Jour. of the KGS, Vol. 20, No. 2. March 2004, pp. 75~85

The Influence of Moisture on the Interface Shear Strength Between Geosynthetics

토목섬유의 접촉 전단강도에 대한 함수비의 영향

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요 지

폐기물 매립장의 침출수를 차수하기 위한 목적으로 다양한 토목섬유들이 폭 넓게 사용되어지고 있다. 이런 토목섬유 사이의 접촉 전단강도는 매립장 바닥차수 시스템 및 종료 매립장 커버 시스템 설계 시 구조물의 안전에 중요한 영향을 주는 설계정수임이 틀림이 없다. 본 연구에서는 폐기물 매립장 설계 시 중요한 설계정수인 토목섬유(지오멤브레인과 지오텍스타일 또는 토목섬유 점토 차수재) 사이의 접촉 전단강도를 산정하기 위하여 대형 직접전단 시험을 수행하였다. 특히, 대부분의 토목섬유가 강우, 침출수 및 지하수에 쉽게 영향을 받기 때문에 토목섬유의 접촉 전단강도에 대한 함수비의 영향을 고려한 연구를 수행하였다.

Abstract

Various geosynthetics are widely installed as a liner or a protective layer of waste landfills. The interface shear strength between the layers of geosynthetics in waste landfills is an important parameter to ensure the safety of bottom and cover system design. In this study, estimations of interface shear strength between geomembrane and geotextile or Geosynthetic Clay Liners (GCL) are performed by large direct shear tests. Especially, this research is focused on the effect of moisture within the interface shear strength between geosynthetics, because most interfaces are vulnerable to rain, leachate and groundwater beneath the liners.

Keywords : Geosynthetics, Interface shear strength, Large direct shear tests, Moisture, Waste landfills

1. Introduction

Various kinds of geosynthetics such as geotextile, geomembrane, and geosynthetic clay liner (GCL) are widely installed at waste landfills for different purposes. Geotextiles have been commonly used as separation layers, filtering layers and geomembrane protectors. Geomembrane is designed as a liner to intercept leachate penetration at the bottom of landfills and to protect landfill gas from escaping at the cover system. However, GCL is a relatively new type of geosynthetic that is installed to function as an alternative to compacted clay liners (CCL) in final covers or bottom-lining systems of waste containment facilities.

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GCL is a good alternative because it has low hydraulic conductivity at a relatively low cost (Bouazza, 2002). It is generally composed of a thin layer of bentonite (1) mixed with an adhesive that is attached to a geomembrane (unreinforced GCL) or (2) sandwiched between two geotextiles (reinforced GCL). With an increase in the application of geosynthetics at the side slopes of landfills, dams, and banks, the slope stability of geosynthetic-installed sites has become an important factor considered in side slope design. Geosynthetics slippage against soil along the weak interface of steep side slopes induces an excessive local stress that leads to tearing and consequently, global failure of the slope. Especially for waste containment facilities, interface shear strength between soil/ geosynthetic or geosynthetics is known to be significantly low. Therefore, structural stability should be considered during all phases of installing a liner or cover system incorporating geosynthetics.

For geomembrane/geotextile interfaces, some studies have been carried out to examine the effect of water on interface shear behavior (Yegian and Lahlaf, 1992; Ellithy and Gabr, 2001; Briançon et al., 2002). Yeging and Lahlaf (1992) performed direct shear tests under static loads and shaking table tests under dynamic loads for both dry and wet conditions. Ellity and Gabr(2001) found out that the influence of moisture on interface shear strength varies on the surface type of the geomembrane. Briançon et al. (2002) revised very large inclined plane testing apparatus (2.0m × 1.2m for lower box) to determine the friction characteristics of geosynthetic interfaces under wet conditions. In addition, Briançon et al. (2002) proposed new procedures to simulate the most common hydraulic conditions to which geosynthetics systems are exposed. However, the tilting table test has a limitation of being incapable of measuring the relationships between interface shear stress and displacement.

In testing the geomembrane and reinforced GCL interface, a variety of hydration methods have been applied (Gilbert et al., 1996; Eid et al., 1999; Triplett and Fox, 2001). Generally, the hydration of GCL is conducted in a shearing machine under shearing normal stress before the actual shearing test is initiated (Gilbert et al., 1996; Eid et al., 1999). However, this process required considerable time and cost, e.g. from 3 to 22 days. To overcome these disadvantages, Triplett and Fox (2001) performed geomembrane/GCL shearing tests using the *four-day, two-stage procedure* of Fox et al. (1998), which requires a significantly shorter period of time; four days, two days out of the machine and an additional two days in the machine.

This paper is focused on the influence of moisture in the interface shear strength between geomembrane/ geotextile and geomembrane/GCL. Laboratory tests are carried out using a large direct shear testing equipment that is capable of measuring peak and large interface shear stress at 80mm. The influence of the magnitude of normal stress is examined and the effects of interface wetting or GCL hydration methods are discussed in detail. Finally, comparisons are made with data of published works and comments on the design of geosynthetic-incorporated waste landfills are provided.

2. Laboratory Testing Program

2.1 Configuration of Materials

Three kinds of geosynthetics, i.e. geotextile, geomembrane and GCL, are used in the testing program (Table 1). Smooth and texured HDPE (high density polyethylene) geomembrane are applied. And two commercial GCL products are also chosen. GCL(A) is a reinforced one in which granular bentonite is held between a woven silt-film PP (polypropylene) geotextile (170g/m^2) and a nonwoven needle-punched PP geotextile (340g/m^2). To provide reinforcement, PP fibers are needle-punched through the bentonite and geotextiles. GCL(B) is an unreinforced GCL consisting of bentonite mixed with an adhesive and bonded to a geomembrane, which is a textured 2.0 mm thick HDPE material. The liquid and plastic limit are 484% and 45% for the bentonite encased within GCL(A) and 453% and 45% for the bentonite attached on GCL(B), respectively.

Table 1. Geosynthetics tested

Notation	Type	thickness (mass/area)
S-GM	smooth geomembrane	2.0 mm
T-GM	textured geomembrane	
GT	nonwoven geotextile	9.0 mm (1,000 g/m^2)
GCL(A)	woven/nonwoven needle punched	7.0 mm (4,100 g/m^2)
GCL(B)	bentonite attached to geomembrane	8.0 mm (6,650 g/m^2)

2.2 Direct Shear Testing

Direct shear tests are performed on large (300 × 300 mm) rectangular geosynthetic specimens. It has a maximum travel of 100 mm with no loss in area of the shear plane. The geosynthetic is cut into rectangular shape for testing and clamped to the end of the lower and upper box. Then, the upper box is placed on the lower box and two geosynthetics are placed next to each other. Five normal stresses, ranging from 6 kPa to 154 kPa, are applied using compressed fluid. The displacement of the lower box is controlled by a precise motor control system with the horizontal movement monitored by a Linear Variable Differential Transformer (LVDT), when a shearing rate is 1 mm/min. The horizontal load required to maintain the chosen shearing rate is measured by a load cell and displayed on a digital transducer readout.

Dry and wet (or hydration) conditions are applied for all of the interface shearing tests, where six types of interfaces are considered. Two kinds of geomembrane, S-GM and T-GM, have interface combinations with three other geosynthetic, GT, GCL(A) and GCL(B). In the case of GCL(A)/GM interface, the nonwoven part of GCL(A) contacts with GM and, for interfaces involved with GCL(B), the bentonite part of GCL(B) compose a interface with GM. Details for the shear testing program are listed in Table 2.

Table 2. List of experimental program

Interface	Condition of the interface
GT/S-GM GT/T-GM	Dry, wet
GCL(A)/S-GM GCL(A)/T-GM	Dry, hydrated (FS*, CH**)
GCL(B)/S-GM GCL(B)/T-GM	Dry, hydrated

FS* : hydrated under no normal stress, CH** : hydrated under a normal stress of 6 kPa

2.3 Wetting (Hydration) of Geosynthetic Interfaces

Geosynthetics are submerged or hydrated before being sheared to simulate the wet condition of interface. The wetting or hydration method is different depending on the type of the geosynthetic. For a case of geotextile, GTs are just submerged for one day to simulate wet condition. Whereas, different hydration methods are applied for two GCLs, GCL(A) and GCL(B). GCL(A) is hydrated (1) under no normal stress (Free Swelling, FS) and (2) under a normal stress of 6 kPa (Constrained Hydration : CH) for 10 days (Daniel et al. 1998). The FS indicates the condition where GCL installed in landfills is hydrated before waste is filled, and the CH models the condition in which GCL is hydrated with waste filling process.

The bentonite part of GCL(B) is assumed to be dry for all phases of landfilling because other geomembrane is generally laid above the bentonite. However, bentonite often becomes hydrated due to unexpected conditions. The testing for GCL(B)/GM interface is conducted to identify the reduction of strength with hydration, quantitatively. Daniel et al. (1993) presented that once water content of bentonite reaches or exceeds 50%, the shear strength declines to a value that is approximately equal to the strength of fully hydrated bentonite. As the water content of bentonite of GCL(B) reaches 50% within 10 min with no normal stress, GCL(B) is hydrated for 10 min in this experiment.

3. Results

3.1 Shear Stress Versus Displacement Behavior

Fig. 1 presents typical shear stress versus displacement relationships for six types of interfaces (Table 2) under a normal stress of 100kPa.

It can be seen that the peak strength is followed by significant strength reduction, i.e. strain-softening, as shear displacement proceeds for all the interfaces. The peak interface shear stress is usually mobilized at a shear displacement within 3mm for interfaces with smooth geomembrnae (S-GM). However, the peak shear resistance is developed at the displacement from 10 to 40 mm for interfaces involving textured geomembrane (T-GM), which implies that more displacements are required to mobilize the peak shear strength than the case with smooth gembembrane. Each failure occurs at the GM/geosynthetic interface and nonlinear behaviors, especially for interface between T-GM/geosynthetic, are observed at the region before peak strength is developed.

For interfaces of GT/GM (Fig. 1(a)), peak strength of S-GM decreased with interface wetting. Whereas, an increase in peak shear strength is observed for the T-GM at a normal stress of 100 kPa. However, these changes caused by interface wetting are not identical for all the ranges of normal stress.

In case of GCL(A)/GM interfaces (Fig. 1(b)), the most significant peak shear strength is observed in the dry condition, and the least on the FS (Free swelling) condition for interface involving T-GM. Also, more displacements are required to develop the peak shear strength on hydration condition compared with dry conditions.

Finally, for the interface of GCL(B)/GM (Fig. 1(c)), peak strength in dry condition is much more significant compared to that in GCL hydration condition. It can be seen that the strength of T-GM interface decreases considerably with the bentonite of GCL(B) hydration, which is attributed to the strength loss with bentonite hydration (Daniel et al. 1993). Then, the behavior of GCL(B)/T-GM in hydration condition appears to be comparable with the value of S-GM in dry condition.

3.2 Peak and Large Displacement Shear Strength

Peak shear strength versus the normal stress is plotted in Fig. 2. Failure envelopes are assumed to be approximately linear and characterized using Mohr-Coulomb failure criterion.

$$\tau = c + \sigma_n \tan\phi \qquad (1)$$

where, c and ϕ are apparent cohesion intercept (kPa) and interface friction angle determined from linear regression. Table 3 lists peak and large displacement (80mm) shear strength parameters for each interface.

For interfaces of GT/GM, peak and large displacement friction angle of S-GM decreases by about 1° as the interface becomes wet. However, peak or large displace-

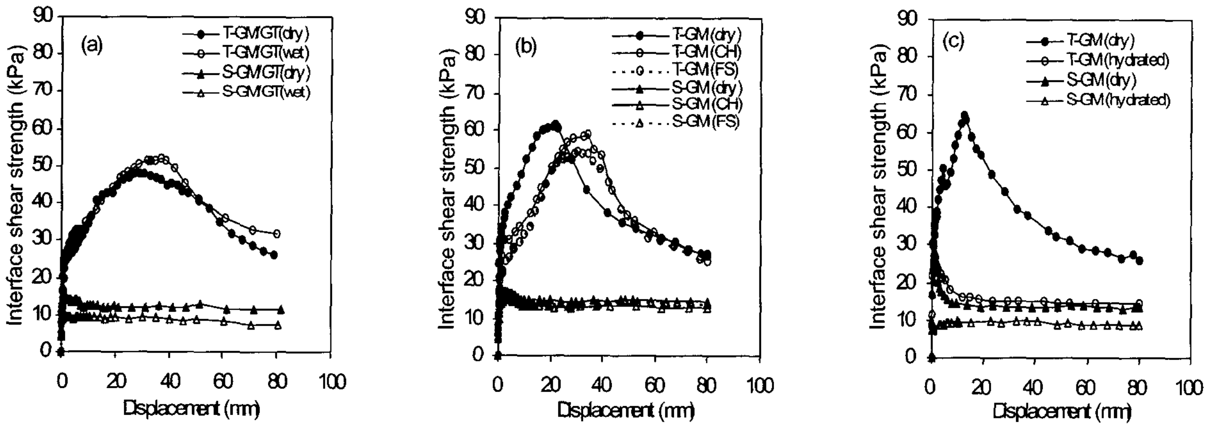

Fig. 1. Shear stress-displacement relationships at a normal stress of 100kPa for; (a) GT/GM, (b) GCL(A)/GM and (c) GCL(B)/GM

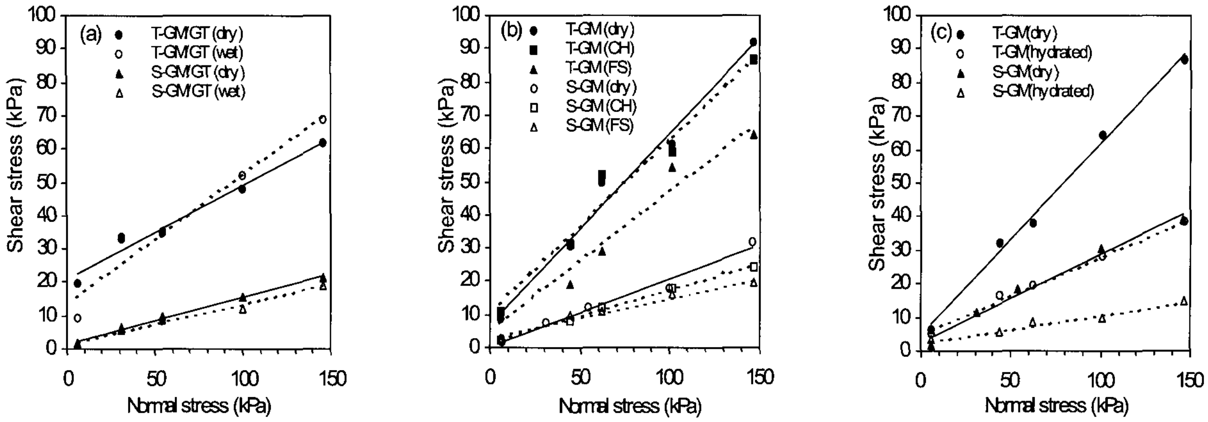

Fig. 2. Failure envelopes for peak shear strength: (a) GT/GM, (b) GCL(A)/GM and (c) GCL(B)/GM

Table 3. Peak and large displacement shear strength

Interface	State of interface	Peak strength		LD* strength	
		Friction angle (°)	Apparent cohesion (kPa)	Friction angle (°)	Apparent cohesion (kPa)
GT/S-GM	Dry	8.7	–	6.2	–
	Wet	7.6	–	5.2	–
GT/T-GM	Dry	15.7	20.7	10.3	9.4
	Wet	21.3	13.4	17.2	5.9
GCL(A)/S-GM	Dry	11.6	0.2	7.8	1.6
	FS*	6.6	3.4	5.6	3.0
	CH*	9.0	1.8	5.4	2.2
GCL(A)/T-GM	Dry	30.0	7.0	16.8	2.4
	FS	22.8	4.9	10.8	2.4
	CH	27.6	10.3	14.1	5.5
GCL(B)/S-GM	Dry	14.6	2.6	7.3	2.5
	Hydrated	4.6	2.7	4.4	1.7
GCL(B)/T-GM	Dry	29.7	4.4	13.1	4.3
	Hydrated	13.0	4.8	4.5	4.5

ment friction angle of GT/T-GM interface increases and cohesion, on the contrary, decreases with the interface wetting, which indicates that the water at the interface between GT and textured GM (T-GM) works as an anti-lubricant under high normal stress ($\geq$50kPa).

In cases of interfaces involving GCL(A), the shear strength under dry condition is comparable with that on the CH condition at the range of low stresses. However, as the normal stress increases, the shear strength on dry condition is seen to be slightly higher than under CH condition, which is observed for both interfaces, S-GM and T-GM. The shear strength on FS condition is the lowest for both interfaces under all ranges of normal stress tested in this experiment. This difference can be explained by the water extruded into the interface. The extruded water or bentonite gets increased as normal stress applied increases under FS condition. Then, the extruded water forms slight water film, which gives rise to strength reduction.

Finally, for GCL(B)/GM interfaces, significant reduction of peak strength is observed with bentonite of GCL(B) hydrated (Fig. 2(c)) as identified from stress-displacement relationship. Especially, the shear strength between GCL(B) /T-GM under hydration condition decreases to the value of GCL(B)/S-GM in dry condition. The decrease is assumed to be the result of the loss in strength of the bentonite part with hydration. The final water contents of GCL(B) are 86% and 73% for S-GM and T-GM, respectively. The water content can be a dominant factor for interface shear strength of bentonite hydrated.

3.3 Strength Reduction (Strain-softening)

Strain-softening is prevalent in many waste containment system interfaces. Most curves identified from this experiment also display marked strength reduction from peak to large displacement state (Fig. 1). In order to quantify the magnitude of strength reduction, strength ratio, i.e. large displacement to peak strength, is evaluated for each interface. The strength reduction with increasing displacement is known to be caused by geosynthetic polishing, geosynthetic failure or clay particle reorientation for interfaces involving soil (Gilbert and Byrne, 1996). The large displacement strength ratio for each interface is plotted versus normal stress in Fig. 3. The average values of strength ratio are summarized in Table 4, where strength ratio is defined as the ratio of large interface shear strength to peak shear strength.

Although it is observed that T-GM interfaces displays more strength reduction than S-GM, any clear relationship between normal stress and strength reduction or consistent effect of moisture on strength reduction has not been found. Simply, some increases of strength ratio caused by water or hydration are observed only for GCL(A)/S-GM under FS condition and GCL(B)/S-GM on hydration state. For GT/T-GM interface, the strength reduction at the displacement of 80 mm is also somewhat mitigated due to water. Finally, the values listed in Table 4 may be referred to on the design of geosynthetic installed sites where large displacements are expected to occur due to steep slope, soft waste and so on.

Table 4. Strength ratio of peak to large displacement state

Interface	State	Strength ratio (large displacement/peak)
GT/S-GM	Dry	0.65
	Wet	0.69
GT/T-GM	Dry	0.56
	Wet	0.65
GCL(A)/S-GM	Dry	0.82
	FS	0.85
	CH	0.70
GCL(A)/T-GM	Dry	0.52
	FS	0.53
	CH	0.49
GCL(B)/S-GM	Dry	0.60
	Hydrated	0.83
GCL(B)/T-GM	Dry	0.55
	Hydrated	0.52

3.4 Effect of Normal Stress on Secant Friction Angle

The interface shear strength parameters, c and ϕ, which are determined using Mohr-Coulomb failure criterion, are obtained from a best-fit straight line of the shear and normal stresses acting on the interface at failure. However, it has been suggested that the failure envelope can not always be characterized as a straight line. The

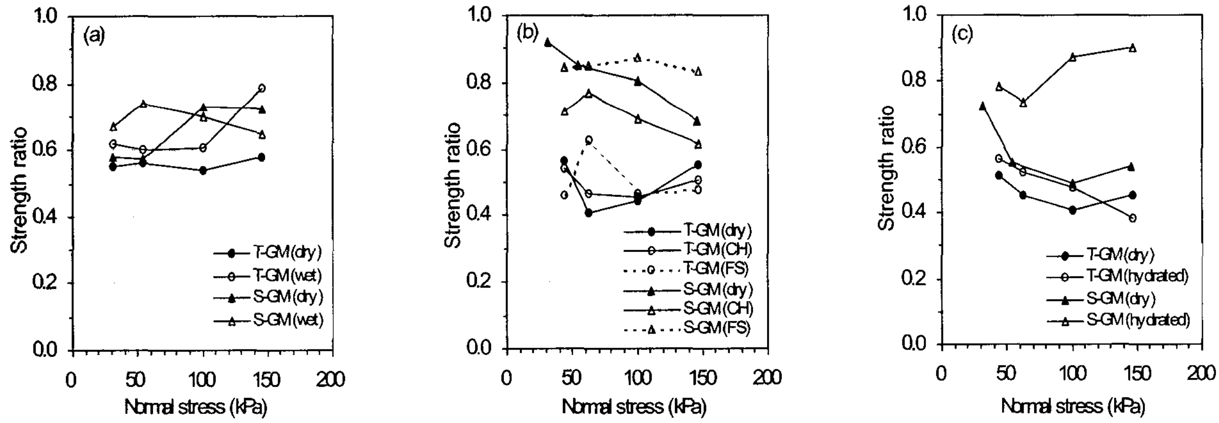

Fig. 3. Strength ratios for; (a) GT/GM, (b) GCL(A)/GM, and (c) GCL(B)/GM interface

peak secant friction angel versus the normal stress is plotted in Fig. 4, showing a dependency of friction angle on the normal stress.

In Fig. 4, a new term, 'secant friction angle', is used to identify the effect of normal stress. The secant friction angle is calculated using Equation (2) and this angle means that of slope at which sliding occurs (Wasti and Özdüzgün, 2001).

$$\phi_{secant} = \tan^{-1}(\tau/\sigma_n) \tag{2}$$

where, τ and σ_n are the shear strength and normal stress, respectively. The friction angles are summarized at Table 5 together with water condition and range of the normal stress. The design values in Table 5 can be used as a good reference showing critical slope angle of sites at which each geosynthetic interface is regarded as the weakest plane.

The plotting of peak secant friction angle versus normal stress illustrates that the friction angle decreases with increasing normal stress and the influence of level of normal stresses is much more pronounced for textured GM (T-GM). Friction angle at peak state is seen to be reduced due to water effect at all the interfaces, but with the only exception for GT/T-GM as shown in the upper lines of Fig. 4(a). The overall trends are supposed to be comparable to the results of interface shear strength according to the normal stress as shown in Fig. 2.

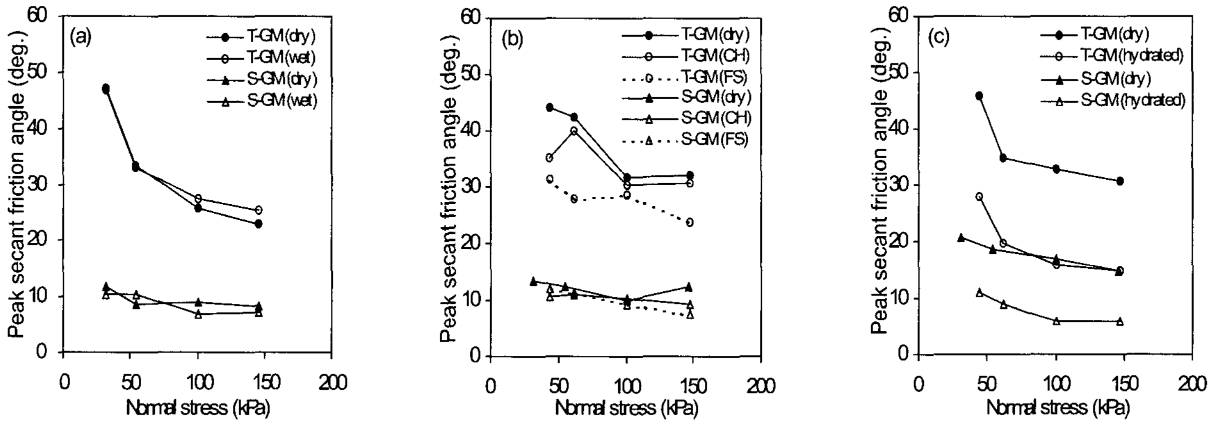

Fig. 4. Peak secant friction angle with the normal stresses; (a) GT/GM, (b) GCL(A)/GM and GCL(B)/GM

Table 5. Range of peak secant friction angle

Interface	State	Range of peak friction angle (deg.)	Range of the normal stress (kPa)	Final average water content (%)
GT/S-GM	Dry	8 - 12	31 - 146	-
	Wet	7 - 10		
GT/T-GM	Dry	23 - 47		
	Wet	25 - 47		
GCL(A)/S-GM	Dry	10 -12	31 - 146	-
	FS	8 - 12		230
	CH	9 - 11		130
GCL(A)/T-GM	Dry	32 - 44	44 - 146	-
	FS	24 - 31		221
	CH	31 - 40		140
GCL(B)/S-GM	Dry	15 - 21	31 - 146	-
	Hydrated	6 - 11		86
GCL(B)/T-GM	Dry	31 - 46	44 - 146	-
	Hydrated	15 - 28		73

4. Discussions

4.1 Comparison with Published Testing Results

4.1.1 Geotextile/geomembrane

Yegian and Lahlaf (1992) conducted static direct shear tests (20.3×30.5cm) to evaluate the interface shear strength between geotextile/smooth geomembrane under dry and submerged conditions. The friction angles corresponding to the submerged condition were consistently smaller than those corresponding to the dry condition by about 1-2°, which is well consistent with the results obtained from this research. As expected, the peak dynamic friction coefficient under submerged conditions was found to be slightly lower than that under dry conditions by about 0.6°.

Briançon et al. (2002) performed an inclined plane tests, known to be more appropriate for the cases of low normal stress, to verify the influence of water on GLS (Geosynthetic Lining System) stability. They found out that the decrease of interface friction angle is usually not consistent, depending on the kinds of geotextile and geomembrane. The difference of friction angle from dry to wet condition varies from one interface to another, 1.5° for smooth PP geomembrane with the geotextile for reinforcement, 1.3° for HDPE geomembrane with the geotextile for protection, and 4.3° for PP geomembrane with the geotextile for protection. Girard et al. (1990) also carried out a tilting table (1.0×1.0m) to measure friction angle between PVC geomembrane and nonwoven geotextile. They observed that the presence of water reduces the angle by between 2.5° for smooth geomembrane and 5.0° for textured geomembrane. The decrease of friction angle for textured geomembrane matches well with these testing results (Fig. 2, Table 3) of reduction of shear strength on the low normal stress.

4.1.2 GCL(A)/Geomembrane

As reinforced GCL (GCL(A)) can transmit more shear stress across the bentonite layer than unreinforced GCL (GCL(B)), the reinforced GCLs like GCL(A) are being widely used as an alternative of compacted clay liner in landfills for higher shear strength applications.

Triplett and Fox (2001) employed a different hydration method in which GCL specimens are hydrated under a normal stress applied during sheared using four-day and two-stage procedure described by Fox et al. (1998). The results of Triplett and Fox (2001) are compared with present testing results to examine the influence of different hydration method on interface shear strength characteristics. The comparison results are illustrated in Fig. 5 for smooth and textured geomembrane.

Fig. 5 displays that the results in CH condition are in good agreement with those of Triplett and Fox (2001). The findings from the comparison support the possibility that the results from hydration under 6kPa can be used as data for design purpose.

4.2 Design Implications

Generally, a factor of safety, Fs, is calculated to evaluate the overall stability of landfill sites in which

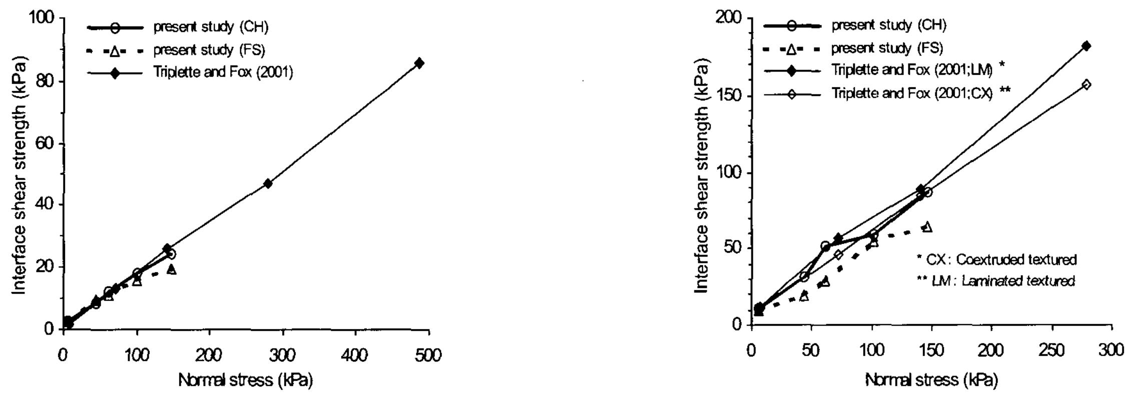

Fig. 5. Comparison results with published data for the interface of GCL(A)/GM; (a) GCL(A)/Smooth GM and (b) GCL(A)/textured GM (LM : laminated textured, CX: coextruded textured)

various geosynthetics are installed and the effect of water or water-flow on interface shear strength is taken into account (Koerner and Hwu, 1991; Giroud et al. 1995). In calculating the F_S of slope stability, Briançon et al. (2002) suggested from the results determined on the inclined plane that water has such different effects as decreasing friction angle, cover soil weight and friction force due to water pressures at the interface. It was also observed from this work that friction angle considerably changes with respect to water and the normal stress applied. Then, some problems about which value of F_S should be used arise. Until now, one value, ranging between 1.25 to 1.5, has been widely chosen as criterion for slope stability.

On the other hand, peak shear strength may not be appropriate to ensure safe stability because the weak interfaces between geosynthetics show strain-softening behavior. In softening displaying material, deformations in the waste under gravity are sufficient in many cases to limit the available shear resistance along an interface to less than the peak strength. Based on comparisons of data at the Kettleman Hills landfill failure with FEM analysis considering progressive failure which reflects the strain-softening characteristic of geosynthetic interfaces, Filz et al. (2001) reported the mobilized strengths are about 7% higher than the residual strengths. Gilbert and Byrne (1996) also suggested analytical model to provide useful insight on the available shear resistance along interfaces in containment systems. They emphasized that the potential for reductions in mobilized resistance is considerably affected by waste stiffness, rate of strain-softening and length of the slip surface. Therefore, the determination of shear strength parameter, peak or large displacement, and the value of FS should be accessed carefully so that the design is not made too conservatively or unstably.

In addition, it is particularly recommended that tests be carried out at the anticipated normal stress, which can be well identified through the fact that friction angle changes with normal stresses (Fig. 4; Wasti and Özdüzgün, 2001). Moreover, the water condition of interface, hydration of GCL and loading condition when hydrated should also be taken into account in the design process of landfill sites, including various geosynthetics. If geosynthectics are installed on rainy days, the friction characteristics of a critical interface on the wet condition should be considered for the evaluation of slope stability. The data included in Tables 4 and 5 can be good reference values on the design of geosynthetic interfaces for the purpose of choosing the friction angle under the range of normal stresses applied and the consideration of water effect.

Finally, the interface shear strength between GCL and other geosynthetics may be a more critical parameter on the design of landfills, where a needle-punched GCL (GCL(A)) is installed, than internal shear strength of GCL. Then, it would not be a problem to use the parameters on CH condition as confirmed by comparison with published results. For the unreinforced GCL, i.e. GCL(B), the bentonite part of GCL(B) is, as mentioned previously, known not to be easily hydrated when geomembrane is placed upon GCLs because two impermeable geomembranes surround the bentonite. Therefore, the use of interface shear strength on dry condition can be accepted reasonable for most landfills only if good QA/QC is assured. However, as is reported by 14 full-scale field test plots (Daniel et al. 1998), the bentonite often gets hydrated and the shear strength reduced as shown in Fig. 2.

5. Conclusions

A series of large-scale direct shear tests have been performed on interfaces of GT/GM and GCL/GM to examine the effect of the presence of water or hydration on interface shear strengths. The interface shear strengths are measured for the following geosynthetics: a smooth geomembrane (S-GM), a textured geomembrane (T-GM), a geosynthetic clay liner (GCL). Consequently, the following conclusions can be drawn based on the test results and discussions above.

(1) Shear stress and displacement relationship curves show that interface shear behaviors are clearly

influenced by moisture presence or hydration of the bentonite portion of GCL. For GCL(A)/T-GM interfaces, more displacements are required to develop the peak shear strength under wet condition compared to dry condition. The differences caused by the effects from moisture are not consistent in all interfaces but variable according to the types of interfaces and materials involved. In addition, the significant decline in shear stress is observed for GCL(B)/GM with interface hydration.

(2) The shear strength failure envelopes at peak shear strength and large displacement were approximated to have linear relationship with the normal stress during the test. From linear approximations, changes in the interface shear strength could be clearly identified. For S-GM/GT interfaces, the shear strength is reduced with interface wetting. In the case of GCL(A)/GM, the strength in FS condition was the lowest value under all ranges of normal stresses. The shear strength of GCL(B) decreased significantly with the hydration of bentonite portion.

(3) The results from large-scale direct shear tests show the interface shear strength degradation from the peak to large displacement range. Relatively significant strength degradation is observed in the interface of T-GM. The suggested strength ratios in this paper can be referred to for the design of geosynthetic-installed sites where large displacements are expected to occur due to steep slope and deformable characteristics of soft wastes.

(4) The plotting of peak secant friction angle against normal stress illustrates the decrease of friction angle due to an increase in normal stress. The influence of changes in normal stress is more pronounced for textured GM. Friction angles at peak state also decrease due to the effects from moisture at all interfaces except GT/T-GM interfaces.

(5) Test results were compared with a few published data for the interfaces of smooth geomembrane/geotextile. Generally, good consistency is found from comparisons of all interfaces. The friction angle corresponding to the wet condition is consistently smaller than that corresponding to the dry condition by 1 to 2 degree. According to published test results, the friction angle also decreases with interface wetting for textured geomembrane. Results of interface shear strength tests that have been performed under low normal stress agree well with published test data.

(6) The shear strength of GCL(A) at CH condition, where 6kPa is applied before shearing, showed good agreement with published data from different hydration methods. This fact implies a possibility that the results from hydration under 6kPa can be used as a data for design purpose.

(7) The selection among peak, residual, and factored values is a critical problem. The use of peak shear strength may not be appropriate in ensuring safe stability due to the strain-softening characteristics of interface behavior. Moreover, the determination of Fs value should be done with great care, while considering the field conditions and imperceptible uncertainties. Therefore, the selection of shear strength parameter and factor of safety values should also be accessed with discretion. In addition, it is particularly recommended that tests should be carried out at the anticipated normal stress.

(8) For GCL(B) design, the values of interface shear strength on dry condition based on test results are reasonably accepted for waste landfills only if good QA/QC are assured. However, field tests show that it is not easy to keep interfaces dry.

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(received on Mar. 11, 2004, accepted on Apr. 10, 2004)