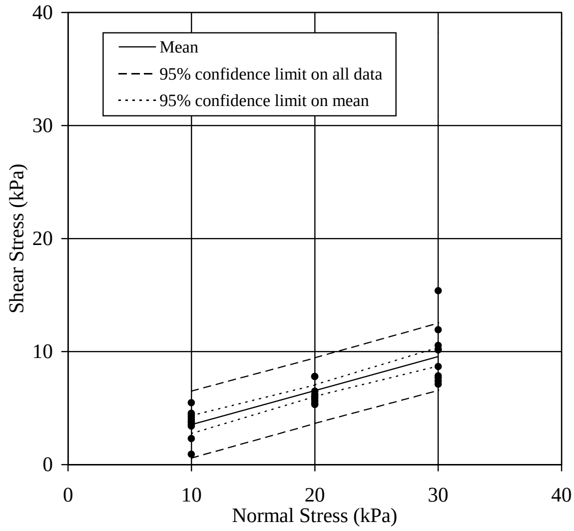


Figure 5. Smooth geomembrane/geotextile: Peak shear strength

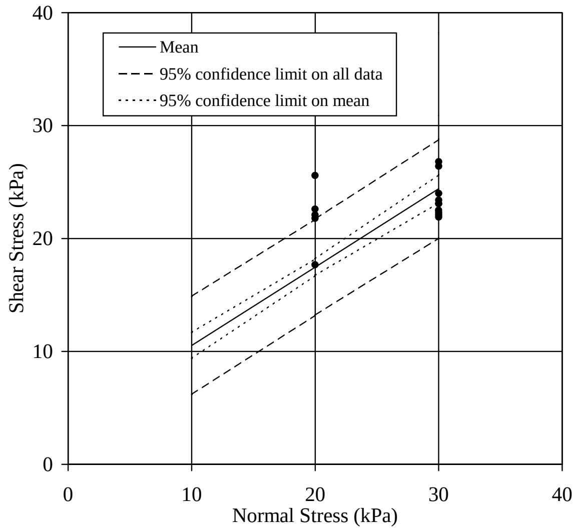


Figure 6. Textured geomembrane/geotextile: Peak shear strength

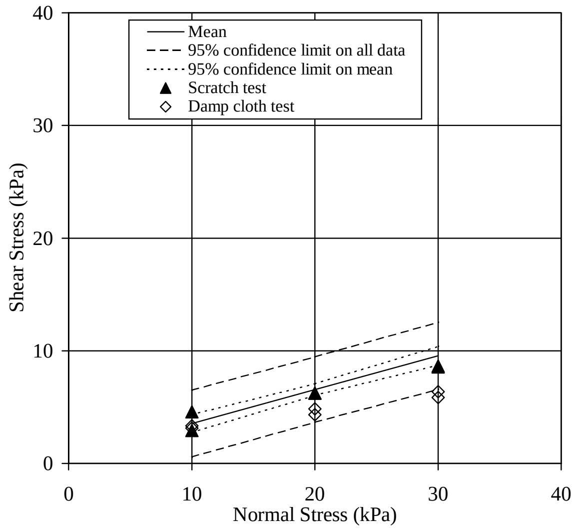


Fig 7. Textured geomembrane / geotextile: Residual shear strength

insufficient deformation to reach full residual conditions. For this reason the term ‘large displacement shear strength’ should be used to de scribe the lowest values of strength obtained, although the term ‘residual shear strength’ has been used here for brevity. The results demonstrate significant variation for a given normal stress.

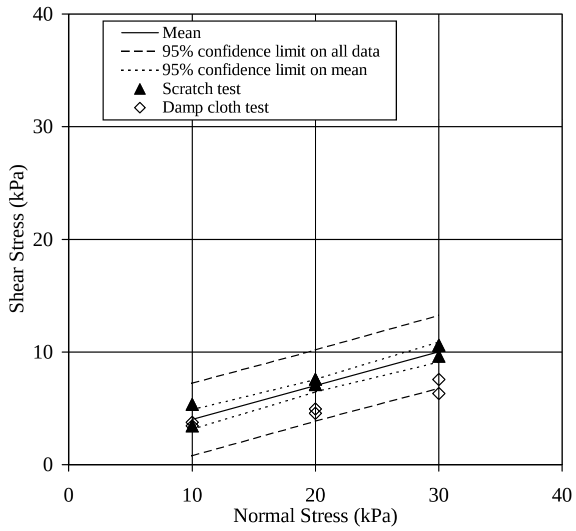


Figure 8. Smooth geomembrane/geotextile: Peak shear strength, special test condition

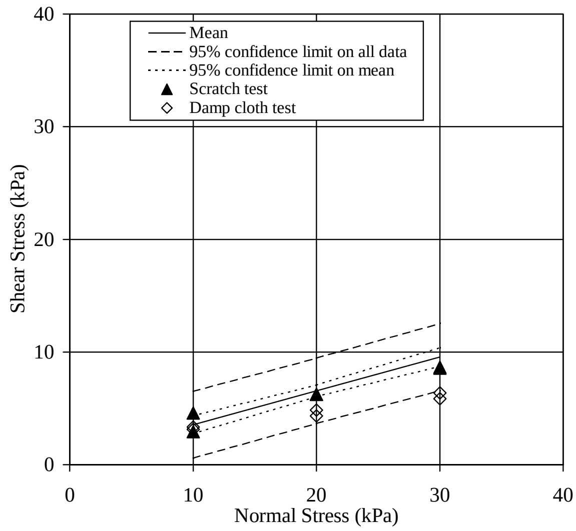
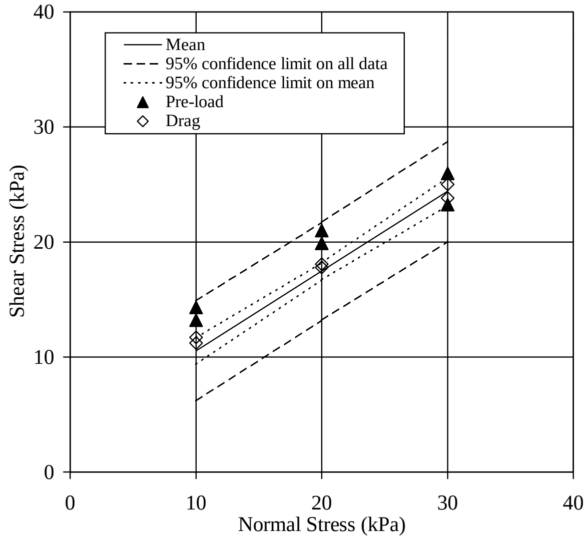


Fig 9. Smooth geomembrane/geotextile: Residual shear strength, special test condition

Coefficient of variation values in the order of 15% and 23% have been calculated for the smooth and textured test series respectively. The coefficient is defined as (*standard deviation / mean) x 100.* This results in a range of peak and residual shear strengths being obtained. These values are consistent with those reported by Blümel *et al.* (2000) for low normal stresses. The data has been obtained from a number of inter-comparison testing programs both in Germany involving testing houses, and between Hanover University and Loughborough University. However, the coefficients are larger than those from tests at higher normal stresses.

The tests described in this paper were carried out under tightly controlled test conditions. One operator undertook all the testing, samples were cut from only one roll of each of the different geosynthetics, the orientation of samples in relation to the direction of shearing was carefully controlled, and one shear device was used for all tests. In addition, it is worth noting that the test set up did not incorporate any soils, as these have been shown to increase the scatter of test data (Snow *et al*., 1998). Given the care taken with the above tests, it is perhaps surprising to obtain the observed scatter of results. However, due to the low values of shear strength being measured, minor factors can have a significant influence on measured shear strength. These have received little attention in the past as they have less significance when testing at higher normal stresses. Some possible reasons for the variation in results have been investigated through the 'special conditions' tests. The significance of these conditions can be assessed by comparing the peak and residual shear strengths, with those from the main body of repeatability tests. It can be considered that the factor investigated is not practically significant if the results fall predominantly within the band defined by the upper and lower 95% confidence limits on the mean (i.e. for the main data set), and is potentially significant if they fall outside the band.



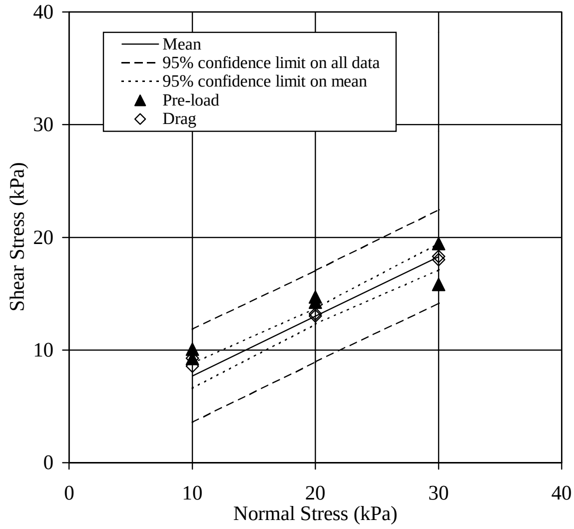


Figure 10. Textured geomembrane/geotextile: Peak shear strength, special test conditions

Figure 11. Textured geomembrane/geotextile Residual shear strength, special test conditions

4.1.1 *Smooth geomembrane/geotextile*

Figures 8 and 9 show that the 'scratch' tests gave both peak and residual shear strengths generally within the band defined by the 95% confidence limits on the mean. This indicates that macro level variations in the geomembrane surface resulting from dam- age during manufacture, or handling, are unlikely to result in significant changes in measured shear strength. Hence it is unlikely to have contributed to the scatter in the data. Results from the 'damp cloth' tests are also shown in Figures 8 and 9. Both the peak and residual shear strengths fall outside and below the >95% confidence limit band, with the differences becoming greater with increasing normal stress. This indicates that the presence of moisture at smooth geomembrane/geotextile interfaces can have a significant effect on the measured strength. Only a very thin film of water was present on the surface of the geomembrane. It is not clear how this could have such a significant effect as pore pressures on the interface should be zero, although it may be having a lubrication affect.

In relation to best practice laboratory testing procedures, it is clear that every attempt must be made to ensure that all moisture is removed from the surface of the geomembrane before testing. This includes perspiration transferred to the surface during handling. Of greater concern is the implication of these results for the field performance of such interfaces. The importance of positive pore pressures on the stability of interfaces is well understood and taken into account during design. However, it is interesting to note that the presence of a thin film of water at the interface could have a significant de-stabilising affect. This is the subject of ongoing research at Loughborough University.

4.1.2 *Textured geomembrane/geotextile*

Figures 10 and 11 show that the 'drag' tests gave both peak and residual shear strengths within the band defined by the 95% confidence limits on the mean. This indicates that variations in the surface structure of the geotextile resulting from dragging it over a piece of textured geomembrane prior to shearing are negligible. Fibre damage during handling (i.e. resulting in their re-alignment in the direction of shearing, and hence in a reduction in interface shear strength) is unlikely to be significant. Therefore, this mechanism is unlikely to have contributed to the scatter of the data.
Results from the 'pre-load' tests are also shown in Figures 10 and 11. The peak and residual shear strengths fall outside and above the 95% confidence limit band for the 10 and 20 kPa normal stress tests. However, both the peak and residual 30 kPa results are within or close to the respective bands. This demonstrates that excess normal stress applied prior to shearing a textured geomembrane/geotextile interface, has a significant influence on the mobilised shear strength up to a threshold test value of 30 kPa. For normal stresses of 10 and 20 kPa the application of an excess stress has resulted in increased interlocking between the geotextile fibres and the geomembrane texturing, thus increasing the peak shear strength. For the 30 kPa test it appears that the use of a pre-load does not result in any significant additional interlocking of the fibres and texturing. However, it is possible that application of a larger pre-load would result in a higher threshold stress (i.e. at which the pre-load has a minimal effect). It is surprising that the residual shear strengths have also been increased for the 10 and 20 kPa tests, as all interlocking between fibres and texturing should have been destroyed for this condition to be established. This indicates that in these tests the true residual conditions have not been reached.

The results of the pre-load tests have important implications for development of laboratory testing procedures. Care must be taken to ensure that the normal stress at which shearing takes place is not exceeded during test set up. Filling of the top box (i.e. with spacer blocks or cover soil if used in the test) and application of the normal stress, must not result in the application of an excess stress. Otherwise, increased shear strengths will be measured leading to unconservative (i.e. high) values being used in design. The implications of pre-loading during construction are not important because any gain in strength will be beneficial.

While the 'special condition' tests give an indication of possible factors that can cause the scatter of data, they can not be used to explain all the observed variation in results. It is believed that much of the scatter is due to variation of the geosynthetics, and hence the repeatability tests could be giving a true reflection of the shear strengths likely to be mobilised in the field.

4.2 *Interpretation of shear strength parameters*

Following the plotting of peak and residual shear strengths on a shear stress vs. normal stress graph (Figures 4, 5, 6 and 7), it is common practice to use the Coulomb failure criterion by defining design lines through both the peak and residual data. The shear strength parameters that describe these lines (intercepts α_p and α_r, and slope angles δ_p and δ_r) can then be used to calculate shear strengths at any normal stress level. In many design situations duplicate tests at each normal stress are rarely carried out, and hence the design line is typically taken as the best fit straight line through the data points. Given the scatter of data shown in Figures 4, 5, 6 and 7 for tests at low normal stresses, this approach produces concern in relation to the design of cover systems. If only one or two tests are conducted at each normal stress, it is not known whether the measured shear strengths are high, low or average values. Depending upon the position of the measured strengths within the possible range at each normal stress, the best-fit line can have a variety of positions, and hence a wide range of shear strength parameters could be obtained.

An assessment has been made of the variation in peak strength parameters that can be obtained using the repeatability data shown in Figures 4 and 6. A Monte Carlo simulation has been carried out to obtain the distributions of strength parameters (α_p , δ_p) that are calculated when sets of three strengths (i.e. one from each normal stress) are selected and a best fit straight line calculated. The measured distributions of shear strength for each normal stress form the input data for the simulation. A total of 1000 trials were conducted for each interface. An example of results from the Monte Carlo simulation for the smooth geomembrane/geotextile test data are shown in Figure 12 for the intercept (α_p) and slope (δ_p) values.

Table 2 contains a summary of results from the simulations in terms of mean and standard deviation of the calculated parameters. In addition, the pairs of shear strength parameters that define each best-fit line have been used to calculate the shear strength for a normal stress of 20 kPa (i.e. typical for a cover system). A summary is given in Table 2 also in terms of mean and standard deviation.

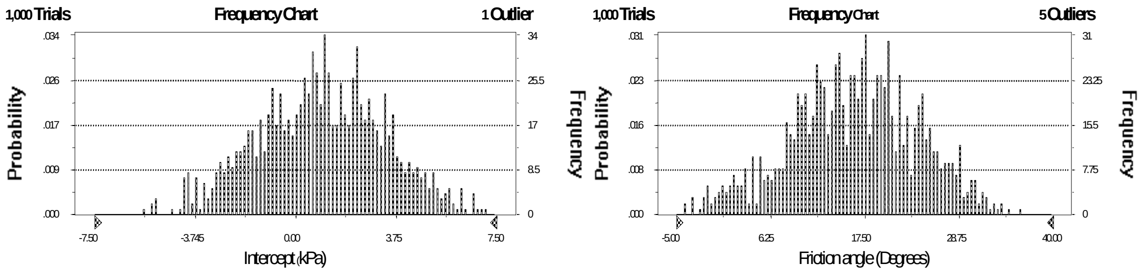


Figure 12. Results of Monte Carlo simulation of shear strength parameters: intercept (upper) and friction angle (lower)

Table 2. Distribution of peak shear strength parameters

Statistics		Smooth/geotextile	Textured/geotextile
α	mean (kPa)	1.0	3.7
	SD* (kPa)		2.4 1.9
δ	mean (°)	16.2	34.5
	SD (°)	7.8	3.5
τ @ σ_n = 20 kPa	mean (kPa)		6.9 17.5
	SD (kPa)	1.1	1.4

* SD is standard deviation

The degree of variation in shear strength data, e.g. see Figures 4 and 5, leads to a wide range of possible interpretations to obtain shear strength parameters for use in design. The calculated values of shear strength shown in Table 2 have a significant range, and this has important implications for design. Data that produces high shear strengths based on one test at each normal stress, could overestimate field values by up to 20%.

Results of the repeatability tests at low normal stresses presented in this paper have important implications for the calculation of shear strength parameters, and the selection of appropriate factors for obtaining design values. Further work is planned as part of a Loughborough University/Hannover University joint research project, funded by British Council and German Academic Exchange Service (DAAD). The joint project is also investigating issues of test procedure and shear box design (Blümel *et al.* 2000).

5 SUMMARY

A carefully controlled testing program has been carried out to assess the repeatability of interface shear strengths measured at low normal stress levels that are appropriate for cover system design. A series of 'special condition' tests have been conducted to investigate some of the factors controlling the variability of the measured values. Both the smooth and textured geomembrane vs. geotextile interfaces produced a significant scatter of peak and residual shear strengths. The coefficients of variation for this data are larger than the values in the literature for tests at high normal stresses, but consistent with the data for low stresses (i.e. <50 kPa).

The high degree of scatter has been achieved despite tight controls on the test procedure. Tests conducted to investigate reasons for the scatter have shown that scratching the surface of the smooth geomembrane, and dragging the geotextile over a textured geomembrane to cause light damage, do not significantly affect the measured shear strengths of the respective interfaces. However, introducing a thin film of water onto the surface of the smooth geomembrane tends to reduce the shear strength, and pre-loading the textured geomembrane/geotextile interface before shearing produces an increase in shear strength for the 10 and 20 kPa tests. These factors contribute to the scatter of data but do not fully explain it. Variability of the geosynthetics material properties is considered to be the main cause of scatter.

Given the unknown degree of variation in measured strengths if a standard set of three normal stresses is used for design, it is not possible to assess the reliability of shear strength parameters obtained. The repeatability test results have been used to demonstrate possible variability of shear strength parameters, and hence of calculated shear strength. These results have an important implication for designers who have to select appropriate factors for use in design. Further work is required to assess other interfaces.

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