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Performances of Landfill Liners Under Optimum Moisture Conditions

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ABSTRACT

This paper addresses the study conducted on the performance of landfill liner interface parameters. Interface shear strength parameters for various combinations of 12 different lining materials were studied and presented in this paper. This comprehensive testing program covers the interfaces between: 1) soil and compacted clay liner (CCL), 2) geomembrane (HDPEs or PVC) and soil, 3) geosynthetic clay liner (GCL) / CCL and soil, 4) geomembrane and geotextile, 5) geotextile and soil, 6) geotextile and GCL / CCL, and 7) geomembrane and GCL / CCL. The experiments were conducted under optimum moisture condition. Tabulated summaries of interface test results under optimum moisture condition are presented in the paper.

KEYWORDS: landfill liner interface, interface shear strength, optimum moisture condition, geomembrane and geosynthetic

INTRODUCTION

The liners and closure cover system of a modern municipal solid waste (MSW) landfill are constructed with layers of material having dissimilar properties, such as compacted clay or geosynthetic clay liner, geomembrane (liquid barrier), geonet (drainage layer), geotextile (filter) and geogrid (reinforcement). While compacted clay liner or geosynthetic clay liner and geomembranes function effectively as flow barriers to leachate and infiltration, their interface peak and residual friction angles are lower than those of the soil alone. Such lower friction angle may present between geomembrane and other geosynthetics which could trigger much rapid failure during seismic loading conditions. The soil-geomembrane interface acts as a possible plane of potential instability of the system under both static and seismic loading (Ling *et al.* 1997; Saravanan *et al.*, 2006a; Saravanan *et al.*, 2006b). Hence environmental geotechnical engineers are concerned about this potential instability caused by the waste containment liner system which could be fatal and also harm the environment. Hence interface tests research was conducted for both optimum moisture condition and at saturated or wet condition to understand the performance trend.

INTERFACE TESTING APPARATUS

The objective of this research is to study the interface shear strength of landfill liner materials. The list of interface test conducted dependent on the configuration and material used for landfill liner system and adopted for the research. One of the typical liner configuration studied in the research is shown in Fig. 1. The research however studied various other configuration which consists of both single and double composite liner system. Figures 2, 3 and 4 shows section of large scale shear box used for the research work for three different test conditions. Namely (i) Case 1 – Interface testing between geosynthetic and geosynthetic, (ii) Case 2 - Interface testing between geosynthetic and soil, and (iii) Case 3 - Interface testing between soil and soil.

Bottom shear box size of 350 x 600mm and top box size of 250 x 500mm were used for the test. Larger 100mm bottom box was used to define test failure of 15% to 20% relative to lateral displacement of top box dimension. However, shearing surface contact areas were made to be similar for both top and bottom box of 250 x 500mm in size. Height adjustable bottom box base plate with spacer blocks were required to cater for variation in sample thickness and provide allowance for settlement or sample deformation during normal loading prior to shearing.

Constant shearing speed of 1 mm/min was used for test normal loads of 100, 200 and 300 kPa for the interface tests. ASTM D3080 -98, ASTM D5321-02 and ASTM D6243-98 was referred for the modifications of the said shear box.

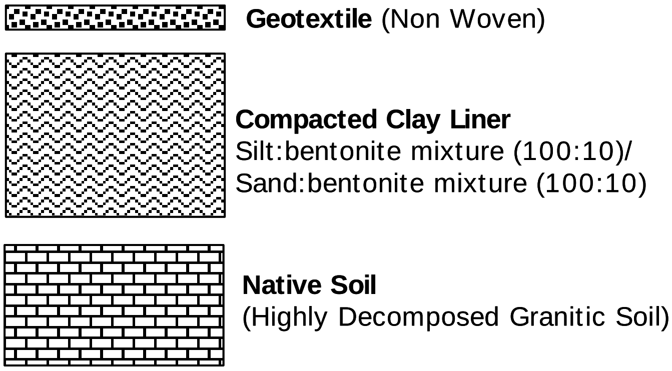

Figure 1: One of typical landfill liner configuration studied in the research

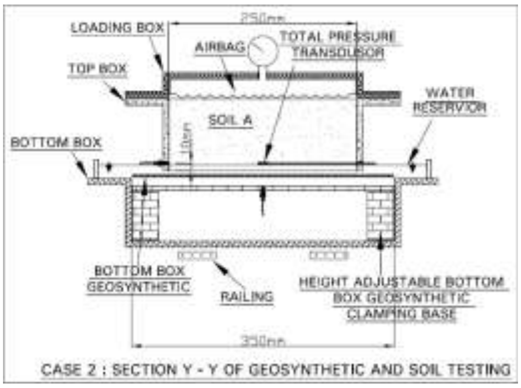

Figure 2: Case 1 – Interface testing between geosynthetic and geosynthetic

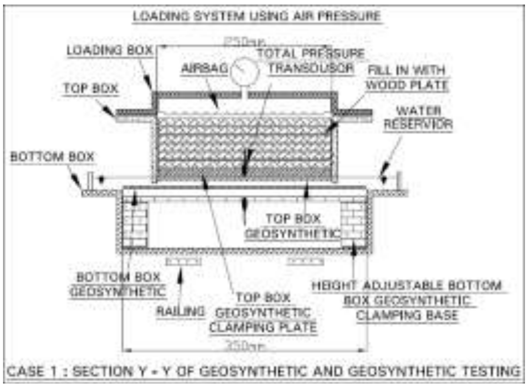

Figure 3: Case 2 – Interface testing between geosynthetic and soil

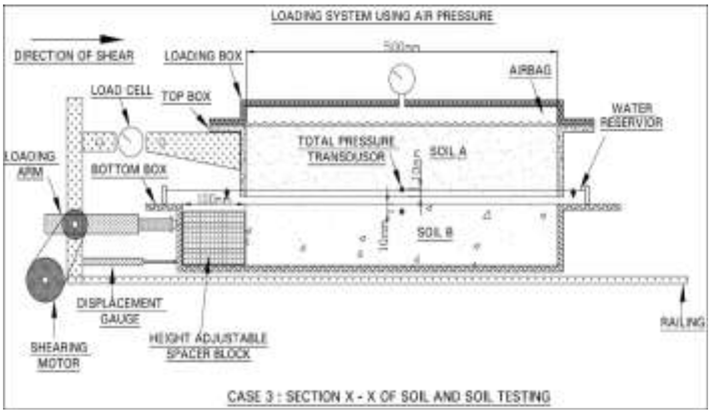

Figure 4: Case 3 – Interface testing between soil and soil

MATERIAL PHYSICAL PROPERTIES

Material physical properties were investigated for all the proposed test materials. Fresh soil and geosynthetic samples were used for each and every tests conducted. Summary of material properties are shown in Table 1, 2, 3 and 4 for soil and geosynthetics respectively.

Table 1: Summary of the physical properties of CCLs and native base soil

TEST USING CASAGRANDE		Sand:bentonite mixture (100:10)	Silt:bentonite mixture (100:10)	Granitic soil / Native soil
Liquid Limit, LL ,w_L	%	47	69	-
Plastic Limit, PL, w_P	%	23	35	-
Plasticity Index,PI, Ip		24	34	-
Average Particle Density, ρ_s	Mg / m^3	2.60	2.64	2.59
Dry Density, ρ_d	Mg / m^3	1.90	1.68	2.06
Optimum Moisture Content, MC	%	10.5	17.5	9.0
Classification as per USCS		CL / OL Organic silt or Clay of low plasticity	CH / OH Clay of high plasticity	Highly weathered granitic soil / SW-SM
SHEAR BOX TEST (Internal Failure)				
Total Cohesion, C_u	kPa	77.0	43.1	31.4
Total Friction Angle, ϕ	^{o}	34.3	35.8	45.5
CIU TEST RESULTS				
Total Cohesion, C_u	kPa	5	4	5
Total Friction Angle, ϕ	^{o}	25	22	30
Effective Cohesion, C'_u	kPa	0	0	0
Effective Friction Angle, ϕ'	^{o}	33.5	28	35
Hydraulic Conductivity	m/s	6 x 10^{-12}	8 x 10^{-12}	6 x 10^{-9}

Table 2: Summary of geosynthetic physical properties

Description	Geotextile	PVC	HDPE (Type 1 and 2)
Mass index	≥ 1070 g/m^2 JIS-L-1908	≥ 1940 g/m^2 JIS-L-1908	≥ 1550 g/m^2 JIS-L-1908
Thickness	≥ 10.0 mm JIS-L-1908	≥ 1.5 mm JIS-K-6250	≥ 1.5 mm JIS-K-6250
Tensile strength	≥ 160 N/cm (Weft - CD) ≥ 80 N/cm (Wrap - MD) JIS-L-1908	300 N/cm for both Weft and Wrap	544 ≥ 350 N / cm both Weft and Wrap JIS-K-6251
Elongation at break	≥ 55 % (Weft - CD) ≥ 70 % (Wrap - MD) JIS-L-1908	320 % for both Weft and Wrap	790 ≥ 560 % for both Weft and Wrap
Tear strength	≥ 200 N (Weft - MD) ≥ 200 N (Wrap - MD) JIS-L-1096	N/A	289 ≥ 140 N JIS-K-6252
Penetration	≥ 1000 N ASTM D4833-88	N/A	≥ 539 N ASTM D4833-88

Note
Asperity height for Textured HDPE (Type 2) is 10 mil average. 8 of 10 readings ≥ 7mils.
Weft – cross direction, Wrap – machine direction

Table 3: Summary of the physical properties of bentonite-glued GCL (Type 1)

Description	Properties
Finished GCL properties	
Bentonite coating (ASTM D5993)	≥ 3.66 kg/m²
Effective hydraulic conductivity (ASTM D5887/E96)	≤ 4 x 10^{-14} m/s
Bentonite moisture content (ASTM D2216)	25% Typical
Geomembrane properties	
HDPE Thickness (ASTM D 5994)	1.45 mm
Density (ASTM D1505)	0.94 g/cm³
Asperity height	7 ~ 10 mil
Tensile properties Tensile break strength (ASTM D6693) GCL tensile strength (ASTM D6768) Elongation at break (ASTM D6693)	16 N/mm 23 N/mm 150 %
Puncture resistance (ASTM D4833)	400 N
Sodium bentonite properties	
Hydraulic flux: Bentonite, (ASTM D5887)	≤ 1 x 10^{-8} m³/m² sec
Hydraulic conductivity of bentonite (ASTM D5084)	≤ 5 x 10 $^{-11}$ m/s
Free swell (ASTM D5890)	≥ 24 ml/2g
Fluid loss (ASTM D5891)	≤ 18 ml

Table 4: Summary of the physical properties of needle-punched GCL (Type 2)

Description	Properties
Finished GCL properties	
Mass per unit area (EN 965)	5000 g/m²
Thickness (EN 964-1)	6.0 mm
Max. tensile strength, md/cmd** (EN ISO 10319)	12.0 / 12.0 kN/m
Elongation at break, md/cmd** (EN ISO 10319)	10.0 / 6.0 %
Peel strength (EN ISO 10319)	≥ 60 N/10 cm
Peel strength (ASTM D 6496)	≥ 360 N/m
Permeability / Hydraulic conductivity (DIN 18130)	2 x 10 $^{-11}$ m/s
Index flux (DIN 18130)	5 x 10 $^{-9}$ (m³/m²)/s
Geotextile layer	
Cover layer 1	
Geotextile type	Polypropylene non-woven
Mass per unit area (EN 965)	220 g/m²
Carrier layer 2	
Geotextile type	Polypropylene woven
Mass per unit area (EN 965)	110 g/m²
Bentonite layer	
Power type	Natural sodium bentonite
Mass per unit area (EN 965)	4670 g/m²
Swell index (ASTM D 5890)	24 ml/2g
Fluid loss (ASTM D 5891)	≤ 18 ml
Water content (DIN 18121 (5 hrs, 105 ºC)	Approx. 10%

** md = machine direction, cmd = cross machine direction

The interface test results indicate different kind of failures at different levels of relative displacement or horizontal strain. The maximum shear stresses ranged from 1 to 15% displacement relative to sample length or top shear box size of 500mm. In order to consistently analyze the horizontal strain and shear stresses associated with failure, the maximum shear stress was a selection of either maximum shear stress, or the maximum shear stress reached within 8% of horizontal strain.

Based on the selection criteria the use of peak or residual interface strength is proposed to be assessed within the prescribed horizontal strain value of 8%. This is due to some of the test results presented in this paper have higher residual interface strength caused by horizontal strain hardening effect. Hence selection purely based on peak or residual interface strength in some cases could over or under estimate the interface resistance. Thus the selection of maximum shear stress within 8% horizontal strain was used as criteria in this research.

The unit of 8% horizontal strain was selected as criteria for landfill liner failure limit. At 8% horizontal strain there are potentials for geomembranes to tear, the tearing could lead to leachate pollution to the environment. Hence, balancing the criteria between geotechnically define peak and residual failure limits to failure limits which could harm the environment due to damages created on geosynthetic material during failure was suggested. The typical detail of shear stress selection method is shown in Fig. 6. Horizontal strain was used to identify shear stresses in place of displacement, as the test results can be compared with tests done with various other shear box sizes as reported by Hsieh *et al.* (2003). The selected shear stresses obtained were plotted against normal stresses to compute the failure envelope. To determine the total cohesion and total interface friction angle, best-fit linear plots were developed. The shear stress intersections were set to be through either axis or positive cohesion only. List of the tests conducted is presented in Table 5. The interface test results obtained are proposed to be grouped into following strength categories.

Friction (^{0})	Cohesion (kPa)	Proposed strength
$0^0 \sim 10^0$	0 ~ 10	Low
$10^0 \sim 20^0$	10 ~ 20	Medium
$>20^0$	>20	High

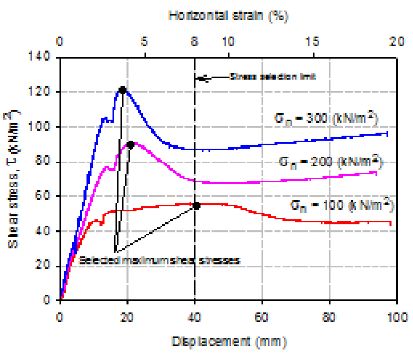

Figure 6: Failure stress selection criteria.

Table 5: List of the tests conducted

Interfacing material	Geotextile	Smooth HDPE (Type 1)	Textured HDPE (Type 2)	Rear side of PVC	Front side of PVC	Bentonite side of bentonite -glued GCL (Type 1)	HDPE side of bentonite -glued GCL (Type 1)	Non woven side of needle-punched GCL (Type 2)	Woven side of needle-punched GCL (Type 2)	Native soil
Smooth HDPE (Type 1)	Test 1A									
Textured HDPE (Type 2)	Test 2A									
Rear side of PVC	Test 3A									
Front side of PVC	Test 3C									
Bentonite side of bentonite-glued GCL (Type 1)	Test 4A	Test 6A	Test 8A	Test 10A	Test 10E					
HDPE side of bentonite-glued GCL (Type 1)	Test 4C	Test 6C	Test 8C	Test 10C	Test 10G					
Non woven side of needle-punched GCL (Type 2)	Test 5A	Test 7A	Test 9A	Test 11A	Test 11E					
Woven side of needle-punched GCL (Type 2)	Test 5C	Test 7C	Test 9C	Test 11C	Test 11G					
Silt:bentonite mixture (100 : 10)	Test 12A	Test 13A	Test 14A	Test 15A	Test 15C	Test 17A	Test 17C	Test 18A	Test 18C	Test 16A
Sand:bentonite mixture (100 : 10)	Test 19A	Test 20A	Test 21A	Test 22A	Test 22C	Test 24A	Test 24C	Test 25A	Test 25C	Test 23A
Native soil	Test 26A	Test 27A	Test 28A	Test 29A	Test 29C					

TEST RESULTS AND DISCUSSION

Geotextile Interfacing With Compacted Clay Liners (CCLs) Under Optimum Moisture Condition (OMC)

The performances of silt:bentonite mixture (100:10) with geotextile had only frictional contribution without cohesions. The performance of geotextile (Test 12A) produced frictional angle of 15.2 degrees. The results are presented in Table 6 and Fig. 7. For silt:bentonite mixture (100:10) and geotextile interface the peak shear stresses were reached within horizontal strain of 4.5 to 5.7%. There were spots of tearing and total internal failure of geotextile took place for higher normal loads of 200 and 300 kPa. Continuous reduction in the shear stresses was observed until constant residual shear stresses were obtained beyond 10% strain. In all normal stresses there were no pre peaks, slippage or plowing taking place before peak stresses.

The interface performances of sand:bentonite mixture (100:10) with geotextile also had only frictional contribution without cohesion. Geotextile (Test 19A) provided friction angle of 15.6 degrees. The test results are presented in Table 6 and Fig. 8. For sand:bentonite mixture (100:10) and geotextile interface the peak shear stresses were reached within horizontal strain of 3.1 to 7.3%. Continuous increment in shear stresses was observed beyond peak stresses into residual region. The geotextile was split into two during the tests. The residual shear stress behaviors were relatively similar for normal loads of 200 and 300 kPa. In all normal stresses there were no pre peaks or slippage or plowing effects taking place before peak stresses.

Table 6: Interface test results of liner configuration shown in Fig. 1 for both OMC and wet condition

Test	Interface Parameter	Cohesion (kN/m²)	Friction Angle (°)
Test 12A (OMC)	Silt:bentonite mixture (100:10) and geotextile	0.0	15.2
Test 19A (OMC)	Sand:bentonite mixture (100:10) and geotextile	0.0	15.6
Test 16A (OMC)	Native soil and silt:bentonite mixture (100:10)	10.3	28.3
Test 23A (OMC)	Native soil and sand:bentonite mixture (100:10)	0.0	31.0

The performance of silt:bentonite mixture (100:10) and sand:bentonite mixture (100:10) were similar when interfacing with geotextile. However, the frictional contribution from the interfaces with sand:bentonite mixture (100:10) was marginally higher than that of silt:bentonite mixture (100:10). In the initial prediction, sand:bentonite mixture (100:10) was predicted to provide much higher frictional resistance as compared to silt:bentonite mixture. The test results were not as predicted due to the presence of bentonite in sand and higher damages were created on interfacing member during shearing by sand

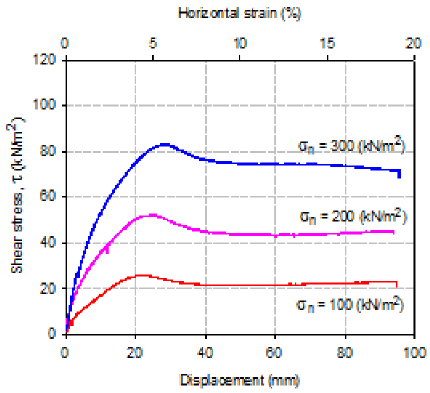

Figure 7: Test 12A – Interface between silt:bentonite mixture (100:10) and geotextile at OMC

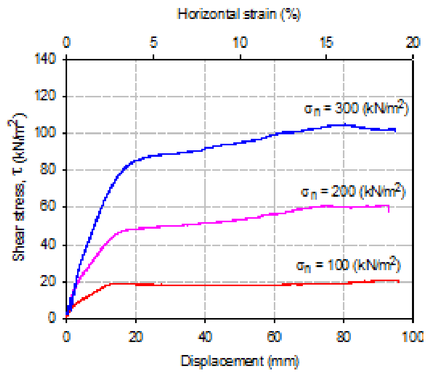

Figure 8: Test 19A – Interface between sand:bentonite mixture (100:10) and geotextile at O

Native Soil Interfacing With Compacted Clay Liners (CCLs) Under Optimum Moisture Condition (OMC)

Interface between native soil and CCLs were covered in wide range of friction angles with cohesion and frictional contribution from silt:bentonite mixture (100:10). Details of the test results are presented in Table 6 and Figs. 9 and 10.

Interface between native soil and silt:bentonite mixture (100:10) (Figure 9, Test 16A), the peak forces were reached within horizontal strain of 7.8 to 8.0%. Constant residual shear stresses were observed in the residual region for all normal loads, beyond 6% horizontal strain. No plowing kind of effects were observed. Good surface contact was obtained and the failure plane intrudes or cut more into silt:bentonite mixture (100:10) as compared to native soil.

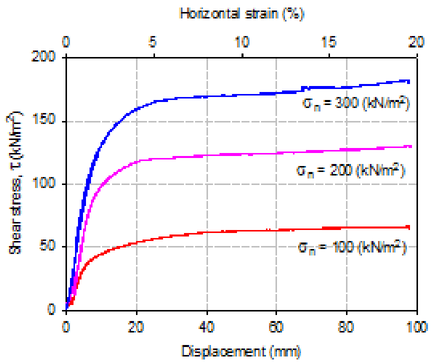

Figure 9: Test 16A – Interface between native soil and silt:bentonite mixture (100:10) at OMC

In the case of native soil and sand:bentonite mixture (100:10) the peak forces were reached within horizontal strain of 8.0% (Figure 10, Test 23A). Constant increments in residual shear stresses were observed in the residual region. No plowing kind of effects were observed. Good surface contact was obtained and the failure plane intrude or cut more into native soil as compare to sand:bentonite mixture (100:10).

The interface properties with native soil exhibits frictional resistance except for silt:bentonite mixture (100:10) (Test 16A).

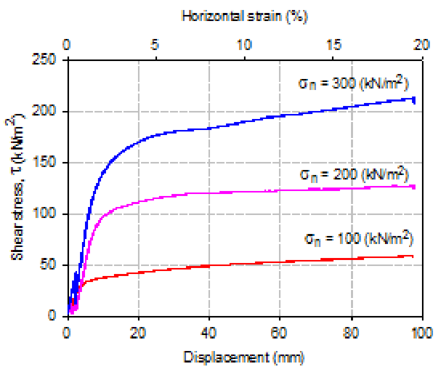

Figure 10: Test 23A – Interface between native soil and sand:bentonite mixture (100:10) at OMC

Detail summary of all other test results are presented in Table 9 *a*, *b* and *c* for tests with silt:bentonite mixture (100:10), sand:bentonite mixture (100:10) and native soil under optimum moisture condition

Table 7: Summary of interface peak shear strength parameters for the interface combinations tested at optimum moisture condition (OMC).

Interfacing material *c*: cohesion in kN/m^2 ϕ: frictional angle in degree.	Geotextile		Smooth HDPE (Type 1) geomembrane		Textured HDPE (Type 2) geomembrane		Rear side of PVC geomembrane		Front side of PVC geomembrane		Bentonite side of bentonite -glued GCL (Type 1)		HDPE side of bentonite -glued GCL (Type 1)		Non woven side of needle-punched GCL (Type 2)		Woven side of needle-punched GCL (Type 2)		Native soil	
	c	ϕ	c	ϕ	c	ϕ	c	ϕ	c	ϕ	c	ϕ	c	ϕ	c	ϕ	c	ϕ	c	ϕ
Smooth HDPE (Type 1) geomembrane	0.0	7.6																		
Textured HDPE (Type 2) geomembrane	3.0	21.0																		
Rear side of PVC geomembrane	11.3	18.6																		
Front side of PVC geomembrane	26.3	16.9																		
Bentonite side of bentonite-glued GCL (Type 1)	11.5	17.2	0.0	9.0	28.9	18.7	19.0	17.7	0.0	24.5										
HDPE side of bentonite-glued GCL (Type 1)	0.0	21.8	2.2	8.9	0.0	19.8	11.8	20.0	0.0	25.1										
Non woven side of needle-punched GCL (Type 2)	1.3	15.0	2.3	7.7	10.4	25.4	17.0	15.2	11.0	17.0										
Woven side of needle-punched GCL (Type 2)	10.6	14.7	2.4	9.2	2.5	22.9	14.4	18.0	22.8	18.4										
Silt:bentonite mixture (100 : 10)	0.0	15.2	0.0	15.3	0.0	24.1	0.0	22.2	0.0	19.8	13.9	16.9	0.0	22.5	6.1	20.8	1.7	21.2	10.3	28.3
Sand:bentonite mixture (100 : 10)	0.0	15.6	0.0	13.7	0.0	24.5	0.0	19.7	0.0	16.9	6.7	17.4	15.3	13.5	0.0	22.6	0.0	22.4	0.0	31.0
Native soil	0.0	17.8	0.0	15.6	0.0	23.0	0.0	18.7	0.0	20.2										

Table 8: Summary of stress and horizontal strain relationship for the interface combinations tested at optimum moisture condition (OMC)

Interfacing material	Geotextile	Smooth HDPE (Type 1) geomembrane	Textured HDPE (Type 2) geomembrane	Rear side of PVC geomembrane	Front side of PVC geomembrane	Bentonite side of bentonite -glued GCL (Type 1)	HDPE side of bentonite -glued GCL (Type 1)	Non woven side of needle-punched GCL (Type 2)	Woven side of needle-punched GCL (Type 2)	Native soil
Smooth HDPE (Type 1) geomembrane	SH – F13 0.7-0.9*									
Textured HDPE (Type 2) geomembrane	SS – F35 3.7-4.9*									
Rear side of PVC geomembrane	SH – F48B 5.1-8.0B*									
Front side of PVC geomembrane	SC – F48B 5.6-8.0B*									
Bentonite side of bentonite-glued GCL (Type 1)	SS – F35 4.1-4.8*	SH - F13 1.1-1.8*	SC - F35 3.0-3.8*	SH – F48B 5.6-8.0B*	SH - F13 1.6-8.0B*					
HDPE side of bentonite-glued GCL (Type 1)	SS – F35 4.2-4.5*	SH – F48B 7.8-8.0B*	SH – F35 3.4-4.1*	SH - F13 1.0-1.4*	SH - F13 1.7-2.0*					
Non woven side of needle-punched GCL (Type 2)	SS – F35 3.1-4.0*	SH - F13 1.1-1.6*	SS – F35 3.1-4.5*	SH - F46 4.6-6.1*	SH – F48 4.4-7.8*					
Woven side of needle-punched GCL (Type 2)	SH – F35 3.9-4.4*	SH - F13 0.9-1.6*	SS – F35 2.7-4.1*	SC - F48 5.1-8.0*	SC – F48B 4.2-8.0B*					
Silt:bentonite mixture (100:10)	SH – F46 4.5-5.7*	SH - F13 1.2-1.9*	SC – F48B 5.0-8.0B*	SC – F48 3.3-7.9*	SC – F48 3.4-7.8*	SH - F46 4.4-6.0*	SC – F48B 5.7-8.0B*	SC – F48 5.8-7.2*	SC – F48 5.5-7.8*	SH – F48B 7.8-8.0B*
Sand:bentonite mixture (100:10)	SH – F48 3.1-7.3*	SH - F13 0.8-1.9*	SH – F48B 8.0B*	SC – F48B 5.8-8.0B*	SC – F48B 3.8-8.0B*	SH – F13 2.5-3.6*	SC – F48B 5.6-8.0B*	SC – F48B 4.0-8.0B*	SC – F48B 6.7-8.0B*	SH – F48B 8.0B*
Native soil	SC – F48 4.2-7.9*	SH - F13 1.1-2.8*	SH – F48B 7.0-8.0B*	SC - F35 2.8-4.7*	SC - F35 1.7-3.0*					

SH: Horizontal strain hardening behavior for all normal stress levels tested. : SS: Horizontal strain softening behavior for all normal stress levels tested.
SC: Shear stress and horizontal strain behavior depends upon the normal stress levels. Horizontal strain hardening for low normal stress and horizontal strain softening for high normal stress.
F13, F35, or F46: Failure occurred within the 1-3%, 3-5%, or 4-6% of horizontal strain respectively.
F48B: Failure occurred within the 4-8% horizontal strain or beyond. : * - Horizontal strain at peak shear stress

Table 9*a*: Detail test results of interfaces with silt:bentonite

Test name	Bulk density Mg/m^3	Dry density Mg/m^3	Initial relative compaction density, %	Average moisture content after test %	Average moisture content before compaction %	Initial moisture content %	Sample dry density Mg/m^3	Estimated OMC, %	Partical density Mg/m^3
Test 12A - Geotextile & Silt:bentonite mixture (100:10)	1.80 1.81 1.78	1.53 1.54 1.52	91.08 91.45 90.25	18.00 17.53 17.71	18.34 17.70 17.70	0.91 3.16 3.16	1.68	17.5	2.64
Test 13A - Smoothe HDPE (Type 1) & Silt:bentonite mixture (100:10)	1.77 1.82 1.81	1.50 1.55 1.55	89.44 92.39 92.08	17.87 17.31 17.29	18.34 17.48 17.48	0.91 0.88 0.88	1.68	17.5	2.64
Test 14A - Textured HDPE (Type 2) & Silt:bentonite mixture (100:10)	1.81 1.81 1.81	1.53 1.53 1.53	91.35 91.21 91.13	18.06 17.89 17.99	18.51 18.39 18.39	0.96 0.82 0.82	1.68	17.5	2.64
Test 15A - Rear side of PVC & Silt:bentonite mixture (100:10)	1.80 1.80 1.84	1.52 1.53 1.56	90.29 90.83 92.88	18.35 18.12 18.08	18.75 18.42 18.51	0.95 1.10 0.96	1.68	17.5	2.64
Test 15C - Front side of PVC & Silt:bentonite mixture (100:10)	1.79 1.76 1.79	1.52 1.50 1.52	90.34 89.06 90.40	18.23 17.85 17.84	18.44 18.01 18.01	1.19 1.00 1.00	1.68	17.5	2.64
Test 16A - Native soil & Silt:bentonite mixture (100:10)	1.79 1.82 1.80	1.51 1.54 1.52	90.01 91.46 90.39	18.35 18.40 18.43	18.75 18.67 18.70	0.98 1.14 0.96	1.68	17.5	2.64
Native soil	2.05 2.05 2.09	1.87 1.87 1.91	90.75 90.58 92.80	9.72 9.71 9.51	9.89 10.21 9.96	1.13 1.16 1.22	2.06	9.0	2.59
Test 17A - Bentonite side of GCL (Type 1) & Silt:bentonite mixture (100:10)	1.79 1.79 1.78	1.52 1.51 1.50	90.20 90.17 89.49	18.31 18.14 18.12	18.75 18.49 18.49	0.95 0.82 0.82	1.68	17.5	2.64
Test 17C - HDPE side of GCL (Type 1) & Silt:bentonite mixture (100:10)	1.79 1.80 1.79	1.52 1.52 1.52	90.21 90.19 90.42	18.13 18.54 18.07	18.63 18.63 18.45	1.24 1.24 1.14	1.68	17.5	2.64
Test 18A - Non woven side of GCL (Type 2) & Silt:bentonite mixture (100:10)	1.79 1.79 1.78	1.51 1.51 1.51	90.08 89.95 88.01	18.20 18.47 18.01	18.42 18.42 18.23	1.05 1.05 0.92	1.68	17.5	2.64
Test 18C - Woven side of GCL (Type 2) & Silt:bentonite mixture (100:10)	1.80 1.79 1.78	1.52 1.51 1.51	90.36 90.02 89.77	18.42 18.18 18.35	18.45 18.70 18.55	1.14 1.05 1.05	1.68	17.5	2.64

mixture (100:10) at OMC (Saravanan, 2007).

Table 9*b*: Detail test results of interfaces with sand:bentonite mixture (100:10) under saturated or wet condition

Test name	Bulk density Mg/m^3	Dry density Mg/m^3	Initial relative compaction density, %	Average moisture content after test %	Average moisture content before compaction %	Initial moisture content %	Sample dry density Mg/m^3	Estimated OMC, %	Partical density Mg/m^3
Test 19A - Geotextile & Sand:bentonite mixture (100:10)	1.95 1.97 1.97	1.75 1.78 1.77	92.29 93.51 93.35	11.36 11.03 10.83	11.17 11.17 11.15	1.13 1.13 1.02	1.90	10.5	2.60
Test 20A - Smooth HDPE (Type 1) & Sand:bentonite mixture (100:10)	1.96 1.96 1.97	1.76 1.76 1.77	92.88 92.57 93.35	11.07 11.26 11.23	10.91 10.91 11.40	1.18 1.18 1.13	1.90	10.5	2.60
Test 21A - Textured HDPE (Type 2) & Sand:bentonite mixture (100:10)	1.97 1.97 1.95	1.77 1.77 1.75	93.33 93.37 92.18	11.30 11.16 11.23	10.89 10.89 11.79	0.91 0.91 1.07	1.90	10.5	2.60
Test 22A - Rear side of PVC & Sand:bentonite mixture (100:10)	1.95 1.96 1.94	1.75 1.76 1.75	92.32 92.60 92.00	11.06 11.13 10.94	11.40 11.67 11.67	1.13 1.01 1.01	1.90	10.5	2.60
Test 22C - Front side of PVC & Sand:bentonite mixture (100:10)	1.91 1.92 1.92	1.71 1.73 1.72	90.07 90.83 90.74	11.40 11.30 11.46	11.90 11.90 11.72	1.70 1.70 1.61	1.90	10.5	2.60
Test 23A -Native soil & Sand:bentonite mixture (100:10)	1.93 1.90 1.95	1.73 1.71 1.75	91.17 90.03 91.94	11.30 11.17 11.74	11.50 12.13 13.15	1.28 1.12 1.20	1.90	10.5	2.60
Native soil	2.07 2.04 2.04	1.88 1.86 1.86	91.16 90.36 90.22	10.00 9.72 9.59	10.72 9.94 10.13	1.43 1.07 1.20	2.06	9.0	2.59
Test 24A - Bentonite side of GCL (Type 1) & Sand:bentonite mixture (100:10)	1.93 1.92 1.92	1.73 1.72 1.72	91.15 90.64 90.65	11.51 11.35 11.38	11.91 11.45 11.45	1.79 1.83 1.83	1.90	10.5	2.60
Test 24C - HDPE side of GCL (Type 1) & Sand:bentonite mixture (100:10)	1.92 1.92 1.94	1.73 1.73 1.74	90.91 90.85 91.80	11.43 11.51 11.37	11.89 11.89 11.91	2.07 2.07 1.79	1.90	10.5	2.60
Test 25A - Non woven side of GCL (Type 2) & Sand:bentonite mixture (100:10)	1.92 1.93 1.91	1.72 1.73 1.71	90.68 90.90 90.26	11.58 11.49 11.45	11.94 11.94 11.74	1.66 1.66 1.50	1.90	10.5	2.60
Test 25C - Woven side of GCL (Type 2) & Sand:bentonite mixture (100:10)	1.93 1.93 1.93	1.73 1.73 1.73	90.97 91.07 91.17	11.45 11.52 11.67	11.74 11.73 11.72	1.50 1.24 1.24	1.90	10.5	2.60

Table 9*c*: Detail test results of interfaces with native soil at OMC (Saravanan, 2007).

Test name	Bulk density Mg/m^3	Dry density Mg/m^3	Initial relative compaction density, %	Average moisture content after test %	Moisture content before compaction %	Initial moisture content %	Sample dry density Mg/m^3	Estimated OMC, %	Partical density Mg/m^3
Test 26A - Geotextile & Native soil	2.17 2.02 2.02	1.98 1.83 1.85	96.15 89.05 89.59	9.46 9.98 9.58	10.24 9.82 10.10	1.15 1.23 1.10	2.06	9.0	2.59
Test 27A - Smoothe HDPE (Type 1) & Native soil	2.09 2.08 2.07	1.91 1.90 1.89	92.54 92.16 91.88	9.53 9.61 9.60	9.82 10.27 10.13	1.36 1.38 1.29	2.06	9.0	2.59
Test 28A - Textured HDPE (Type 2) & Native soil	2.07 2.08 2.09	1.89 1.90 1.91	91.74 92.08 92.80	9.77 9.62 9.43	10.04 10.19 10.12	1.26 1.30 1.28	2.06	9.0	2.59
Test 29A - Rear side of PVC & Native soil	2.08 2.08 2.05	1.90 1.89 1.87	92.20 91.92 90.69	9.72 9.76 9.54	10.15 10.15 9.84	1.18 1.18 1.13	2.06	9.0	2.59
Test 29C - Front side of PVC & Native soil	1.96 2.06 2.05	1.88 1.88 1.88	91.30 91.30 91.45	9.64 9.69 8.87	9.53 9.53 9.35	1.21 1.21 0.28	2.06	9.0	2.59

DISCUSSION AND CONCLUSIONS

Details of other interface test results are presented in Table 7 for tests conducted under optimum moisture condition. Similarly the summary of stress and horizontal strain relationship for the tests conducted under optimum moisture condition is shown in Table 8. By analyzing further the interface strength parameters, example in the case of single member liner there were different in failure strain between geotextile, geomembrane and native soil. As HDPEs are commonly used in landfill liners, the findings from this research conclude the following recommendations to improve HDPE, namely (1) Softer HDPE material, however firmer or harder than PVC, (2) HDPE with ability to mobilize larger strain before preliminary peak forces are reached, and (3) Imprint textured HDPE is proposed against blowed film texture HDPE (textured HDPE Type 2) since the film is sheared easily during interface shearing even with geotextile. Imprint texture of zigzag pattern having 0.2 to 0.5 mm height and 2 mm width is recommended to be imprinted on both sides of HDPE during manufacturing. It is also recommended to apply minor tension within elastic deformation of HDPE before the zigzag patterns are imprinted. Data from the interface test results obtained from this research could be analyzed further by engineers case by case to improvise liner design. The information obtained will be useful in selecting suitable landfill liner configuration without compromising on landfill stability and hydraulic conductivity prior to detailed design.

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