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Dynamic Frictional Properties of Geosynthetic Interfaces Involving Only Non-geotextiles

지오텍스타일을 포함하지 않은 토목섬유 경계면의 동적 마찰 특성

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요 지

지오텍스타일을 포함하지 않은 토목섬유 경계면의 동적마찰저항과 전단변위속도, 그리고 여타 마찰특성의 상관성에 대한 실험적 연구를 수행하였다. 변위속도 조절이 가능한, 진동대를 이용한 진동식 실험장치를 제작하여 사용하였다. 다양한 변위속도를 포함한 실험을 수행한 결과, 지오텍스타일을 포함하지 않은 토목섬유 경계면은 지오텍스타일을 포함한 토목섬유 경계면의 전단특성과 확연히 구별되는 거동을 보였다. 지오텍스타일을 포함한 토목섬유 경계면과 달리 지오텍스타일을 포함하지 않은 토목섬유 경계면의 전단 거동은 전단 변위 속도에 민감하지 않으며 강-완전소성에 근사하다는 결론을 얻었다.

Abstract

Relationship between dynamic friction resistances and shear displacement rate, and other frictional characteristics of non-geotextile-involving geosynthetic interfaces was experimentally studied. A cyclic, displacement rate-controlled experimental setup built on a shaking table was used. The subsequent multiple rate tests showed that interfaces that do not involve geotextiles have distinct shearing characteristics that can be differentiated from the interfaces involving geotextiles. Unlike those of the geotextile-involving interfaces, shear behaviors of the interfaces involving only non-geotextiles tend to be not sensitive to shear displacement rate, and are approximately rigid-perfectly plastic.

Keywords : Dynamic resistance, Geomembranes, Geosynthetics, Interfaces, Shear strength

1. Introduction

In his previous papers, Kim reported pronounced displacement rate effects for geosynthetic interfaces that involve geotextiles (i.e., Kim 2003, Kim et al. 2005). He summarized that for geosynthetic interfaces involving geotextiles, the shear strengths increase nearly linearly with the log of displacement rate under the dry condition. This paper reports a follow-up experimental study that investigated the fundamental shear characteristics of the geosynthetic interfaces involving only non-geotextiles. Kim et al. (2005) briefly described some of the findings from that study only for comparison purpose. This paper reports all the remaining findings in details.

Experimental data on static and dynamic shear properties of geosynthetic interfaces have been compiled over recent decades (e.g., Martin at al. 1984, Mitchell et al. 1990, Koutsourais et al. 1991, Stark and Poppel 1994, De 1996, Yegian and Lahlaf 1992, Yegian and Kadakal 1998, Kim 2003, Seo et al. 2002). The achievement and limitation of the previous research were well summarized by Kim (2003), and therefore are not iterated

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here to save space. It is, however, noted that no comprehensive study has yet been made to investigate a probable dependence of dynamic friction resistance of the non-geotextile-involving geosynthetic interface on shear displacement rate. Hence, an experimental study of dynamic frictional behavior of geosynthetics not involving geotextiles was carried out on a shaking table to investigate the relationship between their dynamic friction resistances and shear displacement rate, and also to provide fundamental information regarding the frictional characteristics of geosynthetic interfaces.

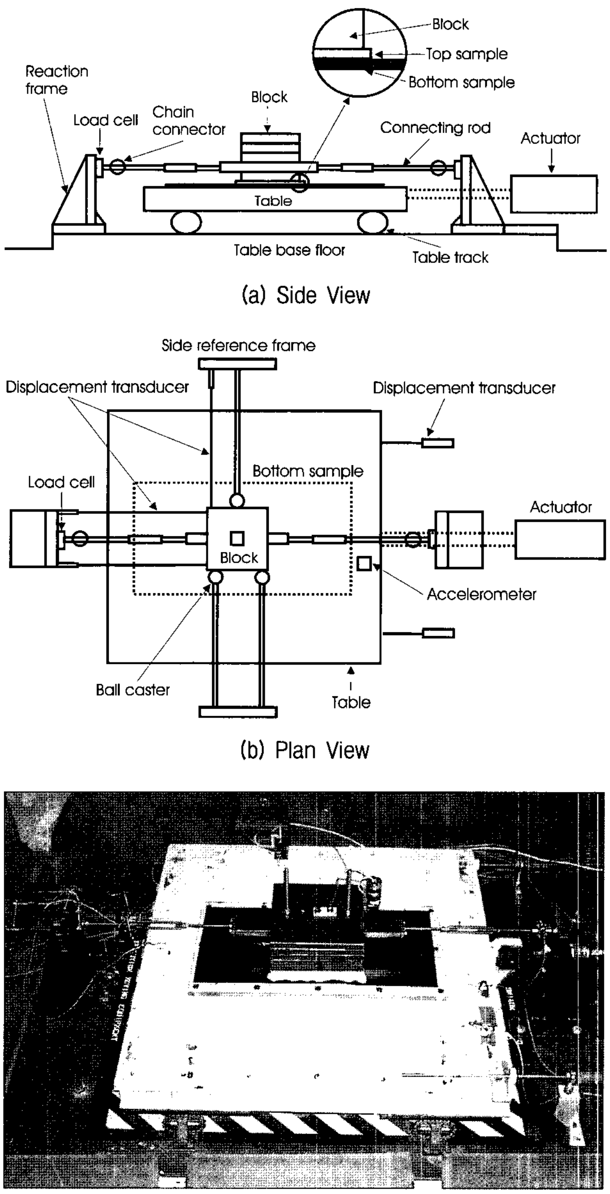
2. Experimental Setup

The experimental setup developed for the interfacial behavior study was described in details in the previous papers (Kim 2003, Kim et al. 2005), and thus only essential information is described here to save space. Those who are interested in more details can refer to the above papers.

There have been basically two different types of test setups (i.e., free and fixed block test setups, Kim 2003). In these test setups, a large piece of a geosynthetic specimen is placed on the table surface and a rigid block, with a piece of the other geosynthetic specimen attached to its bottom surface, is positioned on top of the first specimen. The free block test setup allows the block to move freely over the shaking table. By contrast, the fixed block test setup restricts the movement of the block by fixing the block to reaction frames located outside of the shaking table. Once the shaking table is excited, frictional resistance on the interface is transferred from the table to the block above and is measured by means of load cells mounted between the block and reaction frames. Hence, this setup is capable of controlling the relative displacement between the block and table, and therefore is suitable for displacement rate-controlled tests. The fixed block test is, however, generally more difficult to set up than the free block test.

A cyclic, displacement rate-controlled experimental setup was developed, and the experiments were conducted by using a 1.2 m by 1.2 m uniaxial shaking table at the University of California, Berkeley. Figure 1 shows the schematic profile and plan views of the experimental setup built on the shaking table. The shaking table is driven by a 150 kN, 302 mm stroke hydraulic actuator.

A large piece of plexiglass (864 mm long and 457 mm wide) was attached to the table by screws. A slightly smaller piece of a geosynthetic specimen (760 mm long and 400 mm wide) was then attached on top of the plexiglass. A block consisting of an aluminum plate and a variable number of steel plates (304.8 mm by 304.8 mm), with a piece of another geosynthetic specimen (304.8 mm



(a) Side View

(b) Plan View

(c) Photo View

Fig. 1. Schematic Views of the Experimental Setup Built on the Shaking Table

by 304.8mm) attached to its bottom surface, was placed over the first geosynthetic specimen. ASTM D5321 (ASTM 1998) requires a geosynthetic specimen size to be a minimum of 300 mm by 300 mm. Double-stick fiberglass tape was used to attach the geosynthetic specimens to the plexiglass and block. The magnitude of normal stress on the interface was adjusted by using two different sizes of the aluminum plates (304.8 mm by 304.8 mm and 101.6 mm by 152.4 mm) and a different number of steel plates. With this test setup, relatively low levels of normal stress could be applied (i.e. 7.04 to 63.31 *kPa*). This range of normal stress is indicative of that encountered in solid-waste landfill cover systems. The testing device could not achieve large normal stresses on the large test specimens, but this was acceptable, because the primary objective of this study was to investigate whether common geosynthetic interface strengths were possibly rate dependent. To control the relative displacement between the block and table, movement of the block was restricted by fixing the block through connecting rods to reaction frames, which are located outside of the shaking table (i.e., fixed block test setup). A small water pond was constructed on the shaking table around the geosynthetic interface to simulate a submerged condition for some of the tests.

Redundant displacement transducers measured the displacement of the table and block in both horizontal directions. In addition, relative vertical acceleration between the block and table was measured with two piezoelectric accelerometers, which were installed on the tops of the block and table.

3. Specimen Used in this Test

Two different types of smooth high-density polyethylene (HDPE) geomembranes (manufactured by National Seal and an unknown company) were tested. The first geomembrane was 0.5 mm (20 mils) thick, and the second was 1.5 mm (60 mils) thick. Slight visual differences were observed between two sides of the geomembrane specimens. One side appeared to be smoother than the other side. Tests were all performed on the apparently rougher side of the geosynthetic.

A medium-density polyethylene geonet ("Polynet PN3000") of 5.1 mm (200 mils) thickness manufactured by National Seal Company was also tested. It has openings of 10 mm by 5 mm in a diamond shape. No significant visual difference was observed between the two sides of the geonet specimen. It is known that interfacial resistance involving geonets depends on the orientation of the geonet strands with respect to the direction of shear displacement (e.g., Mitchell et al. 1990). Tests in this study were thus performed both in the transverse shear mode and with the strands aligned parallel with respect to the direction of shear displacement.

All geosynthetic specimens were delivered in a relatively clean condition from the manufacturers. Therefore, no particular cleaning of specimens was performed, except that the geomembranes were cleaned with a dry paper towel to remove any visible dirt. Table 1 summarizes combinations of geosynthetic specimens tested in this research.

4. Experimental Procedure and Interpretation

The test setup is designed to move only the table, while the block above is held stationary. As the table and block displace relatively to each other, frictional resistance in the interfacial area is developed, and transferred to the block

Table 1. Geosynthetic Interfaces Tested in This Study

Interface	Bottom Specimen	Top Specimen	No. of Specimens Tested
1	Geomembrane (20mil) Unidentified	Geomembrane (20mil) Unidentified	3
2	Geomembrane (60mil) Dura Seal HD, NSC	Geomembrane (60 mil) Dura Seal HD, NSC	2
3	Geomembrane (60mil) Dura Seal HD, NSC	Geonet (transverse) Polynet3000, NSC	3
4	Geomembrane (60mil) Dura Seal HD, NSC	Geonet (aligned) Polynet3000, NSC	1

Note: NSC– National Seal Co. USA.

above. The frictional resistance, F can be computed as:

$$F(d) = |f_{right}(d) - f_{left}(d)| \qquad (1)$$

where d is the relative shear displacement, f_{right} and f_{left} are the forces measured in the load cells located on the right and left sides respectively. If the shear resistance is purely frictional, then the friction angle and coefficient can be obtained simply as:

$$\mu(d) = \tan(\phi) = \frac{f(d)}{W} \qquad (2)$$

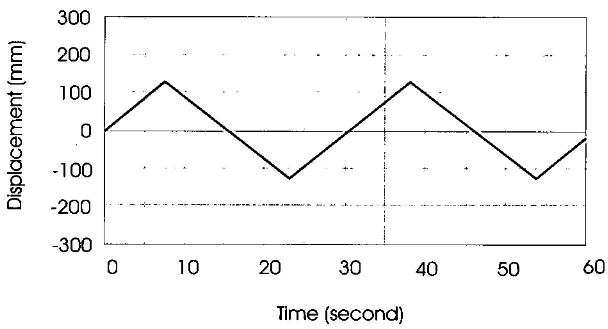
where μ, ϕ, and W are the friction coefficient, friction angle, and weight of the block (i.e., normal load), respectively. If the shear resistance involves cohesion, then normal and shear stresses need to be calculated by dividing the normal load and shear resistance by the interfacial area. The friction coefficient can then be given as:

$$\mu(d) = \tan(\phi) = \frac{\tau(d) - c}{\sigma} \qquad (3)$$

where τ is a shear stress, σ is a normal stress, and c is a cohesion intercept, since $\tau = c + \sigma\tan\phi$.

Figure 2 shows the cyclic table input motion and basic test sequence for each specimen tested. To investigate the effect of shear displacement rate, tests were performed at multiple rates of shear displacement (i.e., seven different table velocities) from a minimum value of 1 mm/min to a high of 10000 mm/min. Due to the vibration on the test system, test rates higher than 10000 mm/min could not be performed reliably. The maximum amplitude of the table motion was set to 12.7 mm (0.5 in.) for 1 and 10 mm/min displacement rates, and 127 mm (5 in.) for other displacement rates. 1000 mm/min tests were interspersed throughout each test series to check the consistency of the test results, and identify potential alterations to the interface due to testing.

Early in the testing program, it was observed that the shearing response of a new interface exhibited changes during the initial cycles of displacement. For interfaces that involved only non-geotextiles, this took the form of a gradual increase in the peak resistance in each successive cycle. As shown in Figure 3 and Figure 8, this peak resistance would stabilize after a sufficiently large amount of cumulative displacement was experienced, and is consistent with the concept that the interface was "polished" from its original condition to a state at which subsequent cycles provided a repeatable response (in fact, instead of polishing, these interfaces appear to become scratched or roughened). In order to directly compare the results from a sequence of tests conducted at different rates, but on the same specimen, it was necessary to "pre-shear" each new interface to achieve this polished state first. This process is shown as the first stage of testing in Figure 2, in which 50 m of cumulative dis-



(a) Cyclic Table Input Motion of Constant Shear Displacement Rate of 1000 mm/min

Run sequence (No. of cycles)	Peak displacement (mm)	Data sampling frequency (Hertz)
3000 mm/min (100 cycles)	127 (5.0 in)	50
1000 mm/min (10 cycles)	127 (5.0 in)	100
10 mm/min (2 cycles)	13 (0.5 in)	10
100 mm/min (2 cycles)	127 (5.0 in)	10
3000 mm/min (10 cycles)	127 (5.0 in)	100
10000 mm/min (10 cycles)	127 (5.0 in)	100
1000 mm/min (10 cycles)	127 (5.0 in)	100
1 mm/min (2 cycles)	13 (0.5 in)	5
1000 mm/min (10 cycles)	127 (5.0 in)	100

(b) Sequence of One Series of Tests under One Specific Normal Stress for Every New Interface Specimen

Fig. 2. Basic Test Procedure

placement are applied at the rate of 3000 mm/min. It is important, therefore, to recognize that the results in this paper refer to the resistance of interfaces on which substantial displacements have already been imposed.

5. Test Results on Geomembrane/Geomembrane (Interfaces 1 And 2)

Despite its rare use in geotechnical applications, tests were performed on the geomembrane/geomembrane interface (Interface 1 and 2), to investigate the fundamental behavior of geomembrane-involving interfaces. 20 mil (Interface 1) and 60-mil (Interface 2) geomembranes were used. The 60-mil geomembrane is commensurate with what is used in most practice, while the 20-mil liner is a "rub sheet" for use during construction, and not intended for containment.

A variation of a large displacement friction angle at a displacement of 254 mm during the pre-shearing process is shown in Figure 3. Unlike the interfaces that involve geotextiles (i.e., Kim 2003), the geomembrane/geomembrane interface specimen (Interface 1) tends to be roughened, and its friction angle increases as the number of cycles (or cumulative shear displacement) increases. The repeated cycles appear to abrade the surface of the geomembrane specimens. Similar behavior was observed again on another geomembrane/geomembrane interface (Interface 2) specimens manufactured by a different company. Widespread scratches on specimen surfaces were observed during the pre-shearing cycles. To make experimental data reproducible, most of the specimens are pre-sheared with 50-100 cycles of the table motion before the tests, while few remaining specimens are not for comparison purpose.

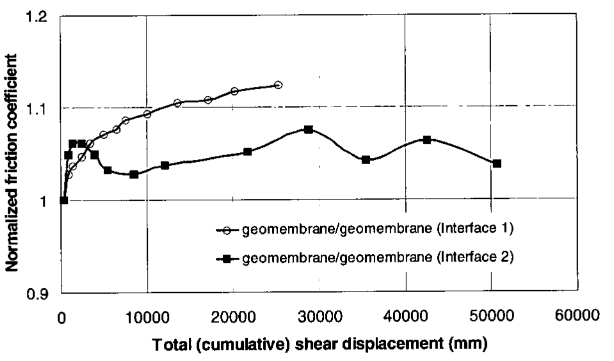
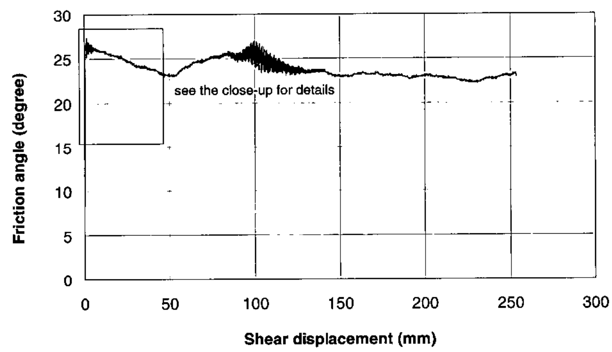
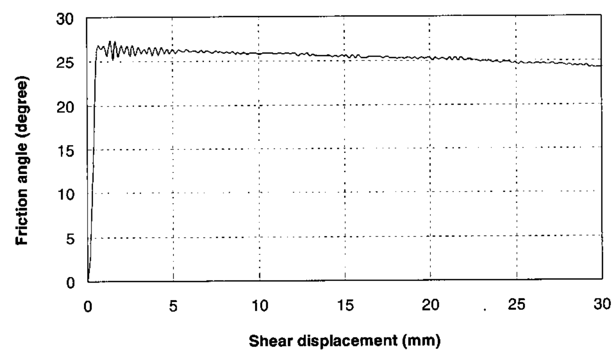


Fig. 3. Variation of Peak Frictional Resistance (or Shear Resistance) During the Pre-Shearing Cycles for Geomembrane/Geomembrane Interfaces

Variation of friction angle with displacement of the geomembrane/geomembrane (Interface 1) for a displacement rate of 1000 mm/min is shown in Figure 4, which is plotted based on one of three tests on the pre-sheared specimens at a normal stress of 8.64 *kPa*. A peak friction angle occurs at a relatively small shear displacement (about 1.5 mm). The curve is not as smooth as that of the geotextile-involved interfaces (e.g., Kim 2003). Figure 5 shows relationship of the large displacement friction angles at a displacement of 254 mm for both non pre-sheared and pre-sheared cases. The interfaces are subject to a normal stress of 8.64 *kPa*. Upper and lower bounds of the friction angle, which represent some uncertainty arising from noise in measurements, are plotted in addition to averages. Unlike the interfaces involving geotextiles, the friction angles are generally not sensitive to the



(a) Full View

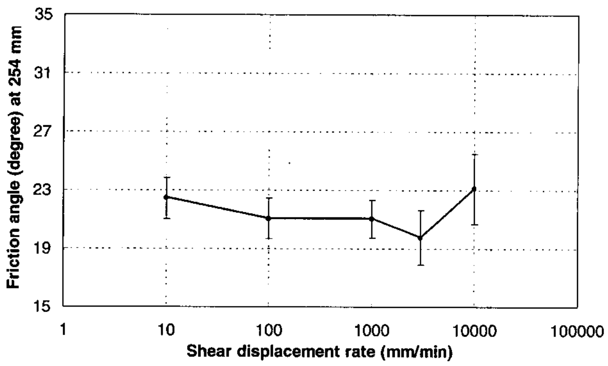


(b) Close-up

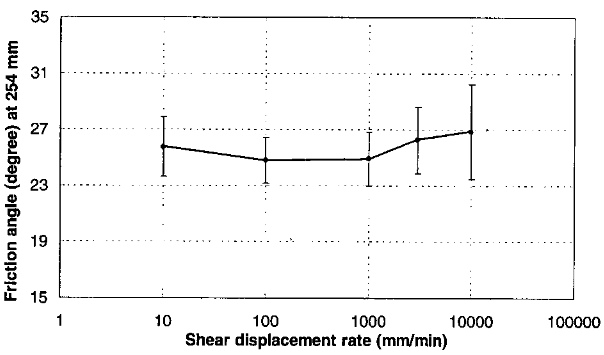
Fig. 4. Typical Plot of Friction Angle Versus Shear Displacement for the Displacement Rate of 1000 mm/min at a Normal Stress of 8.64 kPa for a Pre-Sheared Dry Geomembrane/Geomembrane Interface (Interface 1)

displacement rate.

Two additional tests on geomembrane/geomembrane interface (Interface 2) specimens manufactured by different company were performed. Figure 6 shows relationship between the final friction angle at a displacement of 254 mm and shear displacement rate at a normal stress of 63.31 kpa. Upper and lower bounds of the friction angle, which represent some uncertainty arising from noise in measurements, are plotted in addition to averages. The friction angle appears not sensitive to shear displacement rate.



(a) Non Pre-sheared



(b) Pre-sheared

Fig. 5. Relationship Between the Large Displacement Friction Angle at a Displacement of 254 mm and Shear Displacement Rate for a Geomembrane/Geomembrane Interface (Interface 1) (Note: a value given at 25.4 mm for 10 mm/min)

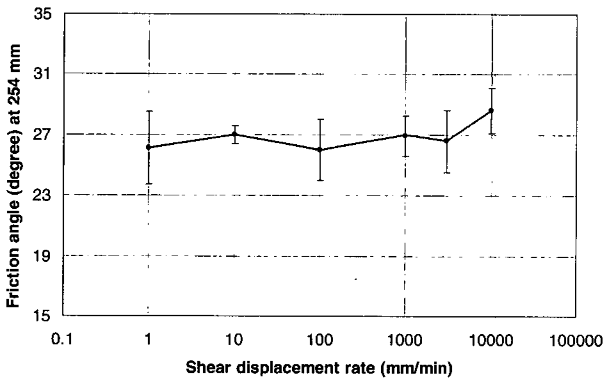


Fig. 6. Relationship Between the Large Displacement Friction Angles at a Displacement of 254 mm and Shear Displacement Rate at a Normal Stress of 63.31 kPa for Pre-Sheared Dry Geomembrane/Geomembrane Interface (Interface 2). (Note: values given at 25.4 mm for 1 mm/min and 10 mm/min)

Results from the dry tests on Interface 2 are compared in Figure 7 as a function of the applied normal stress. One can see that over this limited range of stresses, the friction coefficient does not vary with normal stress, and the resulting envelope implies a purely frictional resistance, with no discernible cohesion.

In summary, a series of tests on the geomembrane/geomembrane interface specimens confirmed that unlike the interfaces involving geotextiles, the friction angles of the interfaces not involving geotextiles are generally not sensitive to the displacement rate. The tests were performed on both pre-sheared and non pre-sheared specimens. It was observed that the friction angle of the "non pre-sheared" interface is typically 3 to 6 degrees less than that of the "pre-sheared" one.

6. Test Results on Geomembrane/Geonet (Interfaces 3 And 4)

Three tests were conducted on the transverse-aligned geomembrane/geonet (Interface 3). A typical variation of a large displacement friction angle at a displacement of 254 mm during the pre-shearing process is shown in Figure 8. Similarly, as with the interfaces 1 and 2, the geomembrane/geonet (transverse-aligned) interface specimen

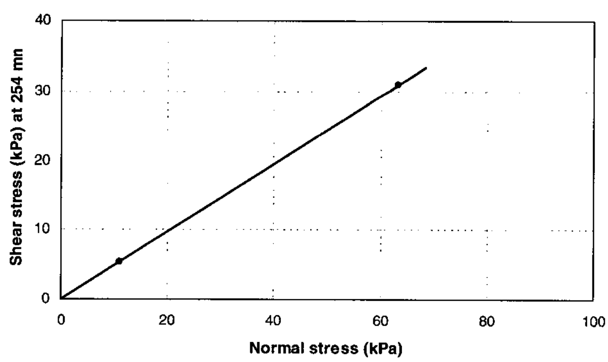


Fig. 7. Plot of Shear Stress Versus Normal Stress for a Pre-sheared Dry Geomembrane/Geomembrane (Interface 2) for a Displacement Rate of 100 mm/min

tends to roughen, and its friction angle increases with increased relative displacement. The increase of frictional resistance appears to occur because tips of the geonet strands dig into and cut the surface of the geomembrane. Under a normal stress of 10.94 *kPa*, the friction angle continues to increase up to around 30 cycles (about 15 meters) and reaches an apparent steady-state after that. It is noted that contact between the geomembrane and geonet specimens is limited to small isolated areas. As a result, pre-shearing is done only on those small areas. Nevertheless, to make experimental data reproducible, most of the specimens are pre-sheared with 100 cycles of the table motion before the tests, while few remaining specimens are not for comparison purpose.

Another series of tests performed on the parallel-aligned geomembrane/geonet interface (Interface 4) specimen yield similar results. Under a normal stress of 10.94 *kPa*, the friction angle rapidly increases up to around 10 cycles (about 5 meters). However, the minimum displacement for reaching a steady-state (or residual strength) was smaller than for the interface 3.

Variation of friction angle with displacement of the transverse-aligned geomembrane/geonet (Interface 3) for a displacement rate of 1000 mm/min is shown in Figure 9, which is plotted based on one of three tests on the pre-sheared specimens at a normal stress of 63.31 *kPa*. A peak friction angle occurs at a shear displacement of about 5 mm, which is slightly larger than that of the geotextile-involved interfaces (i.e., Kim 2003). Like the interfaces 1 and 2, the curve is not as smooth as that

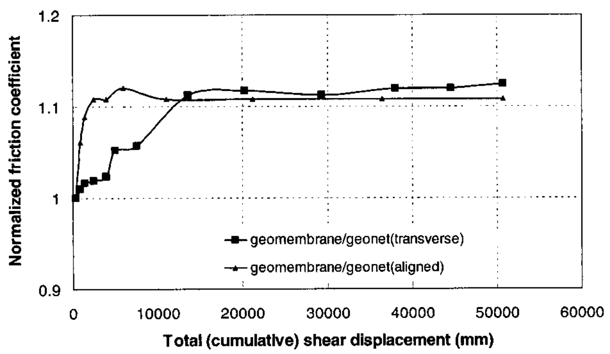


Fig. 8. Typical Variation of Peak Frictional Resistance (or Shear Resistance) During the Pre-Shearing Cycles for Geomembrane/Geonet Interfaces

of the geotextile-involved interfaces. Figure 10 shows the relationship between the large displacement friction angles at a displacement of 25.4 mm and shear displacement rate under both the dry and submerged conditions. A normal stress of 10.94 *kPa* was applied on the pre-sheared specimens. Unlike the geotextile-involved interfaces, the friction angle does not appear to be sensitive to the

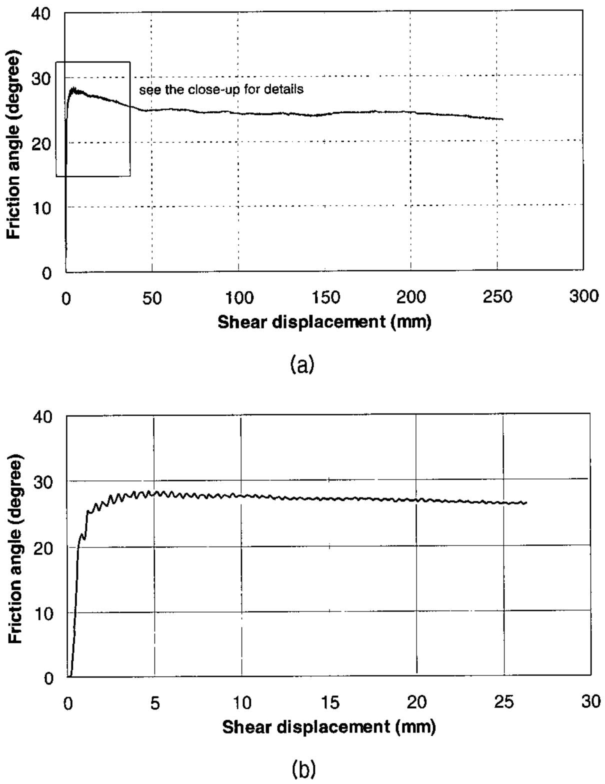


Fig. 9. Typical Plot of Friction Angle Versus Shear Displacement for the Displacement Rate of 1000 mm/min at a Normal Stress of 63.3 kPa for a Pre-Sheared Dry Geomembrane/Geonet (Transversely Aligned) Interface (Interface 3)

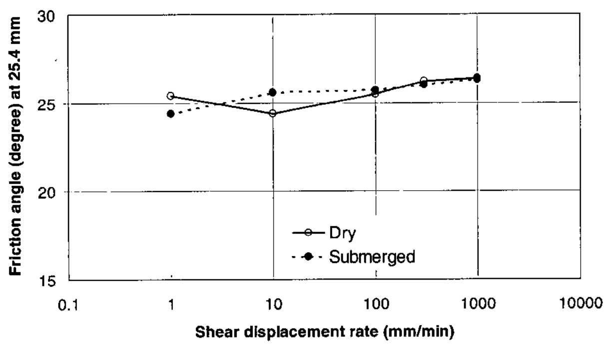


Fig. 10. Relationship Between the Large Displacement Mean Friction Angles at a Displacement of 25.4 mm and Shear Displacement Rate at a Normal Stress of 10.94 kPa Under the Dry and Submerged Conditions for a Pre-Sheared Geomembrane/Geonet (Transversely Aligned) Interface (Interface 3)

displacement rate. The friction angle for the submerged condition is essentially the same as that under the dry condition. It is found that, at two different levels of normal stress (10 .94 *kPa*, 63.3 *kPa*) under the dry condition, the friction angles do not appear to be dependent on the normal stress (Figure 11).

Figure 12 shows the relationship between the large displacement friction angles at a displacement of 25.4 mm and shear displacement rate for both the pre-sheared and non pre-sheared dry specimens. A normal stress of 10.94 *kPa* was applied on the specimens. The test results on the non pre-sheared specimen show a similar different trend to that of the pre-sheared specimen. The friction angle of the non pre-sheared specimen is, however, typically 2 to 5 degrees less than that of the pre-sheared specimen.

To examine the potential effect of alignment, another series of tests were performed on the parallel-aligned geomembrane/geonet interface (Interface 4) specimen. As done for the interface 3, all specimens are pre-sheared with 100 cycles of the table motion before the tests. The large displacement friction angle against shear displacement rate under the dry condition is plotted in Figure 13. Upper and lower bounds of the friction angle, which represent uncertainty arising from measurement noise, are given in addition to averages. Again, the friction angle of the geomembrane/geonet (aligned) interface does not appear to be sensitive to shear displacement rate.

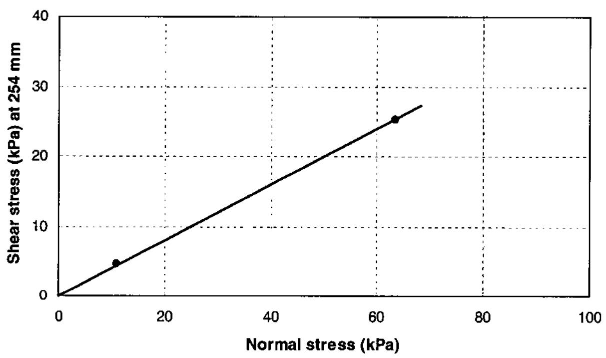


Fig. 11. Plot of Shear Stress Versus Normal Stress for a Pre-sheared Dry Geomembrane/Geonet (Transversely Aligned) Interface (Interface 3) for a Displacement Rate of 100 mm/min

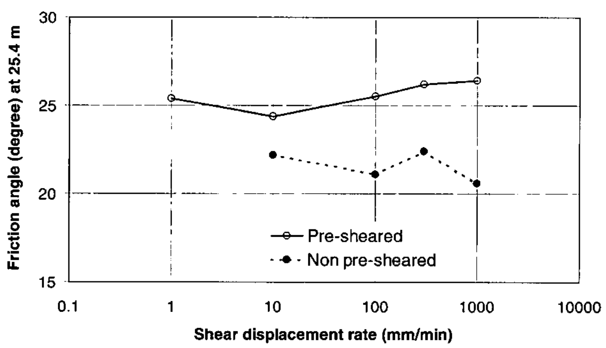


Fig. 12. Relationship Between the Large Displacement Mean Friction Angles at a Displacement of 25.4 mm and Shear Displacement Rate at a Normal Stress of 10.94 kPa Pre-Sheared and Non Pre-sheared Geomembrane/ Geonet (Transversely Aligned) Interfaces (Interface 3)

7. Conclusions

The multiple rate tests show that the interfaces involving only non-geotextiles have unique shearing characteristics that can be differentiated from the interfaces involving geotextiles. Based on the test results, the following observations can be made regarding the frictional behavior of the non-geotextile-involving geosynthetic interfaces.

Unlike the geotextile-involving interface, peak and post-peak shear strengths for the combinations of geosynthetics not involving geotextiles such as the geomembrane/ geomembrane and geomembrane/geonet tend to initially increase with increased cumulative displacement (Figure 14). These phenomena appear to be related to the scratching of contact surfaces.

Unlike the geotexitle-involving interfaces, which show strain softening behavior, non geotextile-involved interfaces behave more like rigid-perfectly-plastic materials.

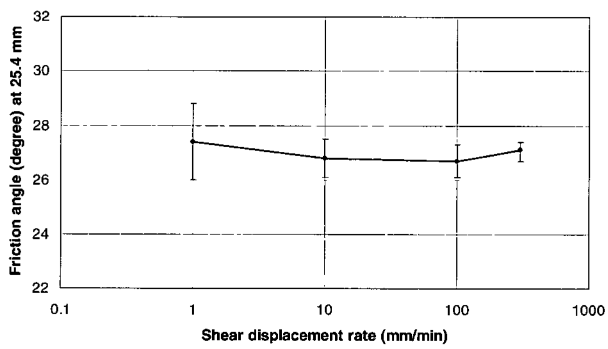


Fig. 13. Relationship Between the Large Displacement Friction Angle at a Displacement of 25.4 mm and Shear Displacement Rate at a Normal Stress of 10.94 kPa for a Pre-Sheared Dry Geomembrane/Geonet (Parallel Aligned) Interface (Interface 4)

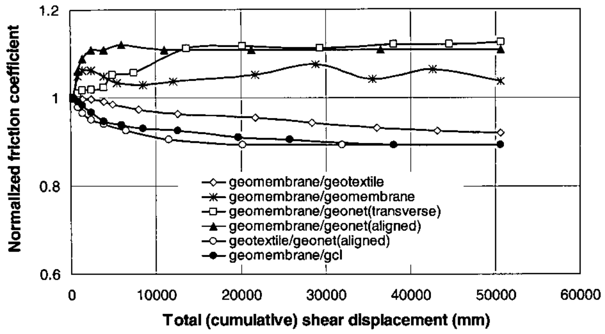


Fig. 14. Typical Variation of Peak Frictional Resistance (or Shear Resistance) During the Pre-Shearing Cycles for Various Types of Geosynthetic Interfaces

For geosynthetic interfaces not involving geotextiles, the shear strengths are generally not sensitive to shear displacement rate. The friction angle under the submerged condition is essentially the same as that under the dry condition.

The shear strength parameters (i.e., the friction angle) of the non-geotextile-involving geosynthetic interfaces are not sensitive to the magnitude of normal stress over the relatively small range of stress levels applied in this study (7.04 to 63.31 *kPa*). Over this limited range of stresses, the friction coefficient does not vary with normal stress, and the resulting envelope implies a purely frictional resistance, with no discernible cohesion. De (1996) reported a small reduction of the friction angle with increased normal stress for some interfaces.

The friction angle of the "non pre-sheared" geoemembrane /geomembrane interface is typically 3 to 6 degrees less than that of the "pre-sheared" one. Similarly, the friction angle of the non pre-sheared geomembrane/geonet specimens is typically 2 to 5 degrees less than that of the pre-sheared specimen.

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