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The Effect of Displacement Rate on Shear Characteristics of Geotextile-involved Geosynthetic Interfaces

지오텍스타일이 포함된 토목섬유 경계면의 전단특성에 대한 변위속도 효과

Kim, Jin-Man*　　김 진 만

요 지

토목섬유 경계 접촉면들의 동적거동을 이해하는데 매우 중요할 수도 있음에도 불구하고 접촉면들의 동적마찰저항과 변위속도 관계에 관한 연구가 아직까지는 미비한 실정이다. 이에 따라 토목섬유에 대한 실험적인 연구를 진동대를 이용하여 수행하였다. 반복적, 변위속도 조절장치를 개발하여 사용하였으며 토목섬유 경계 접촉면들의 동적마찰저항과 변위속도사이의 관계를 조사하였다. 실험으로부터 지오텍스타일이 포함된 경계 접촉면에서는 변위속도 증가에 따라 전단강도도 증가한다는 중요한 결과를 얻었다. 이와는 달리 수침상태에서는 접촉면 사이에 갇힌 물에 의한 윤활효과 등으로 인해 접촉 전단강도가 변위속도에 민감하지 않다는 결과를 얻었다. 본 시험결과는 토목섬유에 비교적 낮은 수직응력이 작용하는 매립장 덮개 및 사면의 동적안정 해석등에 적용할 수 있다.

Abstract

In spite of its potential importance in the assessment of geosynthetic-related dynamic problems, no serious attempt has yet been made to investigate a probable dependence of dynamic friction resistance of the geosynthetic interface on shear displacement rate. Hence, an experimental study of geosynthetics was carried out on a shaking table, and the relationship between dynamic friction resistance and shear displacement rate of geosynthetic interfaces was investigated. A cyclic, displacement rate-controlled experimental setup was used. The subsequent multiple rate tests showed that interfaces that involve geotextiles have such unique shearing characteristics that shear strengths tend to increase with displacement rate. In contrast, once submerged with water, the shear strength appears to be no longer dependent on the displacement rate, partly due to lubrication effect of water trapped inside the interface. The results of the experimental study can be used in the seismic safety assessment of a landfill cover and slope where the geosynthetic materials are exposed to a relatively low normal stress.

Keywords : Dynamic resistance, Geosynthetics, Geotextile, Shaking table, Shear characteristics

1. Introduction

A significant amount of data on static shear properties of geosynthetic interfaces has been developed over recent decades (e.g., Martin at al. 1984, Mitchell et al. 1990, Koutsourais et al. 1991, Stark and Poppel 1994). In contrast, there is relatively little information available regarding dynamic shear properties.

The conventional cyclic direct shear device can only accommodate small size test specimens, and consequently provides shear properties corresponding to small displacement. However, many dynamic problems often

* Member, Senior Researcher, Hyundai Institute of Construction Technology, jmkim@hdec.co.kr

involve large shear displacement. Recently, several investigators (i.e., Yegian and Lahlaf 1992, De 1996, Yegian and Kadakal 1998) have performed dynamic shear tests on various combinations of geosynthetic materials by using shaking tables that allow large displacement. There have been basically two different types of test setups (i.e., free and fixed block test setups). 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. Hence, this setup is capable of controlling the relative displacement between the block and table, and therefore is suitable for displacement rate-controlled tests.

Yegian and Lahlaf (1992) performed a series of shaking table tests to measure dynamic shear properties between some geotextiles and geomembranes by using a free block test setup. They concluded that dynamic interfacial friction resistance between the geosynthetics is not appreciably different from that observed from static tests. De (1996, 1997, 1998) conducted dynamic shear tests with ten different geosynthetic interfaces using a free block test setup on a shake table. It was reported that the shaking table results compared well with those from the cyclic direct shear tests performed by the same investigator. Yegian and Kadakal (1998) tested some geomembrane/geotextile interfaces using both fixed and free block test setups. In the free block test setup, they obtained comparable results to values of interfacial dynamic friction angles as Yegian and Lahlaf (1992) and De (1996). The results from the fixed block setup were not reported in detail.

In spite of its potential importance (e.g., Persson 1998) in the assessment of geosynthetic-related dynamic problems, no serious attempt has yet been made to investigate a probable dependence of dynamic friction resistance of the geosynthetic interface on shear displacement rate. Hence, an experimental study of dynamic frictional behavior of geotextile-involved geosynthetics was carried out, in order to investigate the relationship between their dynamic friction resistance and shear displacement rate.

2. Test Setup and Instrumentation

The experiments were conducted by using a 1.2 meters by 1.2 meters uniaxial shaking table at the University of California, Berkeley (Kim 2001). Figure 1 shows schematic side and plan views of the experimental setup built on the shaking table.

A cyclic, displacement rate-controlled experimental setup was built to investigate the potential effect of displacement rate on the interfacial shear properties. 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 sample (760 mm long and 400 mm wide) was then placed on top of the plexiglass. A block consisting of a aluminum plate and a variable number of steel plates (304.8 mm by 304.8 mm), with a piece of another geosynthetic sample (304.8 mm by 304.8 mm) attached to its bottom surface, was placed over the first geosynthetic sample. ASTM D5321 (ASTM 1998) requires a geosynthetic sample size to be a minimum of 300 mm by 300 mm. Double-stick fiberglass tape was used to attach the geosynthetic samples 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. 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). In order to simulate a submerged condition for some of the tests, a small water pond was constructed on the shaking table around the geosynthetic interface. Geosynthetic samples were soaked with water for about one hour at test stresses so they would be fully hydrated.

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. An infrared thermometer was used to monitor temperature changes in the contact surface between the two geosynthetic samples during the tests.

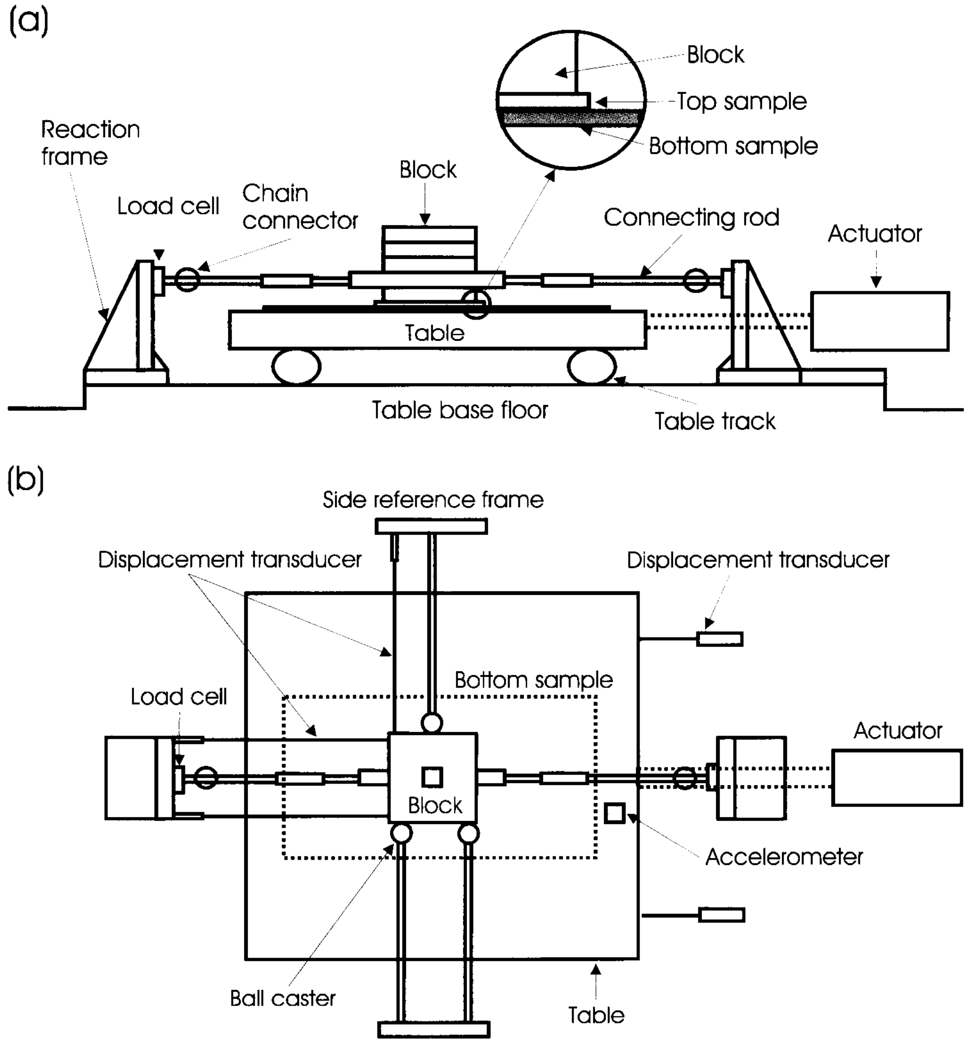

Fig. 1. Schematic views of the experimental setup built on the shaking table: (a) side view; (b) plan view

3. Sample Preparation

Geosynthetic materials most frequently found in field application are geotextiles, geomembranes, geonets, and more recently, geosynthetic clay liners (e.g., Koerner 1998). The experiments were performed on four geosynthetic interfaces often found in field application.

Smooth high-density polyethylene (HDPE) geomembranes (manufactured by National Seal company) were tested. The geomembranes were 1.5 mm (60 mils) thick. Slight visual difference was observed between two sides of the geomembrane samples. One side appeared to be smoother than the other side. Tests were all performed on the rougher side.

Two different types of polypropylene geotextiles made of continuous filament, non-woven needle punched fabrics (manufactured by Amoco and unknown company) were also tested. Some minor textural differences were visually observed between two sides of the geotextile samples. One side was apparently more isotropic and smoother than another side. All tests were performed on the smoother side.

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 sample.

All geosynthetic samples were delivered in a relatively clean condition from the manufacturers. Therefore, no particular cleaning of samples was performed except the geomembranes that were cleaned with a dry paper towel

Table 1. Geosynthetic interfaces tested in this study

Interface	Bottom Sample	Top Sample	No. of Sample Tested
1	Geomembrane (60mil) Dura Seal HD, NSC	Geotextile Unidentified	5
2	Geomembrane (60mil) Dura Seal HD, NSC	Geotextile Amoco4512, Amoco	5
3	Geotextile Amoco4512, Amoco	Geonet (aligned) Polynet3000, NSC	4

Note: 1) NSC: National Seal Co., Amoco: Amoco F&F Co.
2) Interface 1 was employed in the sliding block test performed by Wartman (1999)

to remove any visible dirt. Table 1 summarizes combinations of geosynthetic samples tested in this research.

4. Test Procedure

The setup is designed to move only the table, while the block above is stationary. As the table and block displace relative to each other, frictional resistance in the interfacial area is developed, and transferred to the block above. If the shear resistance is purely frictional, then the interfacial friction angle and coefficient can be obtained simply as:

$$\mu(d) = \tan(\phi) = \frac{F(d)}{W} \quad (1)$$

where μ, ϕ, F, d and W are the friction coefficient, interfacial friction angle, frictional resistance, shear displacement and weight of the block (i.e., normal load) respectively. All interfaces tested in this study showed purely frictional behaviors (Kim 2001) and therefore, the shear resistance is computed by using Equation 1. If the shear resistance involves cohesion then normal and shear

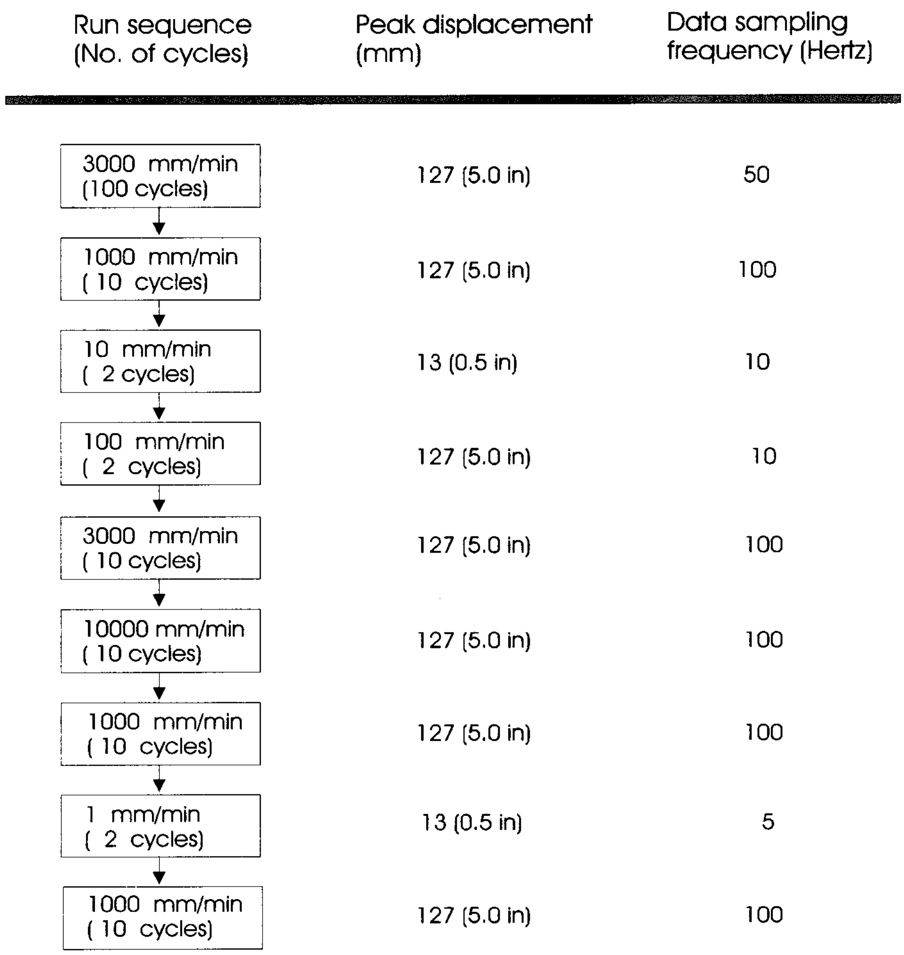

Fig. 2. Basic test procedure: sequence of one series of tests under one specific normal stress for every new interface sample

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:

$$\mu(d) = \tan(\phi) = \frac{\tau(d) - c}{\sigma} \qquad (2)$$

where τ is a shear stress, σ is a normal stress, and c is a cohesion intercept.

Figure 2 shows the basic test sequence for each sample tested. In order to investigate the effect of shear displacement rate, tests were performed at multiple rates of shear displacement (i.e., seven different table velocities) from low 1 mm/min to high 10000 mm/min. Due to the vibration on the test system, the test rates higher than 10000 mm/min were not performed. 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, mainly due to the time constraint of the low-speed experiments (hence, maximum displacements of 25.4 mm and 254 mm respectively) . 1000 mm/min tests were carried out as a base line to check the consistency of the test results. To make tests reproducible, the contact surfaces were pre-sheared with a number of cyclic table motions until a steady-state condition was reached.

5. Test Results

A series of tests were performed on the geomembrane /geotextile interface (Interface 1) samples following the basic procedure outlined above. All new samples were pre-sheared at the displacement rate of 3000 mm/min. A typical degradation of peak frictional resistance (peak friction coefficient) of each cyclic table motion, which is normalized by the peak value of the first cycle, is shown in Figure 3. The interface appears to be polished and its frictional resistance degrades when subjected to repeated relative displacements. Both peak and post-peak frictional resistances decrease in comparable degree with increased displacements. Mitchell et al. (1990) and De (1996) reported similar observations. Under a normal stress of 63.3 *kPa*, the interface appears to be fully polished

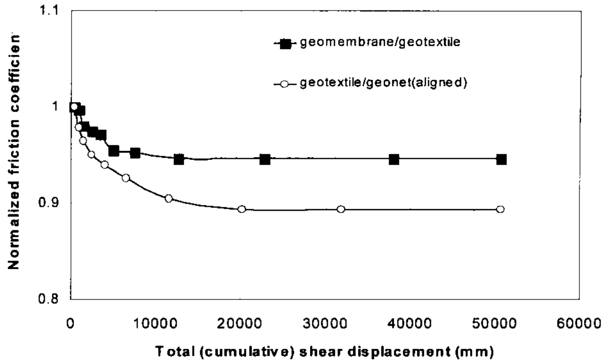

Fig. 3. Typical variation of peak frictional resistance (or shear resistance) during the pre-shearing cycles for geotextile-involved geosynthetic interfaces

within 20 cycles (about 10 meters) and the friction resistance reaches apparently a steady-state condition (often called *residual strength*). The tests performed on the geomembrane /geotextile interface (Interface 2) samples provided by different manufacturers show the degradation trend that is similar to the case of Interface 1.

The other interfaces such as the parallel-aligned geotextile /geonet (Interface 3) that involve geotextiles also degrade considerably during the 100 pre-shearing cycles and reach a stead-state condition in about 40 cycles (20 meters) under a normal stress of 10.94 *kPa.*

One of the main objectives of the experiments was to investigate the frictional resistance of the interface over a wide range of shear displacement rates (or sliding velocities). Figure 4 shows one of the typical relationships of interfacial friction angle versus shear displacement plotted for four different displacement rates on the geomembrane/geotextile interface (Interface 1) at a normal stress of 10.94 *kPa*. The trends of the curves are quite similar over the range of displacement rates. Peak friction angles (and thus peak friction resistances) develop at relatively small shear displacements (typically less than 2 mm). Then, the friction angles decrease continuously up to the limitation of the test setup (i.e., maximum displacement of 254 mm that is twice of the table motion amplitude). The friction angles, however, do not appear to have reached residual values even at a displacement of 254mm, and consequently a new term "*large displacement friction angle*" is used instead of a "*residual friction angle*". The large displacement friction angles at a

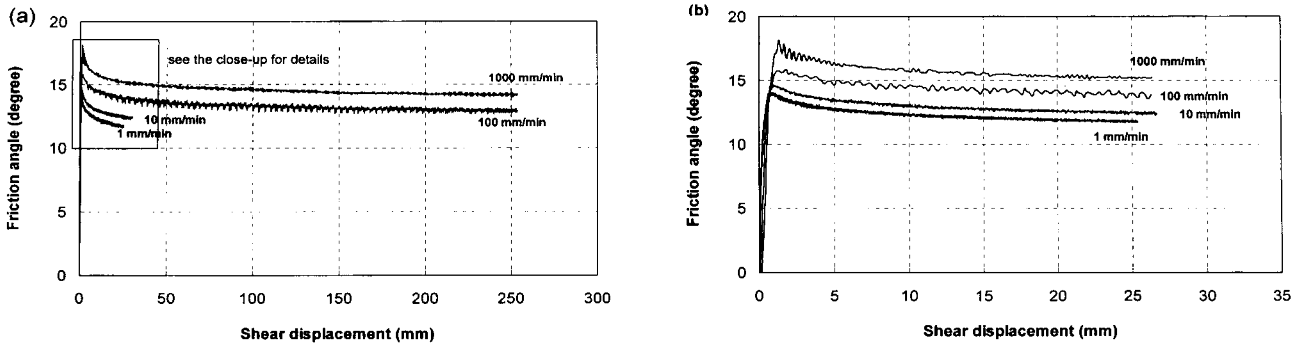

Fig. 4. Typical plots of friction angle versus shear displacement of four different displacement rates at a normal stress of 10.94 *kPa* for a pre-sheared dry geomembrane/geotextile interface (Interface 1): (a) full view; (b) close-up

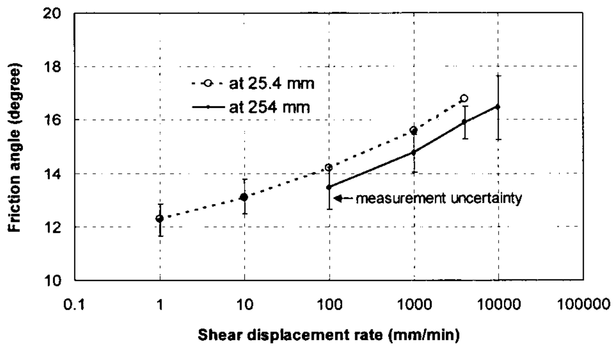

Fig. 5. Relationship between the large displacement friction angle and shear displacement rate for a pre-sheared geomembrane/geotextile interface (Interface 1): lower and upper bounds in addition to averages for a polished dry interface at a normal stress of 10.94 *kPa*

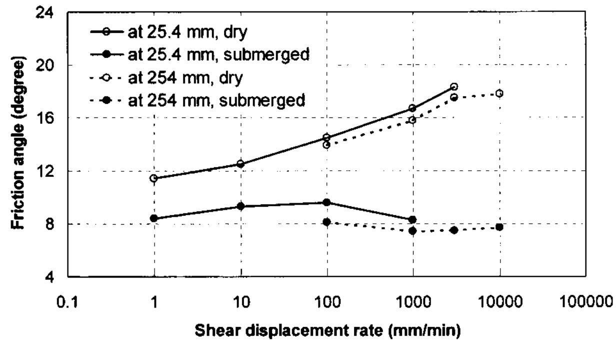

Fig. 6. Relationship between the large displacement mean friction angles and shear displacement rate at a normal stress of 10.94 *kPa* for pre-sheared geomembrane/geotextile interfaces (Interface 2) at both 25.4 mm and 254 mm displacements

displacement of 254 mm are typically 2 to 3 degrees less than the peak friction angles (about 80-90 % of peak values). The plots are based on one of the one-half cycle of the table motion starting from end with reversal table motion because it provides measurements at a displacement twice larger than that of the motion that starts from the neutral position. It was observed that the geosynthetic behavior with each reversal table motion and the behavior with initial motion starting from the neutral position (zero amplitude) are essentially same. In other words, whenever the table reverses its move or resumes to move after a pause, the interfacial resistance rapidly reaches its peak from zero resistance.

The tests were conducted on the pre-sheared samples at normal stresses of 10.94 and 22.53 *kPa*, and on the unpolished samples at a normal stress of 7.04 *kPa*. It was found that, for the pre-sheared interface, the large displacement friction angle increases almost linearly as the shear displacement rate increases in logarithm scale (Figure 5). Upper and lower bounds of the friction angle, which represent uncertainty arising from measurement noise, are given in addition to averages. The large displacement friction angle was found to fall between a low of 12.3 degrees and a high of 16.5 degrees depending on the displacement rate. The large displacement friction angle (12.3 ± 0.6 degrees) at a displacement of 25.4 mm for the rate of 1 mm/min., which is comparable to the static test, is slightly higher than the static residual friction angle (9.6 ± 0.9 degrees) reported from Mitchell et al. (1990). The tests were performed under two different levels of normal stress and the friction angle does not appear to be sensitive to the normal stress within the stress level applied in this study. The test results on the unpolished interface show a similar trend. However, the friction angle of the unpolished interface is typically 1.5 to 3.0 degrees higher.

Additional tests were performed on the geomembrane

/geotextile interface (Interface 2) samples provided by different manufacturers, in order to investigate the likely effects of different manufacturing. The tests yield the results that are similar to Interface 1. The peak friction angle develops at small shear displacements that are comparable to the results of Interface 1. Figure 6 shows the typical relationship between the large displacement friction angles and shear displacement rate under both dry and submerged conditions, performed on the polished samples at a normal stress of 10.94 *kPa*. Average friction angles that are determined as medium values between the upper and lower bounds that represent some uncertainty arising from noise in measurements are given. It is found again as was the interface 1 that under the dry condition, the friction angle increases approximately linearly as displacement rate increases in logarithm scale. The trend does, however, not appear clearly in very low and high ranges of the displacement rate such as 1 and 10000 mm/min. The large displacement friction angle (11.4 degrees) at a rate of 1 mm/min. is comparable to that of interface 1.

The test results on the submerged condition, however, show a completely different trend of the interfacial friction angle from that of the dry condition. The friction angle under the submerged condition is typically 3 to 10 degrees less than that of the dry condition. Furthermore, the friction angle appears no longer proportional to the shear displacement rate. This phenomenon appears to relate to lubrication effect of water trapped inside the interface (i.e., hydrodynamic lubrication, Persson 1998). However, detailed theoretical discussion on this phenomenon is beyond the scope of the paper.

Another series of four tests were performed on the parallel-aligned geotextile/geonet interface (Interface 3) samples. A plot of friction angle against shear displacement for a displacement rate of 10 mm/min is shown in Figure 7, which is typical for all rates of displacement employed in this study. The tests were conducted on the pre-sheared samples at a normal stress of 10.94 *kPa*. The peak friction angle develops at a small shear displacement (typically less than 1 mm). The relationship between the large displacement friction angles at a displacement of 25.4 mm and shear displacement rate (Figure 8) shows again that under the dry condition, the interfacial friction angle increases almost linearly as displacement rate increases in logarithm scale. The trend is, however, not apparent for low range of displacement rates such as 1 and 10 mm/min. The test results from the submerged condition show again a different trend compared with those from the dry condition. The friction angle appears to be independent of displacement rate, and essentially equal to the friction angles in the dry condition at low displacement rates. It also appears that the friction angle is not sensitive to normal stress within the range of stress levels applied in this study.

6. Conclusions

Dynamic shear properties of the geosynthetic interfaces vary drastically from one to another, depending on the combinations of geosynthetics. Based on the test results,

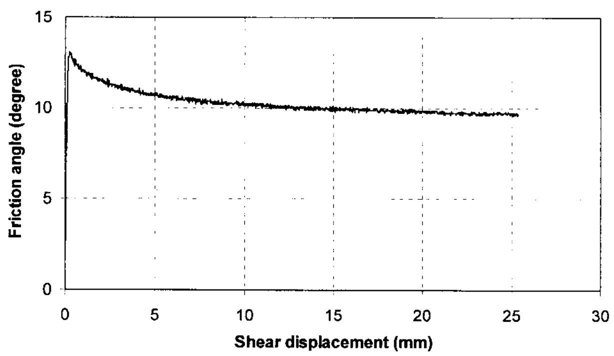

Fig. 7. Typical plot of friction angle versus shear displacement of a displacement rate of 10 mm/min at a normal stress of 10.94 *kPa* for a pre-sheared dry geotextile/geonet (parallel aligned) interface (Interface 3)

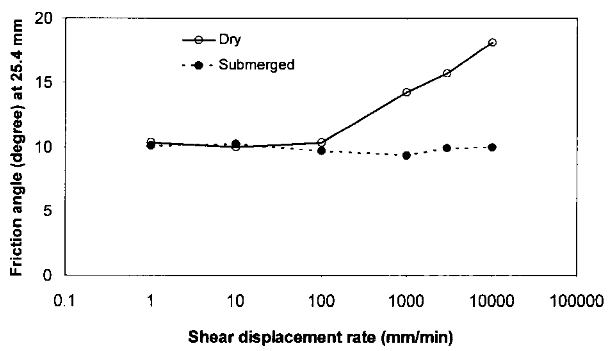

Fig. 8. Relationship between the large displacement mean friction angles at a displacement of 25.4 mm and shear displacement rate at a normal stress of 10.94 *kPa* for a pre-sheared geotextile/geonet (aligned) interface (Interface 3)

the following observations can be made regarding some of the important factors that influence the frictional behavior of the geotextile-involved geosynthetic interfaces.

Geotextile-involved interfaces, such as the geomembrane /geotextile and geotextile/geonet, continue to degrade as displacements increase until they reach an apparent steady -state (or residual strength). These phenomena appear to be related to the polishing of contact surfaces.

Under the dry condition, the shear strengths of geotextile-involved interfaces increase almost linearly as the displacement rate increases in logarithm scale. The rate dependency at the lower rate range is, however, not as obvious as in cases of medium and high rates (i.e., Interfaces 2 and 3). The same interfaces, once submerged with water, show entirely different frictional behavior. The shear strength appears to be no longer dependent on the displacement rate. This phenomenon appears to relate to lubrication effect of water trapped inside the interface.

It appears that shear strength parameters (i.e., interfacial friction angle) of the geosynthetic interfaces are generally not sensitive to the magnitude of normal stress. It should be, however, noted that the levels of stress applied in this study were relatively small (7.04 to 63.31 *kPa*). De (1996) reported a small reduction of the shear strength parameter (i.e., interfacial friction angle) with increased normal stress for some interfaces.

It was observed that the temperature of the interface increases slightly (typically about 0 to 4 Celsius degree) as displacement increases. However, no significant relationship was observed between temperature and frictional behavior of the interface. That may be because the levels of stress applied in this study were relatively low (7.04 to 63.31 *kPa*). A significant temperature increase may develop under normal stresses typically found in field application. Thus, the effects of high normal stress on the displacement rate dependency and temperature on geosynthetic shear behavior need further study.

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