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Chemical and Cyclic Degradation of Geosynthetic-Soil Interface†

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Different materials comprise interface at each boundary and the interface exists inevitably in all geotechnical systems. The interface shows complicated and sensitive behaviour because it is affected by many practical factors such as material, load and environment. Geosynthetic-soil interface is typical at the waste landfill site and the dynamic shear behaviour is critical to the seismic stability of the site. Chemical aggressor in the leachate affects the shear strength of the geosynthetic-soil interface. In this research, chemical degradation of the interface was investigated by cyclic simple shear test and different shear stress degradation patterns were estimated. The disturbed state concept was employed to analyze the test results and new disturbance function parameters with respect to the different damage patterns were suggested. Microscopic observation by focused ion beam was introduced and utilized to clarify the variation of interface damage. Consequently, the variation of the cyclic shear behaviour at geosynthetic-soil interface was due to the different damage pattern at soil particle surface based the focused ion beam results.

Keywords: Geosynthetic-soil interface, Chemical degradation, Cyclic simple shear test, Disturbed state concept, Focused ion beam.

INTRODUCTION

Geosynthetics in the waste landfill site play an important role such as protection, separation, encapsulation, reinforcement. Geosynthetics comprises the interface with surrounding soil and the shear resistance of the interface is the most important factor to maintain overall stability of the waste landfill site. The dynamic response of geosynthetic-soil interface is more complex and significant because dynamic loading can induce various modes of motion such as slip, loss of contact or debonding, recontact or rebonding at the interface[1]. Cyclic simple shear test is commonly used because it can simulate the field conditions during the earthquake at a reasonable cost. Desai *et al.*[2], proposed new constitutive model and parameters of saturated sand-concrete interface using modified cyclic simple shear device.

In addition to the conventional researches on cyclic test condition, chemical effect on the geosynthetic-soil interface is significant. However, it has not been studied intensively yet. In a waste landfill site, leachate is generated by biological and chemical process with water and waste inside. Chemical aggressors in the leachate may affect the behaviour of the interface and it was reported that the cyclic loading could accelerate the effects of chemical attack[3]. Rowe *et al.*[4] investigated the effects of leachate chemical composition on high density polyethylene geomembrane and presented acid or basic solution showed relatively fast antioxidant depletion than neutral according to the temperature. However, majority of previous studies were focused on the geosynthetics, not on the geosynthetic-soil interface. Nowadays, microstructural approach became considered as a useful means to investigate the characteristics of the material and interface behaviours. Raghavan and Ghosh[5] developed a continuum damage mechanics (CDM) model for fiber reinforced composites with interfacial debonding based on micromechanical analysis using finite element method. Menut *et al.*[6] analyzed solid surface by laser-induced breakdown spectroscopy (LIBS) and developed quantitative surface mapping of multiple elements. Kim *et al.*[7] reviewed the developments and processing of focused ion beam (FIB).

In this research, shear behaviours of geosynthetic-soil interface were investigated by experimental work. The disturbed state concept (DSC) was utilized to analyze test results and to estimate the degree of damage quantitatively. New disturbance parameters which represent the chemical degradation of the interface under cyclic loading were suggested. Furthermore,

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microscopic observation was conducted by focused ion beam (FIB) to clarify the different shear behaviour depends on the chemical conditions.

EXPERIMENTAL

The behaviour of interface is complicated and difficult to predict because the contacts between different materials are involved with many practical factors. Especially, the dynamic loading increases the complexity and accelerates the chemical attack in the geosynthetic-soil interface. Therefore, a comprehensive solution is required to estimate the damage at the interface and the disturbed state concept was employed in this study.

It has been proved that this theory shows advantages to analyze the dynamic behaviour of materials and interfaces. Many successful results of the numerical modeling have been reported[8]. The initial theory of disturbed state concept (DSC) was designed by Desai[9] to characterize the softening response of an overconsolidated soil[10]. The details of disturbed state concept including the basic theory, equations and the disturbed functions were reviewed in the previous study[8].

Interfaces exhibit various and complicated shear behaviours and can be affected by practical factors, accordingly, an appropriate and realistic laboratory testing is most critical and vital. Cyclic simple shear tests were performed using a modified multi-purpose interface apparatus (M-PIA) to study the cyclic shear behaviours of the geosynthetic-soil interface under different chemical conditions. Details on the initial and modified versions of M-PIA were introduced in the previous study[8]. Fig. 1 displays the schematic of the modified M-PIA.

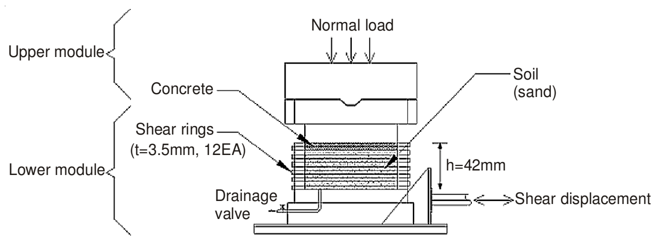


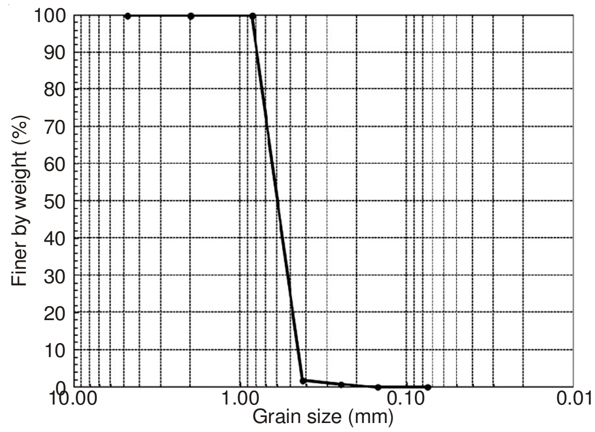
Fig. 1. Schematic diagram of the modifed multi-purpose interface apparatus[8]

Geosynthetic-soil interface is composed Jumunjin sand and geocomposite which is the most common type of geosynthetics in waste landfill sites in Korea. Non-woven fabric was bonded on both faces of HDPE geonet and Carbon black and antioxidant were appended to improve chemical resistance. Fig. 2 shows the conditions of the materials and Table-1 displays the engineering properties of Jumunjin sand.

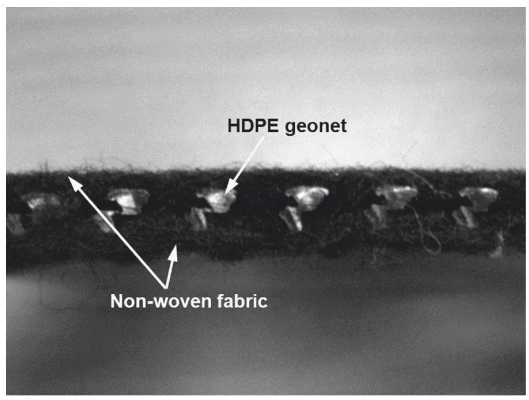
TABLE-1
ENGINEERING PROPERTIES OF JUMUNJIN SAND

Gs	$\gamma_{d,max}$ (kN/m^3)	$\gamma_{d,max}$ (kN/m^3)	e_{max}	e_{min}
2.627	16.37	13.63	0.908	0.527

Based on the previous study, the average unit weight of hazardous waste landfill site shows 15.9-17.3 kN/m^3 [11], 0.3 MPa of normal stress which represent the height of 20 m of waste landfill was applied by upper module. 0.5 Hz of cyclic



(a) Jumunjin Sand (grain size distribution)



(b) Geocomposite (surface and section)
Fig. 2. Material conditions

sinusoidal shear displacement was exerted by the electric-servo motor. Closed loop with PID control program was embedded in the load system to obtain precise and stable output. 3 % of shear strain was applied based on the preliminary tests. pH value is adopted as a main chemical condition since pH values vary dramatically in the leachate[11]. Acid, basic and neutral solutions were prepared by standard buffer solutions. Soil and geosynthetic specimens both were submerged into the solutions for 30 and 850 days to consider short and long-term behaviours. Table-2 demonstrates the chemical conditions.

TABLE-2
DEMONSTRATES THE CHEMICAL CONDITIONS

Solutions	Basic	Neutral	Acid
pH	10	7	4
Main chemical element	Sodium bicarbonate ($NaHCO_3$)	Potassium hydrogen phthalate ($C_8H_5O_4K$), Phosphate (Na_2HPO_4)	Potassium hydrogen phthalate ($C_8H_5O_4K$)
Submerging period	30 days	30 days	30 days
	850 days	850 days	850 days

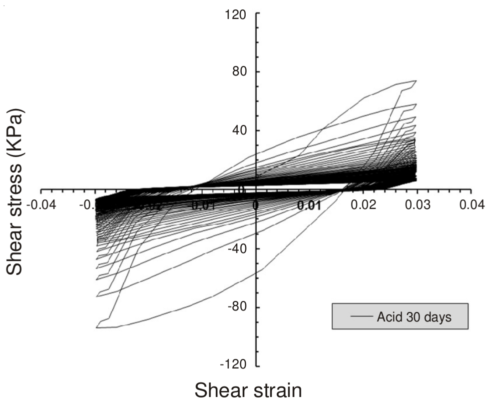
Test condition is divided by submerging period, normal stress and pH, then 6 times of test (totally, 36 sets) were performed at each condition.

General procedure: General procedure for the cyclic simple shear tests were given below: **(1) Specimen setting:** Soil and geosynthetics are located in a mold. Rubber membrane wraps the soil and geosynthetics and 12 shear rings are also encircle the specimen. **(2) Test condition setting:** Input the test conditions such as the frequency, strain and normal load. **(3) Applying static load:** To simulate the *in situ* stress condition, static loads are exerted by the upper module. **(4) Applying cyclic load:** To simulate the dynamic condition, cyclic loads are exerted by the lower module. **(5) Termination:** Cyclic loads are terminated until the specimen reaches the FA state. In this study, maximum 200 cycles are applied.

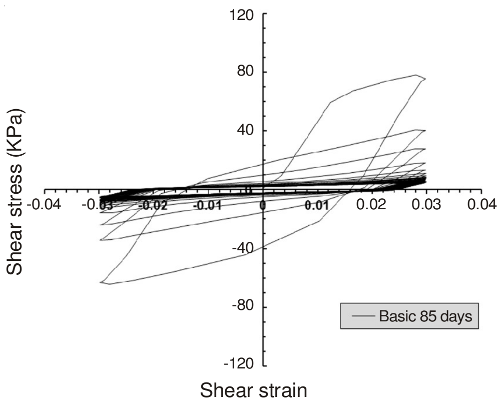
Detection method: All responses such as time, normal force, shear force and strain from the apparatus are stored automatically in the computer.

RESULTS AND DISCUSSION

First of all, shear stress and strain curves were obtained by the cyclic simple shear test using the modified M-PIA. Fig. 3 displays representative shear stress-strain relationships for the chemical conditions. Shear stress degradation was observed in all cases and more loading cycles are required to fail under short-term (30 days) of submerging period. The first cycle was considered as relatively intact state and fully adjusted state was considered after the converging of the hysteresis curves. In short-term behaviour, the hysteresis curves converged after 50 cycles, however, the curves converged after 20 cycles in long-term (850 days of submerging period) behaviour. Therefore, it is induced that the geosynthetic-soil interface undergoes more damage at relatively initial stage of loading cycles. The gradient of shear stress-strain curves at each cycle decreased with the loading cycle, which denotes the increase of the FA parts inside the material.



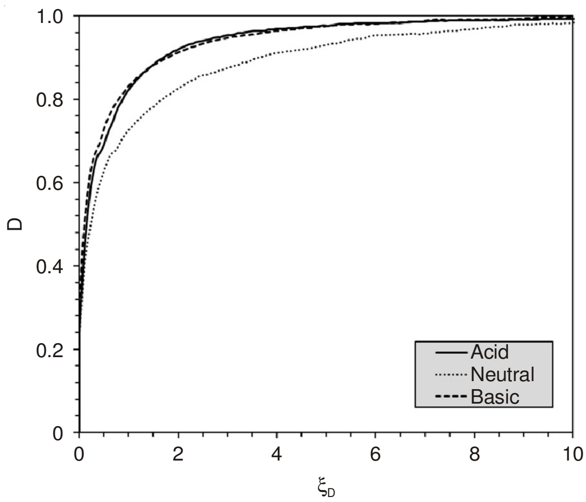
(a) Acid, 30 days of submerging period



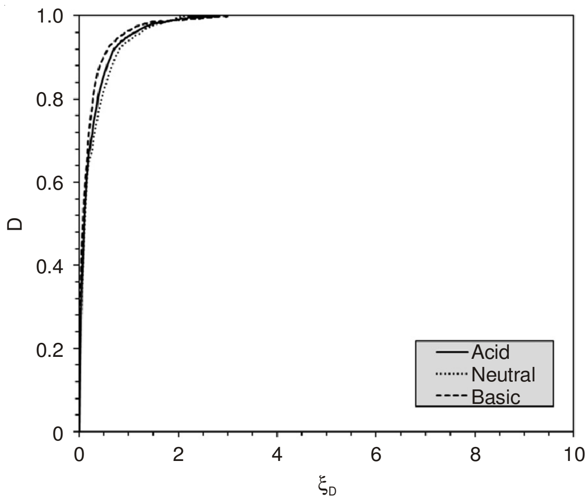
(b) Basic, 850 days of submerging period

Fig. 3. Example of shear stress-strain curves

The degree of damage (D) at the geosynthetic-soil interface can be defined by the disturbance function, D mathematically. Fig. 4 presents the estimated disturbance function curves based on the test results.



(a) 30 days



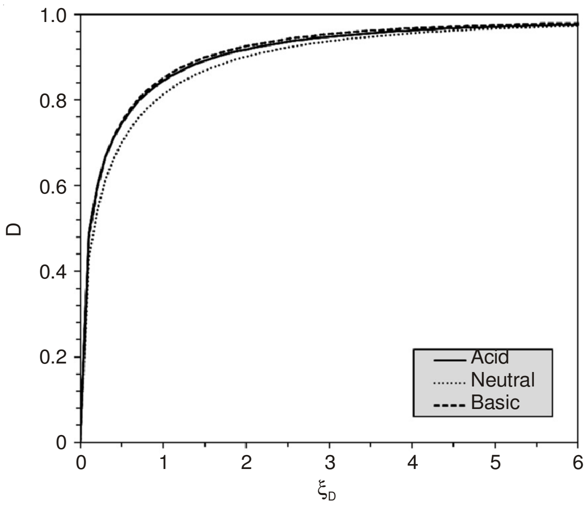
(b) 850 days

Fig. 4. Disturbance function curves according to submerging period

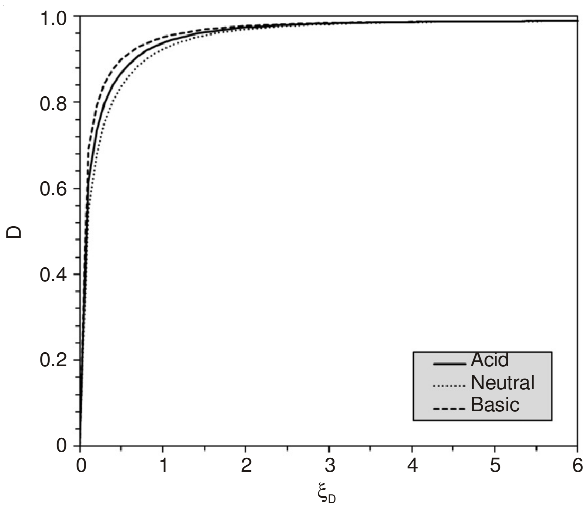
Fig. 4 showed that the disturbance increased more rapidly at the early stage under the long-term condition, which presents the geosynthetic-soil interface is vulnerable to submerging period. In short-term behaviour, more damage was estimated under acid and basic condition than neutral condition. The degree of damage at acid and basic was almost identical. In long-term behaviour, damage was more severe at basic than acid condition. Therefore, it is induced that the basic condition entails more shear-stress degradation at the geosynthetic-soil interface under cyclic loading. The A and Z values in the disturbance function are the intrinsic material properties and affected by practical factors such as loading, material type, stress, *etc*. and determine the shape of the disturbance function. By linear regression method, the A and Z values can be obtained[8] (Table-3). Since 6 tests were performed at each case, the average value, lower and upper limit were suggested. Consequently, the disturbance function curves were reproduced in Fig. 5.

TABLE-3
A AND Z PARAMETERS

Submerging period (days)	Chemical conditions	Parameters	Average	Lower limit	Upper limit	Standard deviation
30	Acid	A	1.9269	1.4850	2.3688	0.4419
		Z	0.4536	0.4284	0.4788	0.0252
	Neutral	A	1.7287	1.6018	1.8556	0.1269
		Z	0.4859	0.4557	0.5161	0.0302
	Basic	A	1.9723	1.7276	2.2170	0.2447
		Z	0.4768	0.4477	0.5059	0.0291
850	Acid	A	2.9476	2.6730	3.2222	0.2746
		Z	0.4852	0.3858	0.5846	0.0994
	Neutral	A	2.7061	2.4916	2.9206	0.2145
		Z	0.5286	0.4171	0.6401	0.1115
	Basic	A	3.2338	2.8210	3.6466	0.4128
		Z	0.4329	0.3231	0.5427	0.1098



(a) 30 days



(b) 850 days

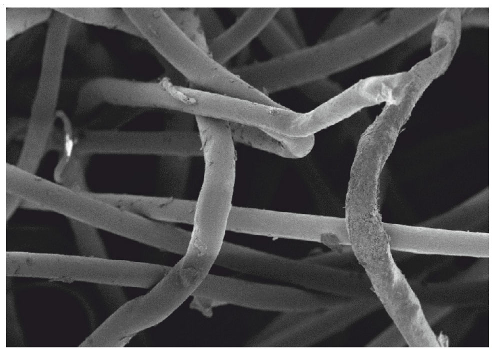
Fig. 5. Reproduced disturbance function curves

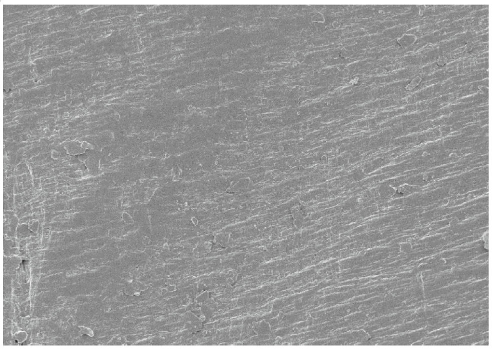
In Figs. 4 and 5, the disturbance function curves exhibited variation at each chemical condition. Different shape of disturbance function curve represents different shear behaviour against the chemical aggressors. The reason was investigated by microscopic approach using a focused ion beam microscope.

Focused ion beam: The technology of scanning an infinitesimal particles and detecting the resulting signals to form a magnified images has been an essential part of material science for about 50 years, since the commercialization of the scanning electron microscope (SEM)[12]. The focused ion beam, introduced more than a decade ago, was mainly developed during the late 1970s and the early 1980s with high brightness which came from the invention of the liquid metal ion sources (LIMS). Focused ion beam has advantages such as high current density, the capability of very fine focusing, choice of a wide variety of ion masses, large energy density and shorter penetration depth in solid. Nano-scaled material element is able to be observed with a high accuracy and 3-dimensional structures also be achieved[7]. Focused ion beam facility in the NICEM (National Instrumentation Center for Environmental Management) was utilized as shown in Fig. 6. Table-4 demonstrates the specification of focused ion beam.

Fig. 6. Focused ion beam laboratory

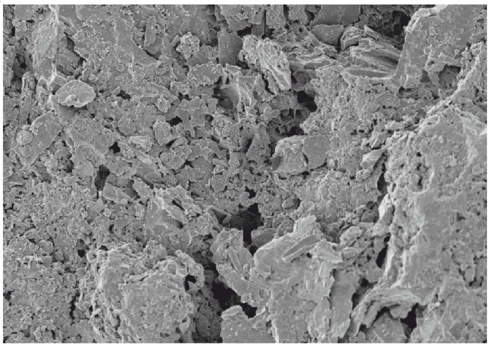
Geocomposite and soil particle were observed by focused ion beam according to the chemical conditions. Focused ion beam images on the geocomposite and soil particles were demonstrated in Figs. 7 and 8, respectively.


(a) Filament under acid (×500)

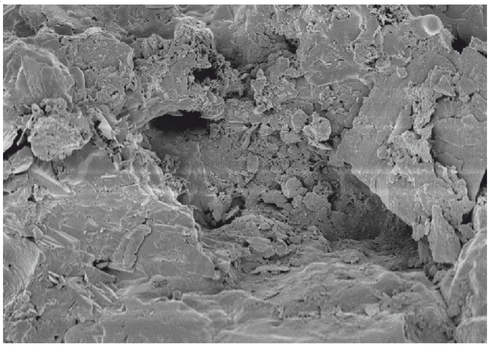


(b) HDPE surface under acid (×5,000)

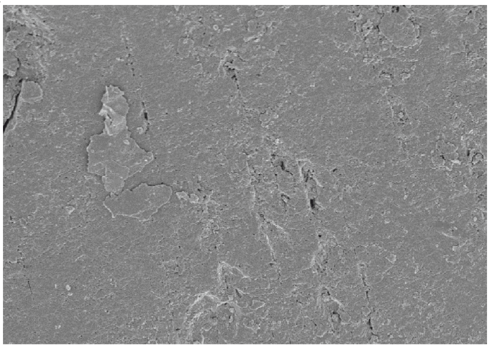
Fig. 7. Focused ion beam observation results on geocomposite (850 days)



(a) acid (×10,000)



(b) basic (×10,000)



(c) neutral (×10,000)

Fig. 8. Focused ion beam observation results on soil particle (850 days)

In Figs. 7 and 8, the damage of HDPE geonet of non-woven fabric was almost negligible at all chemical conditions, which shows consistent with the previous researches[13]. It is induced that the antioxidant and other ingredients such as Carbon black exhibited robust chemical resistance. On the other hands, for the sand particle, diverse patterns of damage were detected. Severe surface exfoliation was widely observed under the acid condition and pitting on the soil surface was observed under the basic condition. Consequently, different damage pattern at soil particle entails variation of the disturbance function curves and accordingly, different A and Z values are estimated.

In long-term behaviour, basic condition presented more severe disturbance than acid. This phenomenon appeared consistently in the tests and it is deduced that the exfoliated fine soil particles under acid condition locate at void and accordingly induce the densification effect during cyclic loading. Additionally, soil particle crushing was detected by focused ion beam due to the weakened material structure by chemical aggressors, as shown in Fig. 9. Sieve analysis with soil specimen after test was also performed to verify the transformation of particle size distribution as shown in Fig. 10. Grain diameter between 0.2 and 0.9 mm displayed diverse distribution under acid and basic conditions. Consequently, the effect of chemical attack was confirmed by FIB observation and sieve analysis.

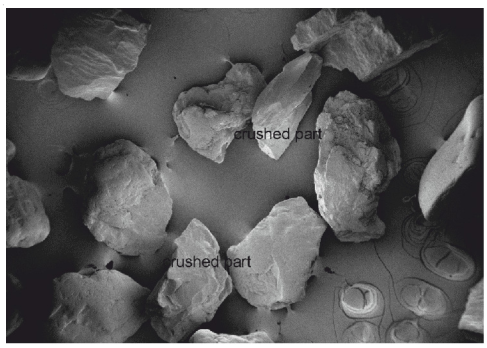


Fig. 9. Particle crushing observed by focused ion beam (acid, 850 days)

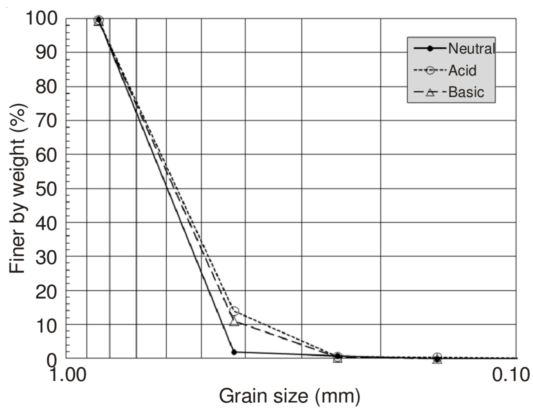


Fig. 10. Sieve analysis result

TABLE-4
SPECIFICATION OF FOCUSED ION BEAM[8]

Apparatus	Focused ion beam
Model name	AURIGA
Manufacturer	Carl Zeiss (Germany)
Main purpose	To observe the surface structures and conditions at the high-resolution, high-powered magnification.
Performance	Resolution: up to 1.0 nm (at 15 kV), acceleration voltage: 0.1-30 kV, magnification: × (12-100 million).

Conclusion

Strain-controlled cyclic simple shear test was performed to investigate the shear behaviour of geosynthetic-soil interface considering chemical effect. Obvious shear stress degradation with the increase of loading cycle was obtained. The disturbed state concept was utilized to estimate the damage at the interface quantitatively. Acid and basic conditions were more severe than neutral in short-term behaviour and basic condition was the most severe in long-term behaviour. Based on the test results, the disturbance function curves were evaluated and new disturbance function parameters A and Z were also suggested. Microscopic approach by focused ion beam observation was performed to verify that reason of different shear response at the geosynthetic-soil interface. Consequently, it was proved that the different damage pattern at soil particle entails variation of the disturbance function curves based on the focused ion beam observation.

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