INTERFACE FRICTION OF SMOOTH GEOMEMBRANES AND OTTAWA SAND

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Abstract *– Geomembranes commonly used in civil engineering constructions are mostly in contact with soils. Some constructions failed due to slippage between geomembrane sheets and interfacing soils. This paper aims at presenting the interface strength of various geomembranes and Ottawa sand resulting from tests with the ring shear device. The interface strength is generally governed by the stiffness, the texture of geomembranes and the imposed stress level. It was found that residual friction angles, $\delta_{residual}$, for the interfaces varied from 10.5° to 28.1° or 0.34 to 0.97 in efficiency ratio. The lower value is for a smooth HDPE, the higher value is mobilised by a soft PVC at higher stresses.*

Keywords: Interface, Geomembranes, Ottawa Sand

BACKGROUND

The uses of geomembranes, geosynthetic materials, have been common in civil engineering constructions (Koerner 1990; Sarsby 2007). In the applications, the materials are mostly in contact with soils. In designs, however, the interface friction behaviouris often forgotten to consider. This led to failures of several constructions, for instance the slippage of landfill facility at the Kettleman Hills, California (Seed 1988). It was identified that the slippage occurred in the liner system, i.e. at its geosynthetic zone. Due to limited references, it is not rare that engineers shoulduse some reduction (i.e., $\frac{1}{2}$ or $\frac{2}{3}$)to the internal friction angle of the interfacing soil as suggested in text books (Bowles 1997; Das 2007). Careful consideration should be taken when specific soils or geomembranesare used since some researchers found that reduction factor could be lower than $\frac{2}{3}$ or even less than $\frac{1}{2}$ (Martin, Koerner, and Whitty 1984; Negussey 1988; Rinne 1989; O'Rourke and Druschel 1990; Druschel and O'Rourke 1991).

Most of the data obtained by the before mentioned researchers resulted from direct shear tests where the residual strength hardly exhibited. Very few data are published from ring shear tests at large displacement. In contrary to that obtained from the ring shear device, the shear displacement from the direct shear test is very limited. Often, the residual tails of the strength-horizontal displacement relationship are not apparent. In this research, the ring shear device was deployed in order to simulate the field condition where the residual strength is reached at large displacement. The Ottawa sand was used as an interfacing soil.

LITERATURE REVIEW

Several researchers have reported the interface strength of Ottawa sand with various types of geomembranes. The well-referenced data are those reported by Martin et al. (1984)from their investigation on various geomembrane sand soils using a modified direct shearapparatus. The stress levels used in the tests ranged from 13.8 kPa to 103.5 kPa. They found the interface friction angles of the Ottawa sand with a smooth HDPE geomembrane was 18°.

Using the UBC ring shear device, Negussey et al. (1988) conducted a test on the interface between an HDPE geomembrane and Ottawa sand. At a normal stress of 50 kPa, they observed that the interface exhibited a peak friction angle of 17.6° and a residual value of 15°. The peak value seems to agree with that found by

Martin et al. (1984), however the residual value does not. Rinne (1989) observes that Martin et al. (1984) possibly failed to simulate large displacements by reversing the direction of shearing in their direct shear box .This comment might be true since Martin et al. (1984) did not mention the maximum displacement obtained in testing. In his study, Rinne (1989) found that the residual interface strengths of the Ottawa sand with smooth HDPE and with PVC were dependent on stress levels. For normal stresses of 100 and 750 kPa, he measured the residual friction angle of the Ottawa sand with smooth HDPE as 14° and 18° respectively. These findings are a little different to, but in reasonable agreement with, those of Negussey et al. (1988). The variation might arise from different properties of the HDPE geomembranes used: detailed properties of the geo-membranes used in these studies are not provided. In the tests on the interface of PVC with the Ottawa sand, Rinne (1989) found residual interface friction angles between28° and 29° for stress levels of 100 and 500 kPa: these values are the same as those obtained from tests on the Ottawa sand alone.

Druschel et al. (1990) and Druschel and Rourke (1991) report tests on 450 geomembrane-sand interfaces, using a 60-mm-square shear box with a strained-controlled displacement system. Accounting for the low stresses that are typical in covers of waste impoundment facilities, the tests were conducted at normal stresses ranging between 3.5 and 35 kPa. Four sands were used in the tests; one of them was Ottawa sand. The geomembranes were smooth HDPE (pipe and lining), MDPE, and PVC (pipe and lining) polymers. They found ϕ = 35° and δ= 19° (peak values) for the tests on the Ottawa sand alone and the interfaces of the Ottawa sand either with the smooth HDPE lining or with the smooth HDPE pipe respectively. A higher peak friction angle of 30° was found on the interface of the PVC lining-Ottawa sand; on the other hand, a peak δ = 17° was observed for the test on PVC pipe-Ottawa sand. They further observed the effect of surface hardness on the ratio of interface to the sand friction angle (δ/ϕ): for this purpose they also include epoxy and plexiglas acrylic. They found that the ratio was dependent on the surface hardness of the geomembranes; the harder materials exhibited lower ratios.

TESTING PROGRAMS

Ring Shear Device

A ring shear device was deployed to investigate interface strength of geosynthetics and sand. The device was originally designed by Bosdet (1980) and used to measure the strength of fine-grained soils. Its major components are schematically shown in Figure 1. In order to measure the constant volume of friction angle for cohesionless materials, Wijecwickeme (1986) then modified the device. He altered the upper confining rings (see Figure 1) which were originally fixed to the moment transfer arms, so that granular soil sample could also be prepared by pluviation. Another multi purpose modification was the inclusion of a bolt to connect the bottom load cell to the bottom base plate, in order tomeasure the upward load caused by dilation during tests on granular materials such as sand.

The modifications also include an upgrading of the gearhead and the chain drive to cope with the high friction that can develop during shear of granular materials. Negussey et.al (1989) and Rinne (1989), in separate studies, used the device to investigate the behaviour and interface strength between granular materials and geosynthetics

The current arrangement of the ring shear device is shown schematically in Figure 1, together with the data acquisition system. The major components of the device are used to impose normal stresses and rates of strain, and monitor the horizontal forces andvertical displacements that develop with increasing radial displacement. Normal loads are imposed from air pressure in a chamber mounted on top of the apparatus, and transmitted through a piston and loading yoke to the sample.

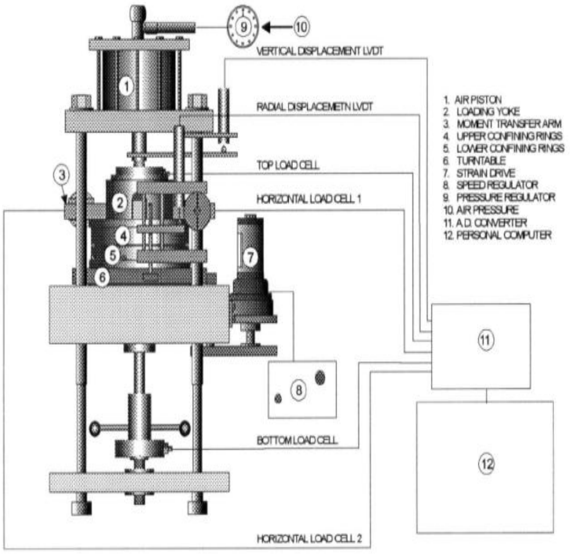


Figure 1. Major components and data acquisition system of the ring shear device

The magnitude of normal load is controlled by a regulator and recorded with a load cell located on the top of the loading yoke. Tomonitor any load that might be developed by friction between the outer and the inner surface of the sample and the upper confining rings, the so-called bottom load cell was installed. The net normal load is the difference between the reading of the top load cell and the bottom load cell. Normal stress is determined knowing the net load and the cross-sectional area of the sample. The capacity of each load cell used in this observation is 1000 lbs.

Materials

The interfacing soil used in this study was the Ottawa C-109 sand and 3 types of smooth geomembrane are VLDPE, PVC, and smooth HDPE.

Ottawa Sand

The granular material used in the study was the Ottawa C-109 sand. A particle size distribution curve from sieve analysis of the sand is shown in Figure 2. The coefficient of uniformity C_u, and coefficient of curvature C_c for the sand are 1.6 and 0.9 respectively; according to the USCS (ASTM D-2487), the soil is classified as SP, a poorly or uniformly graded sand.

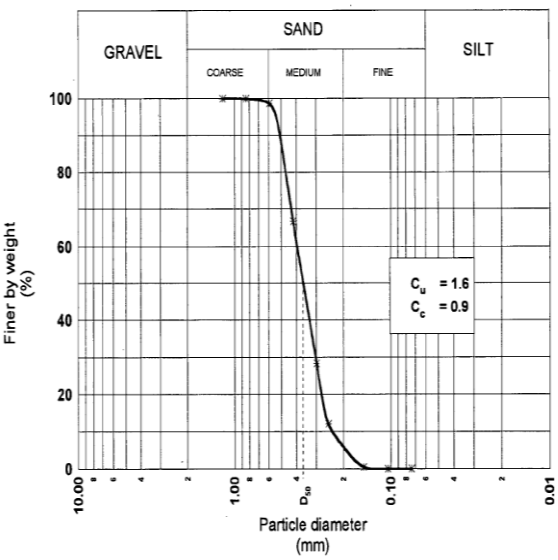


Figure 2. Particle distribution of Ottawa C- 109 sand

Geomembranes

The geomembranes interfacing the Ottawa sand during tests were smooth polyvinyl chloride (PVC), smooth very low-density polyethylene (VLDPE), and smooth high-density polyethylene (HDPE). Although the PVC is described as having a smooth surface, in fact it has slightly rougher surface than the other smooth materials. In addition, it could also be classified as the most flexible material of all geomembranes used in the test program. In comparison, the VLDPE is stiffer and smoother; it is classified as a semiflexible material. Yet, of all above-mentioned geomembranes, the smooth HDPE is the smoothest, the stiffest, and the hardest material. Material properties for all of the geomembranes and geotextiles are documented in Table 1.

Table 1. Properties of geomembranes (GFR 1993)

Manufacturer	Product name	Polymer type	Thickness*) mm	Texture	Specific gravity ASTM D792	Pucture resistance FTMS 101C kN (lb)
Columbia Geosystem Inc.	HDPE 80 mil	HDPE	2.03	smooth	0.940	0.40 (90)
Columbia Geosystem Inc.	60 mil VLDPE	VLDPE	1.52	smooth	0.915	0.35 (78)
Canadian General Tower Ltd.	Geoliner 60	PVC	1.52	smooth	1.238	0.44 (100)

***) ASTM D751, except Geoliner 60: D1593**

Sample Preparation

The general arrangement of the sand sample and a geomembrane specimen for a ring shear test is illustrated in Figure 3 (a). It shows the sample placed in the upper or the top confining rings and the specimen glued to an annular steel base (see Figure 4) in the bottom confining rings. In the case of tests on sand alone, the geomembrane specimen was replaced by the sand.

(a)

(b)

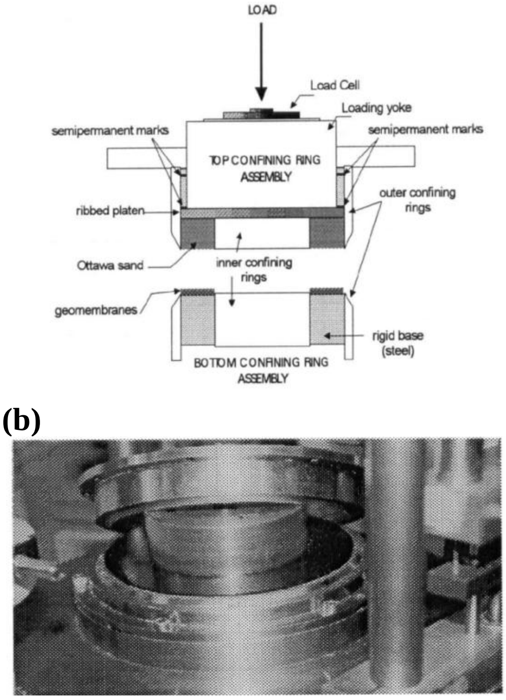


Figure 3. (a) Alternative setups of soil sample and geomembrane specimens for the ring shear tests. (b) Photograph of a geomembrane specimen in the lower confining rings.

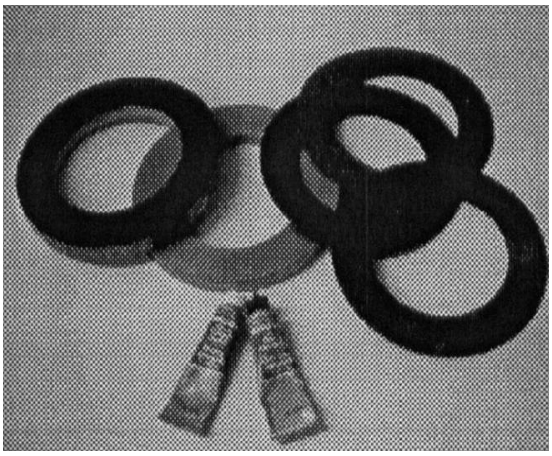


Figure 4. Specimens of geomembranes glued on annular steel platens using epoxy resin

Placement of the Sand

For the tests on the Ottawa sand-geosynthetic, the sand was prepared by air pluviationinto the upper confining rings that were aligned and connected with two pairs of pins to the lower confining rings. As mentioned in the previous section and illustrated in Figure 3a, the geosynthetic specimens were setup on the bottom confining ring assembly. Air pluviation was selected because the soil is uniformly graded and the technique generates repeatable samples. To replicate densities for all tests, the pluviation drop height was maintained at approximately 1 cm.

Levelling (see Figure 5) of the soil sample was carried out using a vacuum device, to siphon off the surplus soil to the targeted thickness of 1 cm. Final steps in the preparation routine were installing the loading yoke with a ribbed porous platen (see Figure 1 or Figure 3) and removal of the pins that were used to connect the upper and lower confining rings during pluviation.

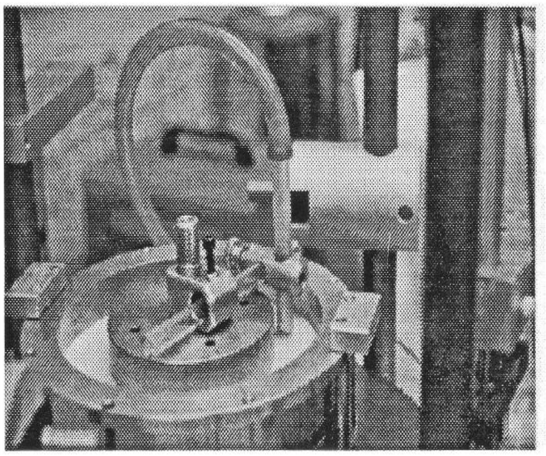


Figure 5. Removal of surplus of sand using a vacuum device to level the sample

To avoid friction between the upper and the lowerconfining rings during testing, the upper confining rings were raised to create a gap of about 0.03 mm. This gap was set from a consideration of the particle size of the Ottawa sand (see Figure 3.3), in order to minimize loss of particles.The same procedures were applied to tests on the Ottawa sand alone. The difference was that the lower confining rings were also filled with sand. Again with a height of 1 cm in the lower confining rings, the final thickness of the sample was 2 cm.

Testing Procedures

Interface strength was examined at different values of normal stress, and with reference to rate of shear. Normal stresses used in this program of testing ranged generally from 50 kPa to 200 kPa; lower stresses of 10 to 25 kPa or higher stresses to 400 kPa were occasionally applied. To more efficiently understand the residual strength of a given interface, multi stage tests that had step wise increments of normal stresses were used to optimize the value of each set-up. Unless stated otherwise, a rate of shear of 0.04 mm/s or 2.4 mm/min was selected forall tests in this investigation. The rate of strain was found by Negussey et al. (1988) and Rinne (1989), using the same device, not to affect the interface friction angle of Ottawa sand and geomembranes.

Results and Discussions

Incomparing results from this work on Ottawa sand with other studies, normalized values of the interface friction angles to that of the given soil are used, resulting in a non-dimensional factor E known as the efficiency ratio. This ratio is expressed as

$$E = \frac{\tan \delta}{\tan \phi} \qquad (1)$$

where

E = efficiency ratio,

δ = interface friction angle between geomembrane and soil (°),

ϕ = internal friction angle of soil (°).

Values ofϕ_{residual} for deriving this ratio in each test are based on best fit line to datafrom tests on the Ottawa sand alone. In the following presentation of test data on residual interface friction angles, and inorder to better appreciate the interface behaviour, the discussion of each geomembrane interfaceis usually preceded by a typical relationship between interface friction angles and shear displacement.

Table 2 illustrates codes used for the tests reported in this chapter. The first and second column represent the materials used in a test, and the third column denotes the approximate normal stresses in kPa. The fourth and the fifth columns describe the procedure of loading (S = multistage loading) and the sequence of tests respectively (for those tests that were repeated). The materials, as listed in Table 2, are

SAND = Ottawa sand (soil only, no geosynthetic),
HD = smooth HDPE,
VL = VLDPE,
PV = PVC,

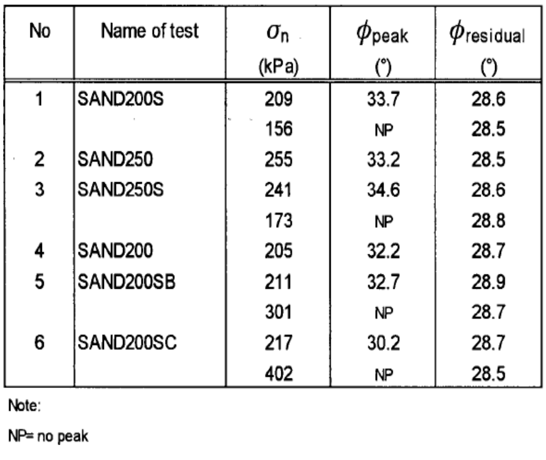
Table 2. Test code for ring shear tests on the Ottawa sand with different geosynthetics.

1	2	3	4	5
SAND HD VL PV	SP	50 100 150 200 250 300	S	B C D

Since the code *SAND* only represents the test on Ottawa sand alone, it does not need thecode in the second colum. The third, fourth, and the fifth columns designate the stress levels in kPa, a multistage loading (S), and the sequence oftests respectively. Hence the code *HDSPI00SB* means that the second test on the smooth HDPE-Ottawa sand interface was performed by applying staged stress levels initiated from approximately 100 kPa.

A determination of E in equation (1) requires a value of ϕ for the Ottawa sand. Mobilized values of ϕ under stress levels from about 100 kPa to 400 kPa are reported in Table3.

Table 3. Summary of internal friction angles from ring shear test on the Ottawa sand



No	Name of test	σ_n (kPa)	ϕ_{peak} (°)	$\phi_{residual}$ (°)
1	SAND200S	209	33.7	28.6
		156	NP	28.5
2	SAND250	255	33.2	28.5
3	SAND250S	241	34.6	28.6
		173	NP	28.8
4	SAND200	205	32.2	28.7
5	SAND200SB	211	32.7	28.9
		301	NP	28.7
6	SAND200SC	217	30.2	28.7
		402	NP	28.5

Note:

NP= no peak

A typical curve relating ϕ to shear displacement, from one ofthe tests on Ottawa sand,is presented in Figure 6. A peak of ϕ is mobilized at a displacement of approximately 2 mm; a constant value of ϕ, known as the residual interface friction angle, generally initiates from a displacements of about 10 to 20 mm.

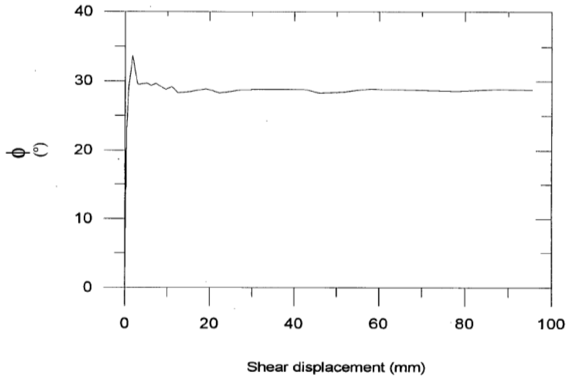


Figure 6. Variation of internal friction angle with shear displacement from a test on Ottawa sand (SAND200S)

Figure 7 illustrates the values of $\phi_{residual}$ listed in the Table 4. The values vary from 28.5° to 28.9°, showing a good agreement with values for Ottawa sand found by Wijewickreme (1986) and Rinne (1989) of 29.9° and 29° respectively, for similar stresses using the same device.This finding verifies the repeatability and the reliability of the apparatus. There sults indicate that values of $\phi_{residual}$ are essentially independent of stress level, for the range used intesting. The line of best fit to the results is given by $\phi_{residual}$ of 28.5°.

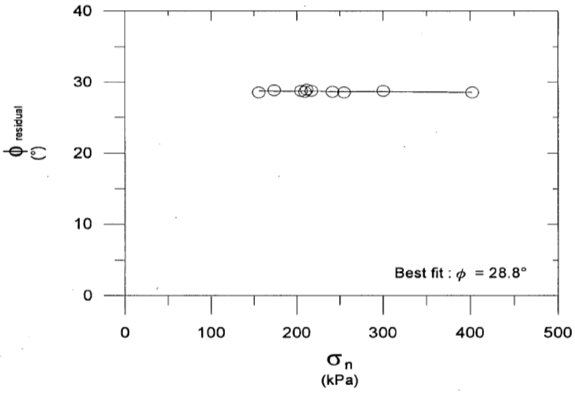


Figure 7. Residual interface friction angles from ring shear tests on the Ottawa sand

Ottawa Sand-Smooth Geomem-branes

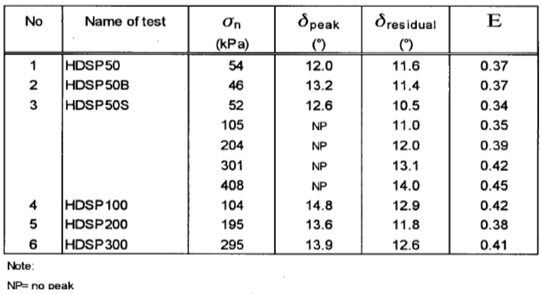
Geomembranes used in this series of tests were smooth HDPE, VLDPE, and

PVC. To allow comment on the effect of stiffness and hardness of the specimens, a series of tests were also performed on an Ottawa sand-steel interface.

Ottawa Sand-HDPE

Ring shear tests on the Ottawa sand-HDPE interface were performed for normalstresses between 46 kPa and 295 kPa in five single stage tests, and from 52 kPa to 408 kPa in one multistage test, see Table 5. A typical result is shown in Figure 8. The interface exhibits a maximum frictionangle at a displacement of about 2 mm and gradually develops residual friction there after.

Table 4. Summary of interface friction angles and efficiency ratios from ring shear tests on Ottawa sand-smooth HDPE



No	Name of test	σ_n (kPa)	δ_{peak} (°)	$\delta_{residual}$ (°)	E
1	HDSP50	54	12.0	11.6	0.37
2	HDSP50B	46	13.2	11.4	0.37
3	HDSP50S	52	12.6	10.5	0.34
		105	NP	11.0	0.35
		204	NP	12.0	0.39
		301	NP	13.1	0.42
		408	NP	14.0	0.45
4	HDSP100	104	14.8	12.9	0.42
5	HDSP200	195	13.6	11.8	0.38
6	HDSP300	295	13.9	12.6	0.41

Note:
NP= no peak

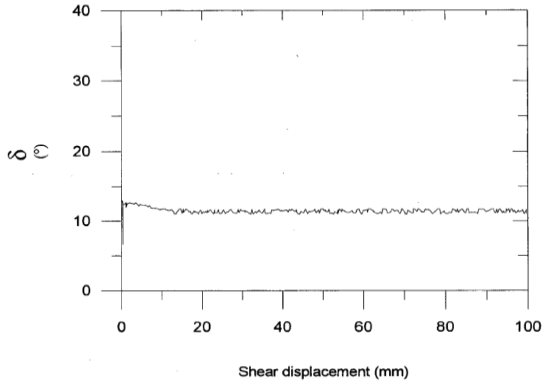


Figure 8. Variation of interface friction angle with shear displacement from a test on Ottawa sand-smooth HDPE (HDSP50B)

Values of $\delta_{residual}$,as reported in Table5, are plotted in Figure 9. They vary from10.5° to 14° and reveal a dependency $\delta_{residual}$ on stress level: a greater friction angle is exhibited at higher stress levels. A residual interface friction of 15° was found by Negusseyet al (1988), using the same UBC ring shear device, for a 60-mil HDPE-Ottawa sand undera normal stress of 50 kPa. Again, using the same device, Rinne (1989) observed a $\delta_{residual}$ of14° and 18° for stress levels of 100 kPa and 750 kPa respectively for tests on 20 to 100-mil HDPE with Ottawa sand. William and Houlihan (1986) reported δ = 19° from their test on HDPE-Ottawa sand (see Ingold 1991). Using a modified direct shear apparatus, Martin et al (1985) observed δ= 18° from their test on Ottawa sand with a 20-mil HDPE, under normal stresses varying from 13.8 to 103.5 kPa.

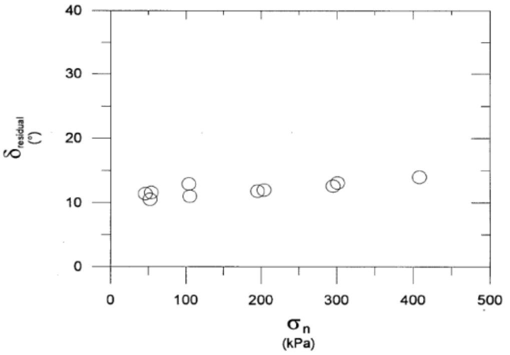


Figure 9. Residual interface friction angles from ring shear tests on Ottawa sand-HDPE

Unfortunately, a detailed comparison of results is precluded, because no information is reported on mechanical properties of the other geomembranes such as puncture resistance. Greater $\delta_{residual}$ are anticipated when higher normal stresses are applied, as a result of more scour on the surface of geosynthetic specimen at higher stress levels.

A determination of efficiency ratios shows them to be less than unity, see Figure 10. The ratios, from 0.34 to 0.46, imply that the shearing occurred at the interface. Martinet al. (1984) report *E* = 0.64 small direct shearbox tests. However it is believed this higher ratio may stem from an inability to achieve a true residual friction angle by repeated reversals in the direction of shearing. In contrast, Rinne (1989) implies that E = 0.45 for Ottawa sand with an HDPE at a normal stress of 100 kPa.

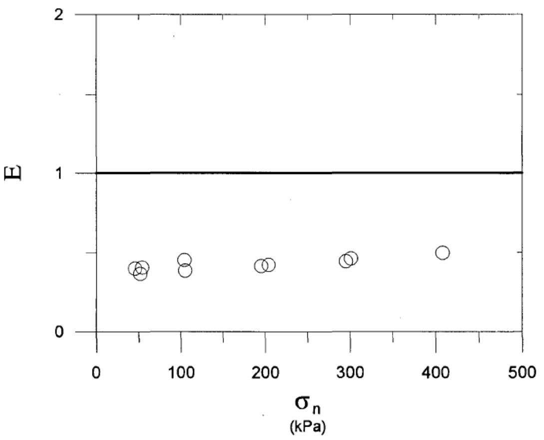


Figure 10. Efficiency ratio of Ottawa sand- HDPE

Ottawa Sand-VLDPE

Nine ring shear tests were conducted on an Ottawa sand-VLDPE interface with normal stresses in the range 50 kPa to 200 kPa. Figure 11 shows a typical curve of interface friction angle versus shear displacement from the test VLSP50B. A noticeable peak value of o is found at a displacement of 2 to 3 mm, decreasing to a constant, residual value at approximately 20 mm.

A summary of results for o and the corresponding efficiency ratios are reported in Table 6. Values of δ_{residual} are plotted against normal stress in Figure 11: they vary from13.5° to 17.9° depending on the applied stress level. At about 50 kPa, the interface exhibited a δ_{residual} of 14.6° in average, increasing to 17° and 17.8° for normal stresses of about 100 kPa and 200 kPa respectively. The dependency of δ_{residual} on stress level is attributed to the somewhat softer surface of the specimens and the consequent susceptibility of the specimens to scour. Deeper circumferential grooves were found on the surface of the geomembrane after the completion of each test at higher normal stresses. Compared with the hard surface of the smooth HDPE, that of the VLDPE is slightly softer, and hence more prone to scour. Intests on a combination of Ottawa sand and an EPDM geomembrane, Martinet al (1984)found that the value of δ was 20° at normal stresses varying from 13.8 to 103.5 kPa: it is likely there was a stress dependency in those results, but the author provides no details. Similar values could be achieved by the Ottawa sand-VLDPE at interface higher normal stresses.

Efficiency ratios (*E*) of the interface are shown in Figure 12, and the values are seen to vary from 0.43 to 0.59. Again they are well below unity, and suggest that the shearing action is developed at the interface.

Table 5. Summary of interface friction angles and efficiency ratios from ring shear tests on Ottawa sand-VLDPE

No	Name of test	σ_n (kPa)	δ_{peak} (°)	δ_{residual} (°)	E
1	VLSP50	48	NP	14.3	0.46
2	VLSP50B	53	19.7	16.0	0.52
3	VLSP50C	49	17.6	13.5	0.44
4	VLSP100	103	19.6	16.5	0.54
5	VLSP100B	105	NP	17.8	0.58
6	VLSP100C	97	NP	15.8	0.51
7	VLSP100D	102	21.4	16.7	0.55
8	VLSP100E	97	21.0	17.9	0.59
9	VLSP200	197	NP	17.8	0.58

Note:
NP= no peak

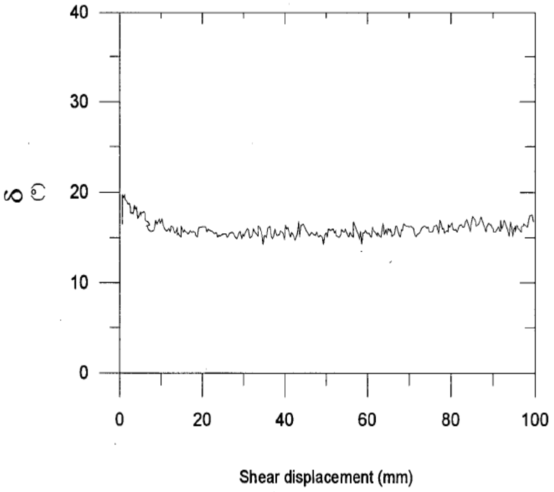


Figure 11. Variation of interface friction angle with shear displacement from a test on Ottawa sand-VLDPE (VLSP50B)

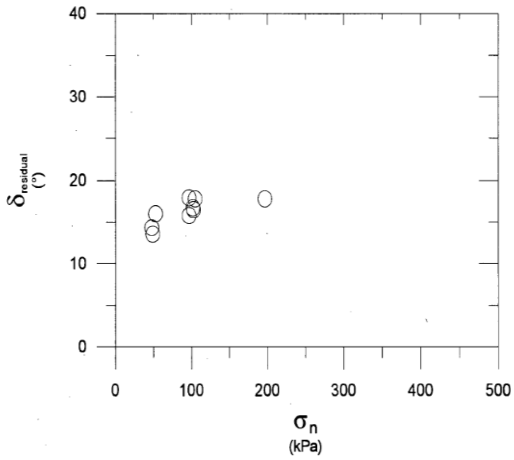


Figure 12. Residual interface friction angles from ring shear tests on Ottawa sand-VLDPE
Ottawa Sand-PVC

Measured values of interface friction angles (δ) from one test on Ottawa sand-PVC, again at 50 kPa, are shown in Figure 13. The peak values of δ were generally found at displacements of 2 to 3 mm. A behaviour that is similar to the previous tests on Ottawa sand with other geomembranes is evident, with a constant value of δ mobilized at a displacement of about 20 mm. Thereafter the values remain constant to the end of a test, typically at a displacement of more than 300 mm.

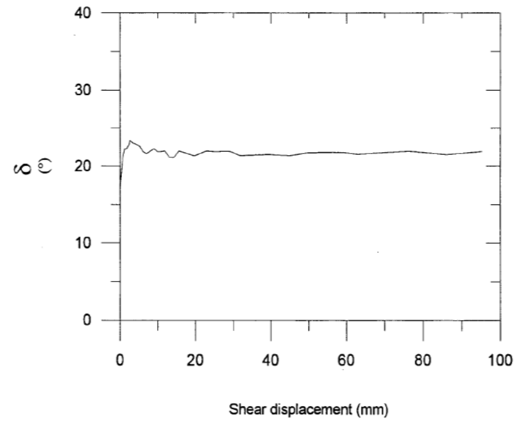


Figure 13. Variation of interface friction angle with shear displacement from a test on Ottawa sand-PVC (PVSP50)

A summary of one multistage test and 5 single stage tests is given in Table 7, and the residual values, $\delta_{residual}$ are plotted against stress level in Figure 14. Again, a dependency of $\delta_{residual}$ on stress level is evident. This can be concluded from the increase in values of $\delta_{residual}$ from 21° to 28.1° with increasing normal stresses from 50 to 223 kPa. Ingold (1991) reports findings from the observations of Williams and Houlihan (1987): the friction angle mobilized at the interface of PVC with Ottawa sand is 26° which still falls into the range of the results in this testing program. However, the applied stress level is not mentioned in the paper. Using the same UBC ring shear device, Rinne (1989) conducted tests onthe interface of the same soil with a similar (but not identical) PVC. He found values of $\delta_{residual}$ of approximately 29° under normal stresses of 100 and 500 kPa, which are the sameas his tests on the Ottawa sand. A similar behaviour was observed in this testing program:the values of $\delta_{residual}$ at high stress levels are equal to those obtained for the Ottawa sand, seenFigure 15, showing the efficiency ratio with applied stress levels. The ratios at stresses from 104 kPa to 223 kPa vary between 0.90 and 0.97, which are almost unity. A ratio of 0.9 is reported by Martinet al (1984) from their tests on the interface of PVC with concrete sand. In another investigation using a specially constructed flat shear device, Weiss and Batereau (1987) conducted tests on the interface of PVC film with sand, and obtained ratiosfrom 0.5 to 0.6 for low stress levels from 5 kPa to 50 kPa. The possibility of gaining the same ratios can be implied from the trend in Figure 15.

Table 6. Summary of interface friction angles and efficiency ratios from ring shear tests on Ottawa sand-PVC

No	Name of test	σ_n (kPa)	δ_{peak} (°)	$\delta_{residual}$ (°)	E
1	PVSP50	50	23.4	21.8	0.73
2	PVSP50B	50	24.2	21.0	0.70
3	PVSP50S	74	27.4	25.8	0.88
		104	NP	26.3	0.90
		202	NP	26.9	0.92
4	PVSP100	119	28.6	27.8	0.96
5	PVSP100B	125	29.3	27.9	0.96
6	PVSP200	223	30.0	28.1	0.97

Note:

NP= no peak

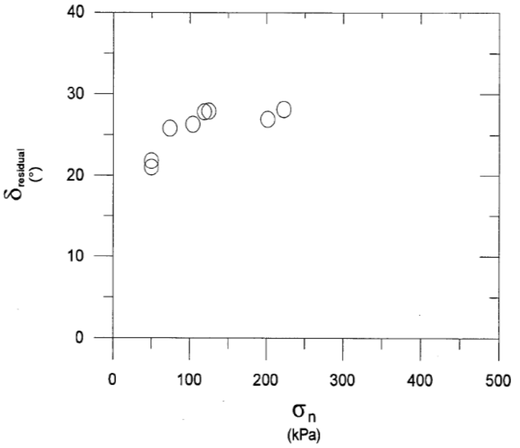


Figure 14. Residual interface friction angles from ring shear tests on Ottawa sand-PVC

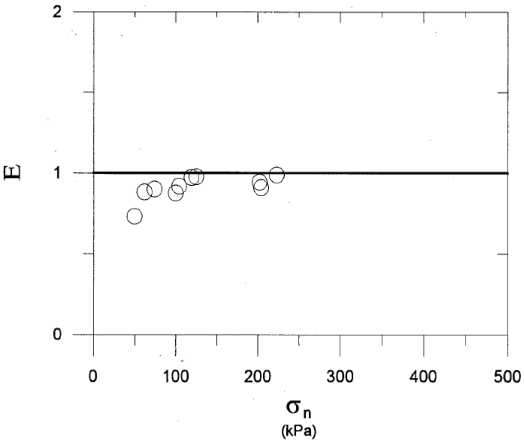


Figure 15. Efficiency ratio of Ottawa sand-PVC

After each test, visual inspection revealed the PVC specimens did not show any signs of scour like that found on the smooth HDPE- or the VLDPE-the Ottawa sand. Nevertheless, the very high friction was believed to be a result of softness ofthe material it was the softest geomembrane used through out this program of testing. At high stress levels the grains of sand tended to press down into the PVC specimen, see Figure 16 , and it is believed this phenomenon caused the shearing action to occur within the sand it self.

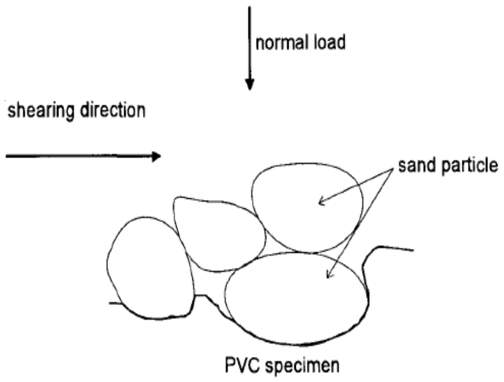


Figure 16. Sketch of shearing behaviour at the interface ofthe Ottawa sand-PVC

To better appreciate the influence ofstiffness and hardness of the geomembrane specimens on$\delta_{residual}$ several ring shear tests were performed on an Ottawa sand-steel interface. The results are reported in Table 8. A comparison of the residual interface friction angles with those from the previous tests on the three geomembranes-smooth HDPE, VLDPE, and PVC-is presented in Figure 17 in term of efficiency ratio and stress level. The data for the Ottawa sand-PVC and the Ottawa sand-VLDPE show a similar trend: both lines are steeper than that for the interface of the Ottawa sand-smooth HOPE. It can be concludedthat the softer specimen, the greater the increase of δ with normal stress. The best fit line for the Ottawa sand-steel data—the steel was the hardest specimen used in testing—furtherconfirms this response. There is no variation of δ with normal stress. The efficiency ratio isrelatively high compared to that of the smooth polyethylene geomembranes (HDPE and VLDPE). This is attributed to the roughness of the steel surface, and was verified by visual inspection using a microscope. Rinne (1989) has documented the influence of surface roughnessof prepared steel specimens on interface friction with different sands.

Table 7. Summary of interface friction angles and efficiency ratios from ring shear tests on Ottawa sand-soft steel

No	Name of test	σ_n (kPa)	δ_{peak} (°)	$\delta_{residual}$ (°)	E
1	STEEL	304	NP	18.1	0.60
2	STEELS	58	NP	18.1	0.60
		108	NP	18.1	0.60
		198	NP	18.0	0.59
		289	NP	18.0	0.59
		66	NP	18.1	0.60
3	STEELSB	58	NP	17.9	0.59
		108	NP	17.9	0.59
		209	NP	17.9	0.59
		298	NP	17.9	0.59

Note:
NP= no peak

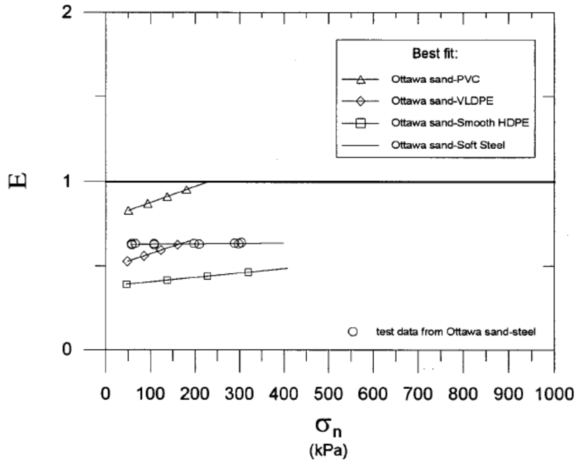


Figure 17. Comparison of interface behaviour for various materials from ring shear tests

CONCLUSIONS

The friction mobilised at the interface of the Ottawa sand with the geomembranes is apparently controlled by the stiffness, the texture of the geomembranes and stress level. The very stiff and smooth surface of the HDPE tended to exhibit the lowest interface friction varying from 34% to 45% (*E* = 0.34 to 0.45) of the residual friction angle of the Ottawa sand (ϕ_{average} = 28.8°). A higher residual friction between 44% to 59% of that of the Ottawa sand was mobilised in the tests with the VLDPE geomembrane: it is attributed to the relatively softer surface of this geomembrane. The same type of response is even more apparent in tests with the PVC, which was the softest material used in the program of testing. At normal stresses from 50 kPa to 223 kPa, the interface exhibited a residual friction resistance of 70% to 97% of the Ottawa sand. In all cases the interface strength of these smooth geomembranes was found to be dependent on stress level: the PVC was most dependent and the smooth HDPE least dependent. Test conducted on the Ottawa sand with steel confirmed that the level of stress dependency is also governed by the hardness of a material. Harder materials tend to exhibit less dependency on stress level.

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