A comparison of geomembrane/geotextile interface shear strength by direct shear and ring shear

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ABSTRACT: The stability of landfill side slopes and capping lining systems is dependent on the shear strengths on the geosynthetic interfaces within the lining system. Imposed loading on these systems change with time as the settlement of the waste induces displacements at the geosynthetic interfaces. The shear strength developed at a geosynthetic interface is dependent on both the normal stress applied to the interface and the displacement at the interface. Several authors (e.g. Byrne 1994 etc.) have indicated that most geosynthetic interfaces are strain softening, i.e. they exhibit a reduction in shear strengths at displacements beyond peak strengths. Most geosynthetic interfaces reach their peak shear strength at relatively small displacements, typically 1 mm to 5 mm. This paper presents the results of interface shear strength measurements for various geomembrane/geotextile interfaces using a large direct shear apparatus and a modified Bromhead ring shear apparatus. The large displacement shear strength (after approximately 100 mm displacement in the large shear apparatus) and the residual shear strength (from the ring shear apparatus) are compared. A summary of interface shear strength parameters together with strain softening coefficients are presented.

1 INTRODUCTION

The stability of geosynthetic landfill lining systems is controlled by the shear strengths mobilised at the interfaces between various soils and geosynthetics and indeed within the geosynthetics themselves. Guidance is provided in national and international standards (e.g. BS 6906, ASTM D5321, etc.) on the methods to be used to measure these shear strengths but the designer must use engineering judgement to evaluate what values to use in design. Most interfaces involving geosynthetic are strain softening, i.e. the shear strength reduces with displacements beyond peak. If the designer uses peak strengths then an unsafe design may be produced; conversely the use of residual shear strengths may lead to an uneconomic design.

Displacements can be induced at these geosynthetic interfaces by a number of means including the placement of soils onto the geosynthetic and the large settlement that the waste body undergoes. Therefore, since the amount of shear strength mobilised at these interfaces is dependent upon the displacement at the interfaces, an estimate of the displacement is needed to provide values for mobilised interface shear strengths.

This paper presents a summary of the large strain interface shear strengths for one smooth and two textured geomembranes against two non-woven geotextiles of differing mass per unit areas. Shear stress vs. displacement plots are given for tests carried out using both direct shear and ring shear apparatus, and a discussion of the testing procedures is given.

2 TESTING PROGRAMME

2.1 *Introduction*

The shear stress/displacement behaviour of the various interfaces was measured using a 300 mm by 400 mm direct shear apparatus (DSA) specifically designed for geosynthetic testing. This measures interface shear strengths for displacements up to around 100 mm. However it is worth noting that a true residual (i.e. no further loss) shear strength may not be reached. A Bromhead (1979) Ring Shear Apparatus (RSA) was therefore used to measure true residual strengths. Similar testing has been carried out by Stark & Poeppel (1994).

Three High Density Polyethylene (HDPE) geomembranes were used for the testing; one smooth, one textured by impingement of hot polyethylene, and one textured by coextrusion using the blown film process. Two geotextiles commonly used as protection layers between a granular drainage layer and a geomembrane in the UK were used in the testing programme. They comprised a 750g/m^2 and a 1200g/m^2 non-woven stable fibre needle-punched polypropylene geotextile.

2.2 *Testing procedures*

The large strain or residual shear strength of geomembrane/geotextile interfaces were obtained in three different ways; using the DSA with three different gravel cover soils above the geotextile, using the DSA with a nylon block above the geotextile, and using the RSA. A nylon block was placed in the lower container for all the DSA tests to provide a bearing for the geomembrane. The geomembrane was then placed onto the block and clamped to the lower container using four bolts and a spreader bar. The geotextiles were placed on top of the geomembranes and clamped to the top box. For textured geomembranes, a piece of thin plastic sheet was placed between geotextile and geomembrane to prevent any disturbance of the geotextile fibres, and was removed prior to lowering the top container into position.

Gravel was then placed into the top container in two 50 mm layers and compacted by light tamping using a 5 kg weight. Tests were carried out on each interface at normal stresses of 25, 50 100 and 200 kPa with virgin geosynthetic samples used for each of the normal stresses. The normal stress was held for 5 minutes and adjusted if required, before shearing commenced. A shearing rate of 3 mm/min was used for all tests.

For the RSA testing annular samples, 100 mm OD and 70 mm ID, were formed from the various geomembrane sheets by firstly cutting to within 1 mm of the final profile with a band saw, and then trimming to size by turning on a lathe. All geotextiles were punched from sheets into the same annular shape as for the geomembrane. The geotextile samples were glued onto wood with care taken to ensure that the glue did not extrude through the geotextile. The geomembrane samples were secured to the top platen in two ways. For the textured geomembranes four small holes were drilled into the ring at locations corresponding to screw holes in the top plate, counter sunk, and screwed into place. Smooth geomembranes were glued to a thin wooden ring which had four nails that could be located in screw holes in the top platten. A shearing rate of 3 mm/minute and normal stresses of 27, 52, 102 and 201 kPa were used for this series of tests to enable comparison with the DSA results. Full details of the testing apparatus and procedure are given by Jones & Dixon (1998).

3 LABORATORY TEST RESULTS

3.1 *Shear stress vs. displacement behaviour*

The behaviour of a smooth geomembrane/geotextile interface using a 10 mm crushed gravel as cover soil above the geotextile is shown in Figure 1. This is typical of behaviour observed in all tests using smooth geomembranes. There is an initial increase in shear stress as soon as displacement starts, with a rapid increase in shear stress with increasing displacement, followed by a loss of shear stress with further deformation.

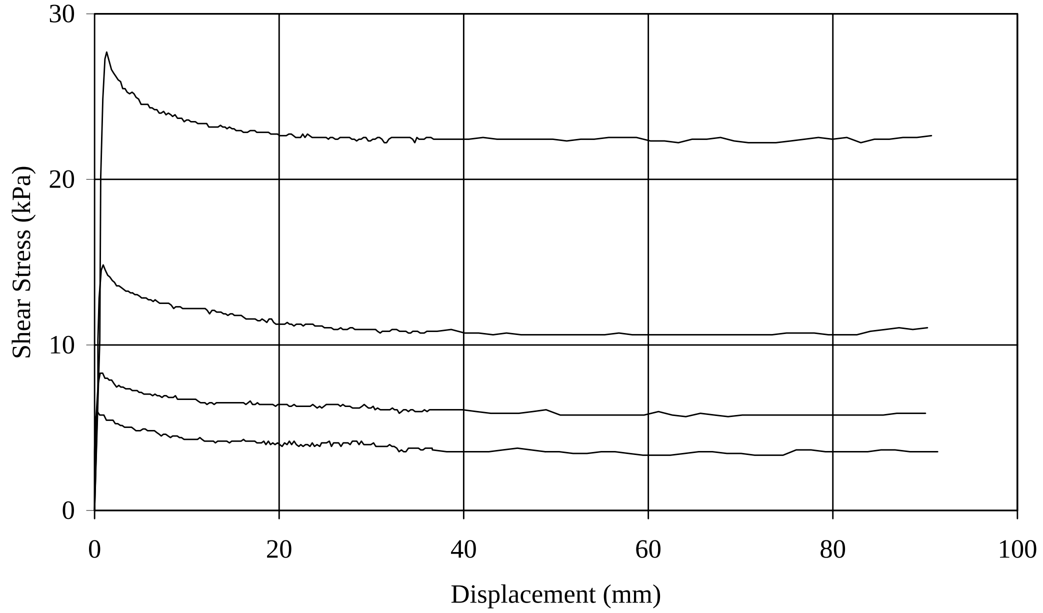

Figure 1. Shear stress vs. displacement for smooth geomebrane/geotextile interface using DSA.

This strain softening behaviour is evident at all four normal stresses applied. For smooth geomembranes the peak shear stress occurs typically at displacements of less than 2 mm, with the shear stress reducing by 20 to 30 % at displacements of around 40 to 50 mm. Little further change in shear stress with increasing displacement is evident.

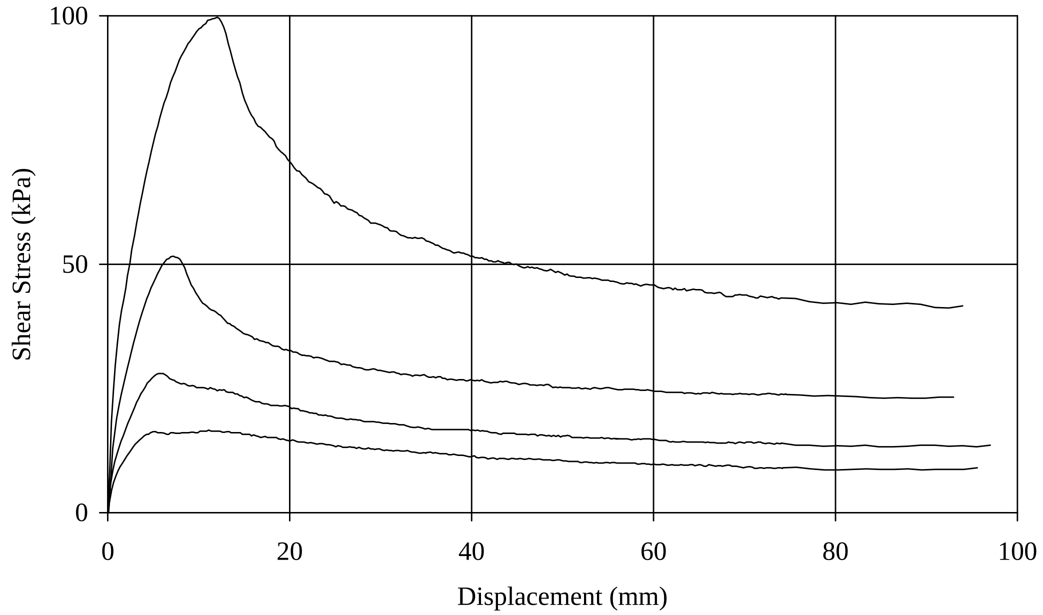

Figure 2. Shear stress vs. displacement for textured geomembrane/geotextile interface using DSA.

A typical example of the shear stress vs. displacement behaviour for a textured geomembrane against the same geotextile is shown in Figure 2. Much larger displacements are required to mobilise peak shear stresses, which are significantly higher than for smooth geomembranes, however a greater decrease in shear stress from peak is experienced with increasing displacement.

Peak shear stresses are reached at displacements of between 5 and 15 mm, depending on the normal stress applied. This interface exhibits a higher degree of strain softening than the smooth geomembrane with around 50 % reduction of shear strength at displacements over 50 mm. Both types of textured geomembrane gave similar shear stress vs. displacement curves.

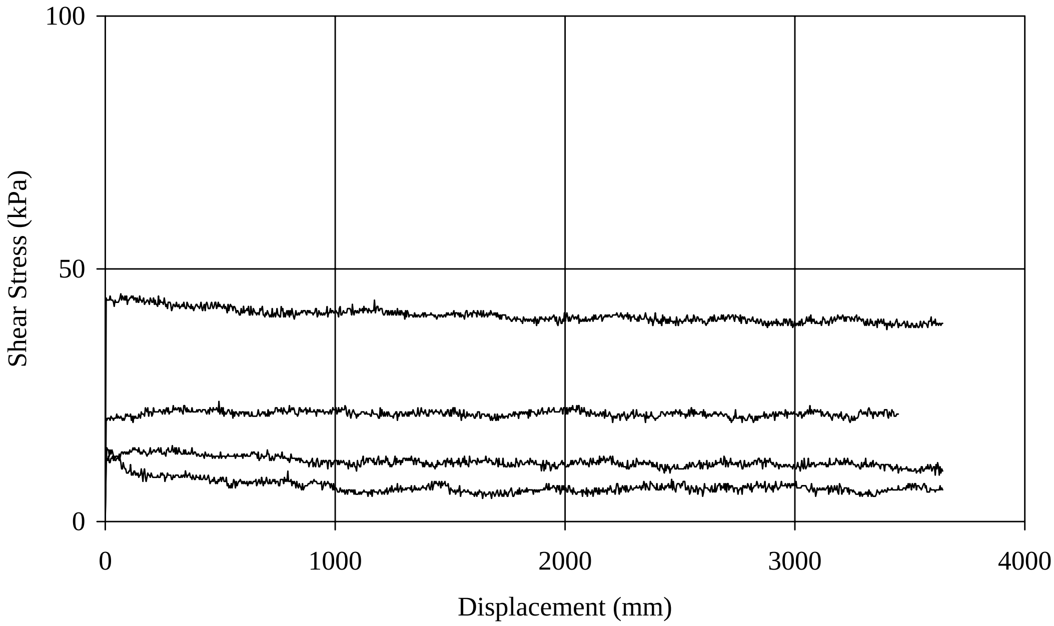

Figure 3. Shear stress vs. displacement for textured geomembrane/geotextile interface using RSA.

A typical shear stress vs. displacement relationship for a textured geomembrane against the 750 g/m^2 geotextile from a RSA test is shown in Figure 3. For the lowest normal stress, there is a rapid increase in shear stress with displacement to an initial peak, followed by a reduction in shear stress to a near constant large strain or residual value. This initial peak interface shear strength is reached at displacements of around 10 mm, which is similar to the results of the DSA testing. This peak can be regarded as an initial "bedding-in" of the geotextile and geomembrane, i.e. a realignment of fibres along the asperities of the textured geomembrane. No significant peaks were observed for the higher normal stresses. It should be noted that the normal stresses were increased without dismantling the specimens, and hence one pair of samples was used to produce each complete failure envelope. Similar trends were obtained from tests on smooth geomembrane.

3.2 *Interface shear strength parameters*

The interface shear strength can be expressed as a function of the normal stress by a modified Coulomb criterion:

$$\tau = \alpha' + \sigma_n'.\tan\delta' \quad (1)$$

It is assumed that for sliding to occur at an interface, the shear stress (τ) has overcome a frictional resistance which is dependent on the effective normal stress σ_n' acting on the interface and on a friction angle δ', together with a component α' which is independent of the normal stress. This component α′ is often called cohesion but is more usefully regarded merely as an intercept on the shear stress axis, which defines the position of the failure envelope.

The nomenclature used in this paper is as follows:

δ'_p Peak friction angle of the interface
α'_p Peak cohesion intercept of the interface
δ'_r Residual, or large strain friction angle of the interface
α'_r Residual, or large strain cohesion intercept of the interface

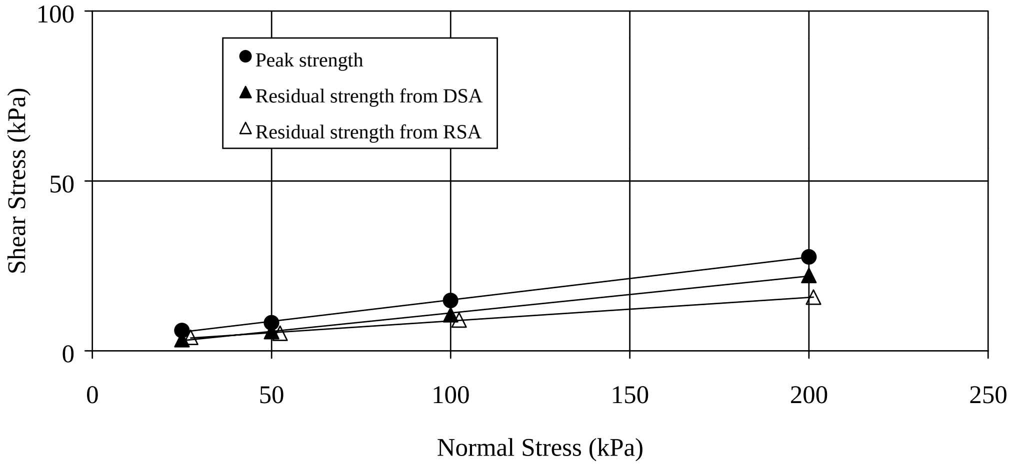

Figure 4. Typical shear stress vs. normal stress for smooth geomembrane/geotextile interface.

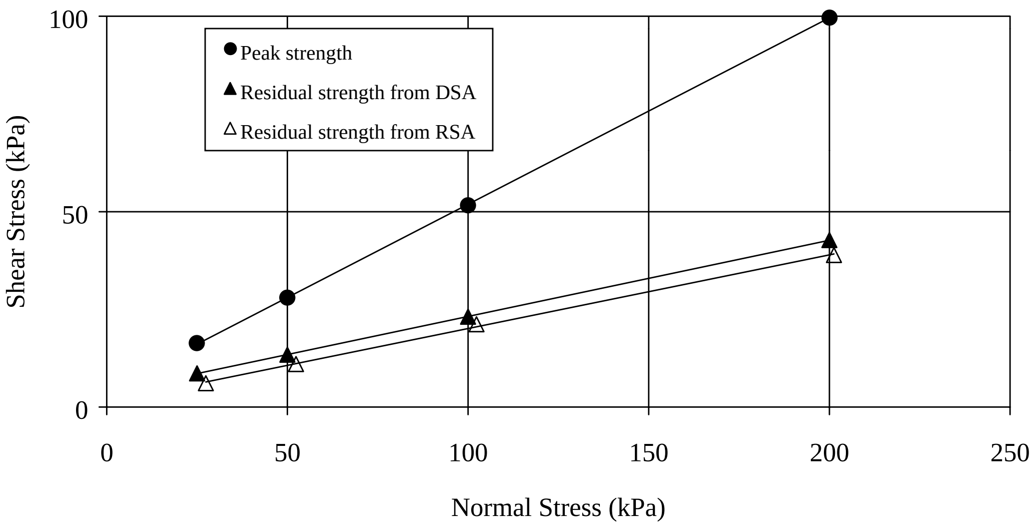

Figure 5. Typical shear stress vs. normal stress for textured geomembrane/geotextile interface.

Typical shear stress vs. normal stress plots for a smooth geomembrane/geotextile interface are given in Figure 4. Peak shear strengths measured using the DSA are plotted together with large strain shear strengths using both DSA and RSA, and linear regression has been used to develop the best fit line through the data. The accuracy of the linear representation of the shear strength data can be described using the coefficient of determination, R^2. The coefficient of determination represents the fraction of the total variation accounted for by the fitted equation. An R^2 value of 0.990 indicates that 99% of the total sum of squares of shear stresses is accounted for by this equation.

A typical shear stress vs. normal stress plot for a textured geomembrane/geotextile interface is given in Figure 5. It is clear that there is a much greater reduction from the peak shear strength to the residual measured using the DSA; with a slight further reduction for the residual strength measured using the RSA.

A summary of the results from the testing programme is given in Table 1. The DSA results are the mean values taken from tests using three different cover soils above the geotextile. For the smooth geomembrane, the large strain friction angle for the 750 g/m^2 interface for the DSA tests was 6°, while the RSA tests gave a friction angle two degrees lower. The 1200 g/m^2 geotextile RSA tests also gave a lower friction angle than the DSA tests.

The results for the impingement textured geomembrane indicate the residual shear strength of the interface with both the 750 g/m^2 and 1200 g/m^2 materials has a friction angle ranging from 10° to 12° with cohesion intercept values in the region 1 kPa to 6 kPa.

The large strain shear strength developed in the DSA tests are greater than the strength measured in the RSA, however the calculated friction angle is lower. This is because of the high cohesion intercept value of 5.8 kPa calculated in the DSA test. This can be attributed to the "Velcro effect" of interlocking between the asperities of the textured geomembrane and the tangled fibres of the non-woven geotextile. The continual rotation of the RSA will break these interlocks which may not be completely destroyed in the DSA even after 100 mm of displacements.

Table 1. Summary of interface shear strength parameters

Geomembrane	Geotextile	Test	δ'_r (°)	α'_r (kPa)	R^2
Smooth	750g/m^2	DSA	6.2	-0.2	0.993
		RSA	4.0	1.9	0.998
	1200g/m^2	DSA	4.8	-0.1	0.963
		RSA	3.0	1.7	0.998
Impingement	750g/m^2	DSA	10.5	5.8	0.961
Textured		RSA	11.7	0.8	1.000
	1200g/m^2	DSA	10.0	5.8	0.987
		RSA	-	-	-
Coextruded	750g/m^2	DSA	10.9	3.9	0.992
Textured		RSA	10.7	1.2	0.999
	1200g/m^2	DSA	11.5	3.7	0.983
		RSA	9.0	0.8	0.970

The coextruded textured geomembrane tests gave a range of large strain friction angles from 9° to 12° with cohesion intercept values varying from 0.8 kPa to 3.9 kPa for the two geotextiles. Again, the RSA results produced the lowest cohesion intercept values for these tests.

It has been shown previously (Jones & Dixon, 1998) that the particle size and shape of the cover soil above the geotextile can influence the interface shear strength. In order to assess this variable, a series of DSA tests were carried out with a nylon block above the geotextile. A comparison of these results with the DSA tests is given in Table 2.

The use of a nylon block as the cover material in DSA tests on both smooth and textured geomembranes, produces consistently higher large displacement interface shear strengths than the RSA tests. Both test set-ups involved the application of normal stress through rigid planar elements (i.e. a 100 mm deep nylon block in the DSA, and a steel platen in the RSA). The large differences in measured shear strength are considered to be due to the degree of fixity between the geotextile and the load platens. In the nylon block tests the interface between the geotextile and nylon is relatively weak, thus allowing the geotextile to stretch, whereas the geotextile was glued to the load platen in the RSA tests.

Table 2. Comparison of results with no cover soil

Geomembrane	Geotextile	Test	δ'_r (°)	α'_r (kPa)	R^2
Smooth	750g/m^2	DSA	6.1	1.3	0.991
		RSA	4.0	1.9	0.998
	1200g/m^2	DSA	6.5	-0.4	0.998
		RSA	3.0	1.7	0.998
Impingement Textured	750g/m^2	DSA	17.4	0.6	0.995
		RSA	11.7	0.8	1.000
	1200g/m^2	DSA	14.7	2.9	0.999
		RSA	-	-	-
Coextruded Textured	750g/m^2	DSA	15.0	4.1	0.994
		RSA	10.7	1.2	0.999
	1200g/m^2	DSA	14.1	4.8	0.999
		RSA	9.0	0.8	0.970

A number of the shear stress vs. displacement relationships from the DSA tests undertaken using a nylon block provide evidence of geotextile stretching. The DSA nylon block tests also produce higher shear strengths than the DSA tests involving cover soils. This can also partially be explained as a result of geotextile stretching, as interaction between the soil particles and geotextile prevents significant stretching from occurring. The remaining difference being due to the cover soil particles having an influence through the geotextile (Jones & Dixon, 1998).

4 DISCUSSION

The loss of interface shear strength with displacement can be quantified by considering the strain softening coefficient, D where:

$$D = \frac{\tan \delta'_r}{\tan \delta'_p} \qquad (2)$$

The smooth geomembrane/geotextile interface results give strain softening coefficients ranging from 0.43 to 0.80 with a mean value of 0.6, see Table 3. The mean soil results have been used as the DSA results, and these peak values have been used to calculate the D ratio for both the DSA and RSA results. There is greater loss of shear strength for the geomembrane/geotextile interface when textured geomembranes are used. The D values for the two types of textured geomembranes range from 0.33 to 0.43 with a mean value of 0.4.

Table 3. Calculated values of strain softening coefficient, D

Geomembrane	Geotextile	Test	δ'_p (°)	δ'_r (°)	$\tan\delta_r/\tan\delta_p$
Smooth	750g/m^2	DSA	7.7	6.2	0.80
		RSA	-	4.0	0.52
	1200g/m^2	DSA	7.0	4.8	0.68
		RSA	-	3.0	0.43
Impingement Textured	750g/m^2	DSA	25.8	10.5	0.38
		RSA	-	11.7	0.43
	1200g/m^2	DSA	24.7	10.0	0.38
		RSA	-	-	-
Coextruded Textured	750g/m^2	DSA	24.5	10.7	0.41
		RSA	-	10.7	0.41
	1200g/m^2	DSA	25.9	11.5	0.42
		RSA	-	9.0	0.33

It is suggested that the D values could be used at preliminary design stage to estimate the residual friction angle based on knowledge of the peak friction angle from the literature. For this purpose, D values of 0.7 and 0.4 could be used for smooth and textured geomembrane/geotextile interfaces respectively. It should be noted however, that this approach does not take into account any cohesion intercept that the interface may have, and since the majority of interfaces have positive cohesion intercepts, this will therefore tend to give conservative values.

A comparison of DSA and RSA methods for obtaining large displacement interface shear strengths has indicated significant differences in the measured values. These differences can partially be attributed to aspects of the test set-up such as fixity of the geotextile, presence of cover soil, grading and particle shape of cover soil (Jones & Dixon, 1998a) and direction of shearing. (i.e. rotational/linear).

However, there is also a degree of idealisation inherent in analysis of DSA results. The shear box used for this study had a top box 300mm x 300mm in plan area and a bottom box 300mm x 400mm. This allows a maximum displacement of 100mm without a change in the shear area of the interface. However, this does not mean that at the end of a test there has been 100mm relative displacement between the geotextile and geomembrane over all parts of the interface. As the test progresses the geosynthetic attached to the top box shears over a region of ‘virgin’ geosynthetic (i.e. material that was initially outside the footprint of the top box).

It is common practice to attach the geotextile to the top box.. This minimises the above affect as the shear surface of the geotextile remains constant, with all parts experiencing 100mm of displacement relative to the geomembrane. This is particularly important for tests including textured geomembranes because it is alignment of the geotextile fibres, combed by the asperities, that is responsible for much of the drop from peak to residual conditions. However, it must still be remembered that reductions in shear strength of the geomembrane surface (i.e. polishing of smooth geomembranes and flattening of the asperities on textured material) will be non-uniform across the interface. Due to these affects it is not possible for the DSA to produce true residual shear strength conditions over the entire shear area, and hence the DSA results will always be higher than the RSA results. ‘Residual’ shear strength parameters obtained from DSA tests will therefore be unconservative. The degree of error will depend upon the properties of the materials tested.

Results from the RSA are considered to be lower bound values because of the very large displacements achieved and due to the effect of cover soils not being modelled. In addition, once the RSA has rotated through 360° the geotextile fibres have undergone realignment due to combing by the geomembrane asperities. The observed subsequent reduction in shear strength has been attributed to polishing and fibre loss effects. This mode of shearing is an extreme case and possibly does not model the field condition of a linear shear direction, where the random nature of most geomembrane texturing would result in continuing fibre tangle even after large displacements.

Although “true” residual interface shear strengths can only be measured using a RSA, the design engineer must decide whether these values should be used in stability analysis. The mechanism of shearing in the RSA is not comparable to that exhibited in the field and therefore the use of RSA derived residual strengths may be over-conservative.

5 SUMMARY

Results of laboratory testing of the interface shear strength between geomembranes and geotextiles have been reported. The large strain interface shear strengths have been measured using a direct shear apparatus and a ring shear apparatus. It has been shown that the results of RSA testing always gives a lower interface shear strength, however the designer needs to consider whether this method of shearing is comparable to the shearing expected on site.

As an aid to the design engineer, values of the strain softening coefficient D have been calculated and values of 0.7 and 0.4 are suggested as values to be used in preliminary design for the interface shear strength between geotextiles and smooth and textured geomembranes respectively.

Site specific testing should always be carried out at detailed design stage to verify any assumptions made during preliminary designs. Further, the full stress vs. displacement relationship for each test should always be presented in order to enable an assessment of whether residual conditions have been reached, and hence to allow a rigorous analysis of the lining system.

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