Case Histories of Multi-Layer Interface Tests for Composite Liners and Comparison to Single Interface Tests

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ABSTRACT

This paper presents multi-layer interface shear test results for composite liner systems from fourteen landfill projects in California. The multi-layer configuration utilizes site-specific materials including low-hydraulic conductivity compacted soil (CSL), geosynthetic materials [geosynthetic clay liner (GCL), geomembrane (GM), drainage geocomposite (GC), and geotextile (GT)], leachate collection and removal system (LCRS) gravel, and/or protective cover soil (PCS), as applicable. This paper describes the test configuration and test procedures to represent field configurations, including soaking and saturation conditions, choice of normal stresses, and California Water Board recommended procedures for calculating shear strengths for encapsulated GCLs. The importance of simulating field conditions is discussed. In addition, a comparison was made between results from single and multi-layer interface tests for two of the projects. This paper also includes a discussion of pros and cons of multi-layer interface tests compared to single interface tests.

INTRODUCTION

Current California regulations require that municipal solid waste and hazardous waste landfills be lined with a composite liner system involving multiple layers of geosynthetic and earthen materials. Interface and internal shear strengths of these liner components govern the stability of refuse slopes and are critical for optimization of landfill capacity (Stark and Choi 2004; Stark et al. 2015). There are two approaches to determine the interface shear strength to be used in slope stability analyses: (a) performing single interface shear tests using two materials in contact at a time for all the interfaces involved and interpreting the combination shear strength envelope for the weakest interface, and (b) performing a multi-layer interface shear test using all the liner components in a sandwich configuration. While the single interface tests provide a better understanding of each interface behavior, it requires multiple tests (typically 5 to 6 interfaces depending upon the number of liner material components) to determine the weakest interface. The multi-layer tests, on the other hand, directly measure the shear strength of the weakest interface that can directly be used in the slope stability analyses (ASTM D7702).

This paper presents the multi-layer interface test results from the following nine sites involving 14 landfill expansion projects. For two of the projects, single interface tests were also performed, and the test results are compared with the multi-layer test results.

- Lamb Canyon Landfill, Riverside County, CA
- North County Recycling Center and Sanitary Landfill, San Joaquin County, CA: 2 Phases
- Puente Hills Landfill, Los Angeles County, CA
- San Timoteo Landfill, San Bernardino County, CA

- Badlands Landfill, Riverside County, CA
- Mesquite Regional Landfill, Imperial County, CA
- Foothill Sanitary Landfill, San Joaquin County, CA
- Frank R. Bowerman Landfill, Orange County, CA: 5 Phases
- Camp Roberts, San Luis Obispo County, CA

COMPOSITE LINER SYSTEMS

The majority of landfill liner systems for the projects discussed in this paper consist of engineered alternative to Title 27 California Code of Regulations (CCR) liner system and include needle-punched GCL as a barrier layer in lieu of a compacted soil liner (CSL). Four of the projects include CSL as the barrier layer in accordance with Subtitle D, Code of Federal Regulations (CFR). Figure 1 shows typical details for floor (base/bottom) and side slope composite liner systems. They include the following layers:

Floor Liner (from Top to Bottom)

- PCS or operations layer soil: typically, minimum 0.6 m of minus 25 mm material
- GT filter: typically, 271 g/sm non-woven (NW)
- Granular drainage media: typically, LCRS gravel or coarse sand; sometimes replaced with drainage geocomposite (GC), in which case GT filter and cushion layers may be eliminated
- GT cushion: typically, 407 g/sm NW
- Double-side textured (DST) high-density polyethylene (HDPE) GM: typically, 1.5 mm or 2.0 mm thick
- GCL: typically, granular bentonite encapsulated between two layers of NW GT or between NW and woven GT layers, and needle punched (reinforced) to increase the internal strength
- DST HDPE GM (in case of encapsulated GCL): typically, 1.0 mm or 1.5 mm thick
- Prepared subgrade, foundation layer soil (FLS), or low-hydraulic conductivity CSL: typically, a 0.3 to 0.6 m engineered fill material with typical hydraulic conductivity between 1.0×10^{-5} cm/sec and 1.0×10^{-6} cm/sec

Side Slope Liner (from Top to Bottom)

- PCS or operations layer soil: typically, minimum 0.6 m of minus 25 mm material
- GT cushion or GC: typically, 542 g/sm NW GT or 7.5 mm GC
- Single-side textured (SST) HDPE GM: typically, 1.5 mm or 2.0 mm thick and installed textured side down to create a slip layer on the smooth side; in a few cases, DST HDPE GM is used on the side slope, where higher interface strength is desired for slope stability consideration
- GCL: typically, granular bentonite encapsulated between two layers of NW GT or between NW and woven GT layers, and needle punched (reinforced) to increase the internal strength
- Prepared subgrade soil that may be native soil or engineered fill

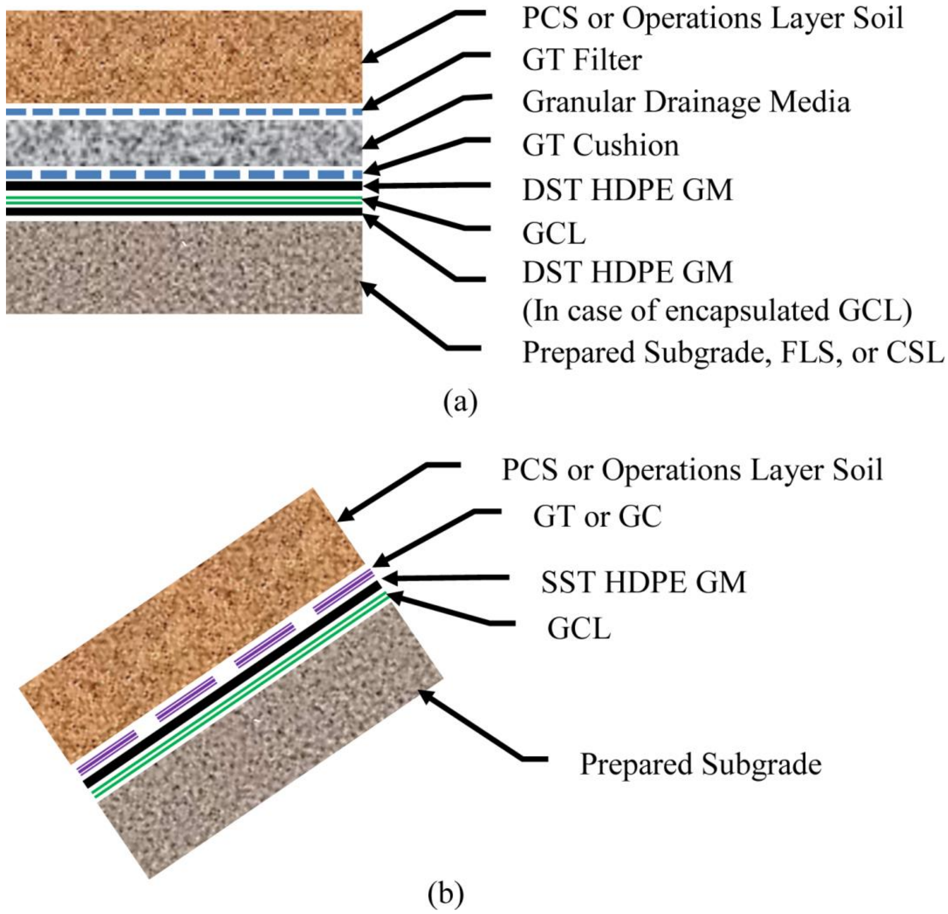

Figure 1. Typical Composite Liner System: (a) Floor Liner and (b) Side Slope Liner

One of the main parameters that controls the critical interface and the corresponding interface shear strength is texturing of GM. When SST GM is used, the critical interface would almost always be the smooth side of the GM against GT or GC, as applicable. On the other hand, when DST GM is used, the weakest interface could be on GT/GM, GM/GCL, or GM/Subgrade depending on the peak strength of the respective interfaces (the critical interface would be the one with the lowest peak strength). For an unencapsulated GCL, i.e., GCL installed directly on subgrade (or CSL), the critical interface could even be GCL/subgrade (or CSL), although that is rare. Based on the major components used, the composite liner systems discussed in this paper fall into the following four categories:

(a) DST GM/GCL/DST GM
(b) DST GM/GCL/subgrade
(c) DST GM/CSL (no GCL) – Subtitle D liner
(d) SST GM on GCL and overlain by GT or GC (for side slope liner)

TYPICAL TEST SETUP AND TEST PROCEDURES

ASTM test methods D5321 and D6243 describe the test procedures in detail. However, the site-specific methods, e.g., test setup, hydration, and displacement rate, must be developed by the Design Engineer to simulate the field conditions for the respective project.

Site-Specific Materials: The interface shear strength parameters are material specific. For example, the textured GMs may consist of either coextruded (blown film) membrane or embossed (such as microspike) membrane and they exhibit a different stress-shear displacement behavior during interface tests against adjacent geosynthetic materials (GT or GCL). The orientation of geosynthetics is important as the two sides may have different characteristics/shear strength properties (ASTM D5321). Therefore, it is important to supply the testing laboratory with site-specific earthen materials and geosynthetics and to specify the orientation of geosynthetics.

The Design Engineer has to assume interface shear strengths for slope stability analyses much before the geosynthetics materials are manufactured for the project. These parameters are typically selected based on the available site-specific database or pre-design interface tests on commonly supplied materials. It is important that the strength parameters be verified using actual materials during construction phase.

Normal Stress: As many researchers and practicing engineers have concluded, interface shear strengths are typically stress-dependent (Fox and Stark 2004; Giroud et al. 1993; Khilnani et al. 2017; Koerner and Koerner 2007; Stark and Choi 2004; Stark et al. 2015). Any Mohr-Coulomb strength envelope (defined by apparent cohesion/adhesion, C, and friction angle, Φ) or linear approximation of the shear strength envelope is valid only for the range of normal stresses used (ASTM D5321 and D7702).

Typically, the best-fit strength envelope through the data points curves towards the origin at lower normal stresses. On the other hand, the envelope could deviate from the linear approximation at higher stresses due to internal failure of geosynthetic, e.g., GCL, reduction in roughness of textured geosynthetic surface (polishing effect), etc. Therefore, the normal stresses specified for testing should cover the entire range of normal stresses from placed refuse including interim and final refuse geometry.

Moisture Conditioning/Soaking: Typically, the relative compaction and moisture content relative to optimum based on ASTM D1557 are specified for the soil components of the liner system. Geosynthetic components other than GCL are wetted by spraying. For tests involving a GCL under a hydrated condition, the following test setup is recommended:

- Soak GCL separately, outside the shear box, for a minimum of 48 hours under a nominal load of about 69 kPa to prevent swelling of GCL/bentonite that could result in plucking of needle punched fibers.
- Use sacrificial NW GT on top and bottom of GCL to allow uniform soaking and better drainage during soaking.
- Transfer the soaked GCL to the shear box taking care not to damage the specimen and place in the specified orientation.
- Once the complete system is set up, gradually apply the normal stress corresponding to the test point and allow the GCL to consolidate for 48 hours or longer until at least 90 percent of consolidation is complete, measured by the square-root-of-time method.

Shear Box Setup: Standard shear box is square or rectangle with a minimum dimension that is the greater of 300 mm, 15 times the d_{85} of the coarser soil used in the test, or a minimum of five times the maximum opening size (in plan) of the geosynthetic tested (ASTM D5321). Sometimes, for larger normal stresses (typically greater than 1,035 to 1,380 kPa), tests on a 300 mm x 300 mm box may not be feasible due to maximum load limitation. For such cases, smaller shear box (150 mm x 150 mm) may be used for tests at high loads. However, verification tests using both shear boxes should be carried out at the highest normal stress permissible for the larger box to calibrate the test data and to verify that tests in the smaller box would be representative without specimen size effect.

Unless an ultimate or residual strength is required, a maximum shear displacement of 75 mm is adequate to measure the post-peak or large displacement (LD) strength and has been accepted as typical industry standard for LD strengths. However, the shape of load-displacement relationship or allowable permanent displacement should determine the need for testing in torsional shear to determine residual strength.

A typical multi-layer (sandwich) test setup for a composite liner involves two earthen materials (CSL/subgrade soil and LCRS gravel or subgrade soil and operations later soil) each placed in upper and lower box and geosynthetics layers floating in between. The test setup should use more compressible material (such as CSL) in the upper box and stiffer material (LCRS gravel) in the lower box to minimize potential for plowing and lip effect near the edge of the shear box. When the two soil materials are similar in composition, such as subgrade below the liner system and operations layer derived from onsite excavations, the material with higher relative compaction (in-place subgrade) should be placed in the lower half of the shear box and the material with lower relative compaction (operations layer soil, typically loosely placed in the field near 85 percent compaction) should be placed in the upper half of the shear box.

For single interface tests, the clamping method and the selection of specimen substrate typically influence the test results. Tests performed using soil substrate rather than rigid substrate, such as wood or metal plate, may represent actual field conditions, but might be subject to plowing due to compressible substrate.

Rate of Shearing: Typically, a rate of 1 mm/min for interface shear and 0.1 mm/min for internal shear of GCL are used (ASTM D5321 and D6243). The Design Engineer should evaluate if a different rate is warranted to simulate anticipated field conditions.

Procedure for Interface Strengths for Encapsulated GCL: If the geosynthetic materials, as installed in intimate contact with each other and with soil layers, were to remain in perfectly flat condition, there should be no change in moisture content of GCL following installation. However, under actual field conditions of temperature variations, geosynthetic materials do exhibit wrinkles and the air trapped between wrinkles causes condensation and at least partial hydration of GCL. Therefore, the tests performed with GCL at its in-situ moisture content do not represent partially hydrated GCL strength and cannot be used for stability analyses. The actual degree of hydration that could occur is difficult to estimate. California regulatory agencies require that, for the encapsulated GCL liner system, the design interface strengths be estimated as arithmetic mean/average of tests on fully hydrated GCL and unhydrated GCL (tested at as-supplied moisture content). Therefore, two series of interface strength tests are performed including GCL in unhydrated condition and in fully hydrated condition.

A discussion of the test results from multi-layer tests for 14 landfill projects and single interface tests for two landfill projects is presented below. Also discussed is a comparison of test results for single and multi-layer tests and authors' opinion on pros and cons of the two test types.

RESULTS FROM MULTI-LAYER TESTS

A total of 82 multi-layer tests (including 3 to 5 normal stresses each) for 14 landfill projects were carefully reviewed and discussed herein.

Category (a) - Composite Liner with DST GM and Encapsulated GCL: Figure 2 shows LD shear strength results from five projects, with a total of 65 test points for hydrated (soaked) GCL and 53 tests using unhydrated GCL.

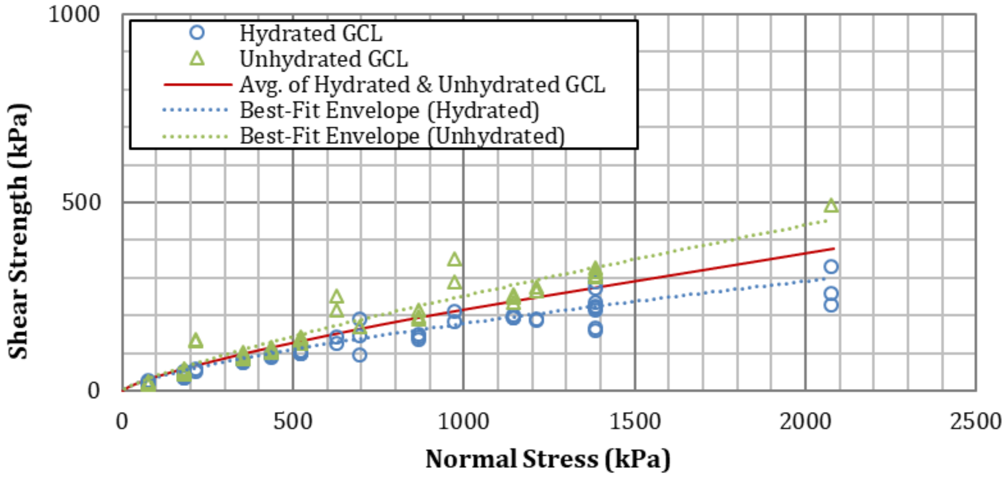

Figure 2. LD Shear Strength: Composite Liner with DST GM and Encapsulated GCL

The results indicate the following:

- For the tests with hydrated GCL, the critical interface was the GM/GCL interface for 61 of the 65 points. For four (4) points, the failure surface was GM/CSL interface.
- For the tests with unhydrated GCL, the critical interface was mostly upper or lower GM/GCL (31 out of 53); for 16 out of 53 tests, the critical interface was GM/GT or GC.
- For both hydrated and unhydrated GCL test series, LD shear strength envelopes curve towards origin. Partial internal failure of GCL was observed for tests at high normal stresses (1,380 kPa and beyond). This signifies the need for testing under the full range of normal stresses anticipated in the field.
- Figure 2 also shows the best-fit strength envelopes developed for the floor liner systems with hydrated and unhydrated GCL. For preliminary design purposes, before the actual materials are tested, the approximate interface shear strength may be estimated from the following equation:

$$\tau_{LD} = a.\sigma^b \quad (1)$$

where, τ_{LD} is LD shear strength in kPa, σ is normal stress in kPa, and a and b are empirical parameters.

- For the best-fit LD shear strength envelope,

  a = 1.4038 and b = 0.7017 for hydrated GCL, and

  a = 0.9966 and b = 0.8012 for unhydrated GCL.

- The secant friction angle, Φ_{sec} (normal stress-dependent) for hydrated GCL ranges from 12.4° to 9.0° for normal stresses of 500 to 1,500 kPa. The corresponding Φ_{sec} ranges from 16.2° to 13.1° for unhydrated GCL.

Category (b) - Composite Liner with DST GM and Unencapsulated GCL: Figure 3 shows the results from 73 tests performed using unencapsulated GCL for five projects. Because GCL is placed directly on subgrade and it will become hydrated, all the tests were performed with fully hydrated GCL.

The following observations are made:

- Similar to the systems with encapsulated GCL, those with unencapsulated GCL also show stress-dependent shear strength behavior.
- The best-fit LD shear strength envelope may be estimated using a = 0.9321 and
- b = 0.7971 in Eq. 1.

- The best-fit strength envelope for unencapsulated hydrated GCL is slightly higher than that for hydrated GCL in encapsulated condition in Figure 2 (Φ_{sec} ranges from 14.8° to 11.9° for normal stresses of 500 to 1,500 kPa). This is because the critical interface in the unencapsulated GCL case was predominantly (49 out of 73 or 67%) GM/GT or GC interface rather than GM/hydrated GCL interface. Typically, the GM/GT interface has a lower peak strength, but higher LD strength than the GM/GCL interface. This highlights the benefit of using cushion geotextile between GM and LCRS gravel. The GT, in addition to acting as a cushion layer to protect against GM puncture, serves as the critical interface.
- In one of the projects, internal failure of the GCL was observed at a relatively low normal stress (575 kPa) even with a relatively high GCL peel strength (ASTM D6496) of about 2,100 N/m. The liner system for this project did not contain the GT cushion and the subgrade soil happened to be relatively frictional material forcing the internal failure of GCL. A GT cushion would have shifted the critical interface to GM/GT interface and would have prevented the GCL internal failure.
- GCL with high peel values of 2,100 to 2,625 N/m, is typically recommended for projects where liner is subject to high normal stresses to minimize risk of GCL internal failure.

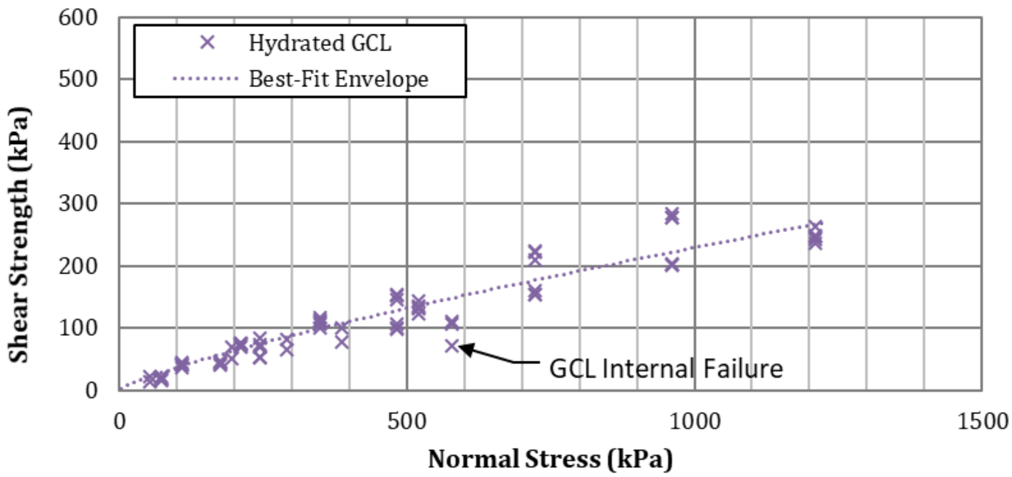

Figure 3. LD Shear Strength: Composite Liner with DST GM and Unencapsulated GCL

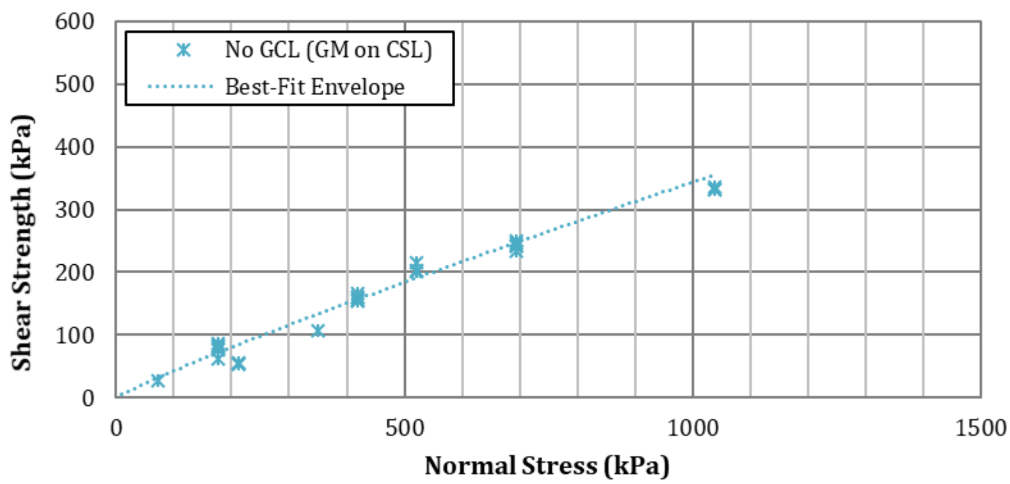

Figure 4. LD Shear Strength: Composite Liner with DST GM and No GCL (GM on CSL)

Category (c) - Composite Liner with DST GM on CSL: Figure 4 shows results from 32 tests performed for five projects, where Subtitle D composite liner with GM underlain by 600 mm thick CSL, with hydraulic conductivity ≤ 1 x 10^{-7} cm/sec, was used as the composite liner. The following observations are made:

- Critical failure surface was either GM/CSL (15 out of 32) or GM/GT or GC (17 out of 32).
- The best-fit strength envelope may be estimated using a = 0.6898 and b = 0.8991 in Eq. 1.
- Φ_{sec} ranges from 20.2° to 18.3° for normal stresses of 500 to 1,500 kPa.

Category (d) - Composite Liner with SST GM (Typically for Side Slope Liner): Figure 5 shows the results from 80 tests performed for seven projects, where SST GM was used on side slopes. The sandwich test configuration included GM with textured side down against hydrated GCL and overlain by cushion GT or GC.

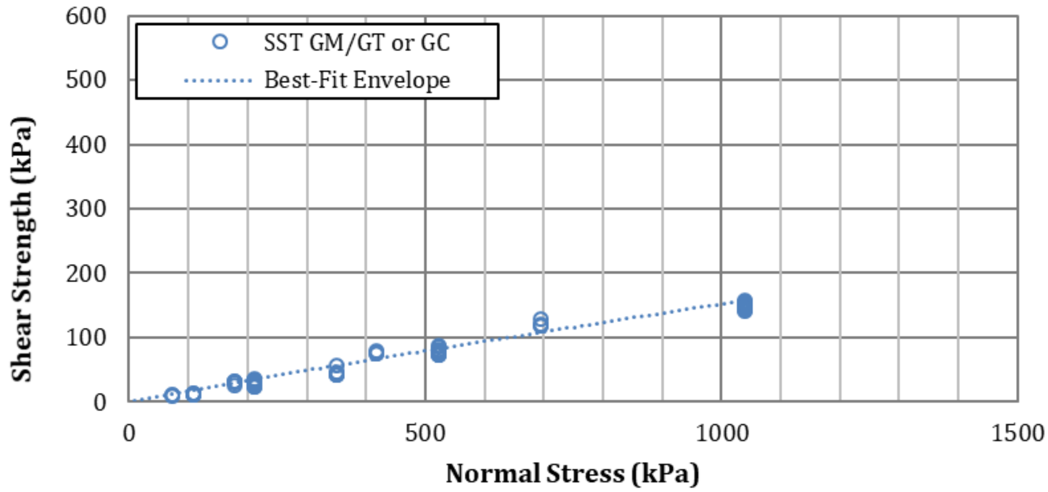

Figure 5. LD Shear Strength: Composite Liner with SST GM (Typically for Side Slope Liner)

The following observations are made:

- The critical surface was always smooth GM/GT or GC.
- As expected, the LD shear strengths are consistent and repeatable because of the smooth geomembrane surface.
- Although the strength envelope is almost linear, a and b of 0.2262 and 0.9428, respectively, in Eq. 1 depict the best-fit strength envelope.
- Φ_{sec} ranges from 9.0° to 8.5° for normal stresses of 500 to 1,500 kPa.
- Because the failure is always on smooth GM/GT or GC interface and the LD strengths are in a narrow range (Φ_{sec} 8° to 9°), it would be appropriate for such side slope liner configuration to use single interface tests with GM/GT or GC interface, rather than a multi-layer test. However, given the limited variability, planning level design can be performed with the information provided herein.

Comparison of LD Shear Strengths using Best-Fit Strength Envelopes: Table 1 presents a comparison of LD shear strengths estimated using best-fit envelopes shown in Figures 2 through 5 at select normal stresses. The table also presents the calculated Φ_{sec}.

Table 1. LD Shear Strengths and Secant Friction Angles based on Best-Fit Strength Envelopes

	Category (a) - Encapsulated GCL						Category (b) - Unencapsulated GCL		Category (c) - No GCL (GM on CSL)		Category (d) - SST GM/GT (Side Slope)	
	Hydrated		Unhydrated		Avg. Hyd./Unhy.		Hydrated		-		-	
	τ_{LD}	Φ_{sec}	τ_{LD}	Φ_{sec}	τ_{LD}	Φ_{sec}	τ_{LD}	Φ_{sec}	τ_{LD}	Φ_{sec}	τ_{LD}	Φ_{sec}
a	*1.4038*	-	*0.9966*	-	-	-	*0.9321*	-	*0.6898*	-	*0.2262*	-
b	*0.7017*	-	*0.8012*	-	-	-	*0.7971*	-	*0.8991*	-	*0.9428*	-
Σ												
100	36	19.6	40	21.7	38	20.7	37	20.1	43	23.4	17	9.9
500	110	12.4	145	16.2	127	14.3	132	14.8	184	20.2	79	9.0
1000	179	10.1	252	14.2	216	12.2	229	12.9	344	19.0	152	8.7
1500	238	9.0	349	13.1	293	11.1	317	11.9	495	18.3	223	8.5

Note: σ and τ_{LD} are in kPa and Φ_{sec} in degrees

The following observations are made:

- LD shear strength envelopes are stress-dependent, especially at low normal stresses. The best-fit strength envelopes may be estimated using empirical parameters a and b in Table 1 and Eq. 1.
- When the composite liner includes SST GM, the smooth GM/GT or GC interface is almost always the critical interface, and the corresponding LD shear strengths are the lowest compared to other interfaces.
- LD strength envelope for the liner with unencapsulated GCL is slightly higher than the average of best-fit envelope for encapsulated GCL. This is mainly due to the shifting critical interface from predominantly GM/GCL for encapsulated GCL case to GM/GT or GC in the uncapsulated GCL case.

COMPARISON OF SINGLE AND MULTI-LAYER INTERFACE TESTS

Data from two projects, where both single interface and multi-layer interface shear tests were performed are presented in this section. Site-1 includes a floor composite liner system with Granular drainage media/GT/DST GM/GCL/DST GM/Subgrade. Both single and multi-layer tests were performed using unhydrated and hydrated GCL. Figures 6 and 7 show the results for the DST GM with unhydrated and hydrated GCL, respectively. The following observations are made:

- For the unhydrated test, single and multi-layer test results show excellent agreement except for at the highest normal stress tested.
- For the hydrated test, the results for multi-layer interface test are slightly higher than those for single interface tests for normal stresses ≥ 700 kPa.
- In the multi-layer test, the total shear displacement in the critical interface could be slightly lower than the overall displacement of 75 mm, and thereby showing a slightly higher strength. However, the corresponding load-shear displacement relationships for individual test points show substantial levelling out, suggesting some other mechanisms

such as rigid substrate, could have contributed to the difference.

A detailed discussion of the test configuration, load-shear displacement behaviors of interfaces, and interpretation of these results are presented in Stark et al. (2015).

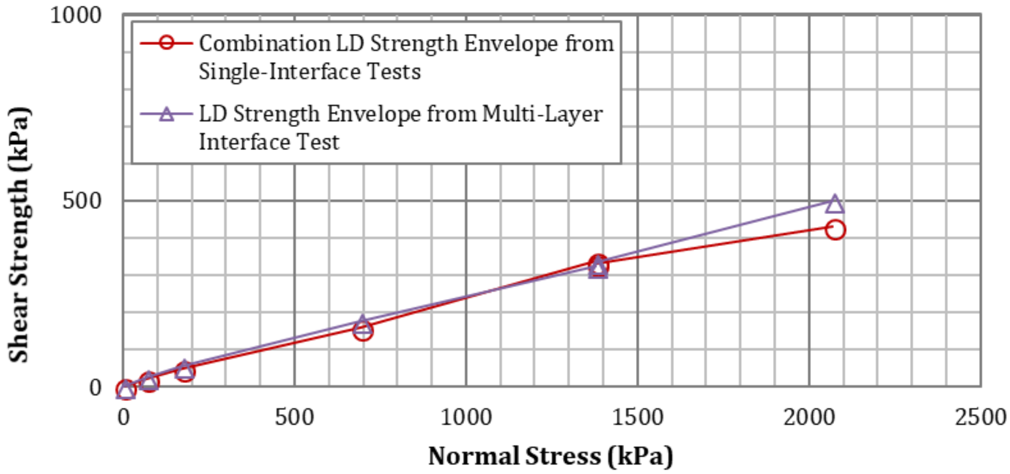

Figure 6. Site 1 – Encapsulated GCL-Unhydrated (Failure on GCL/DST GM or DST GM/GT)

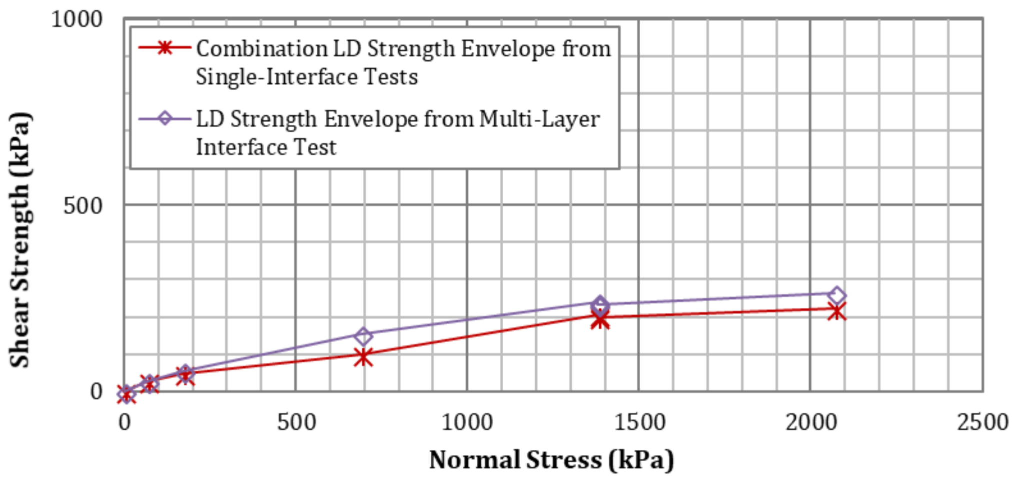

Figure 7. Site 1 – Encapsulated GCL-Hydrated (Failure on GCL/DST GM)

Site-2 consists of unencapsulated GCL overlain by DST GM for both floor and side slope liner systems. Floor system includes LCRS gravel/DST GM/GCL/FLS and side slope includes PCS/GC/DST GM/GCL/Subgrade. The test results for floor and side slope liner systems are shown on Figures 8 and 9, respectively. The following observations are made:

- Both single and multi-layer interface shear test results show excellent agreement for the full range of normal stresses.
- A notable difference in the test setup is the usage of compacted concrete sand as the substrate during geosynthetic-geosynthetic single interface tests.
- For the floor liner system, GCL internal failure was observed at the highest normal stress during both single and multi-layer tests. As discussed previously, it is due to the frictional nature of the subgrade material and elimination of the GT cushion layer.
- The multi-layer test at the highest normal stress was repeated using a GCL with higher

peel strength of about 2,500 N/m instead of 2,100 N/m originally tested to determine the effect of peel strength. As expected, an increase in LD strength was observed, but the GCL internal failure still occurred.

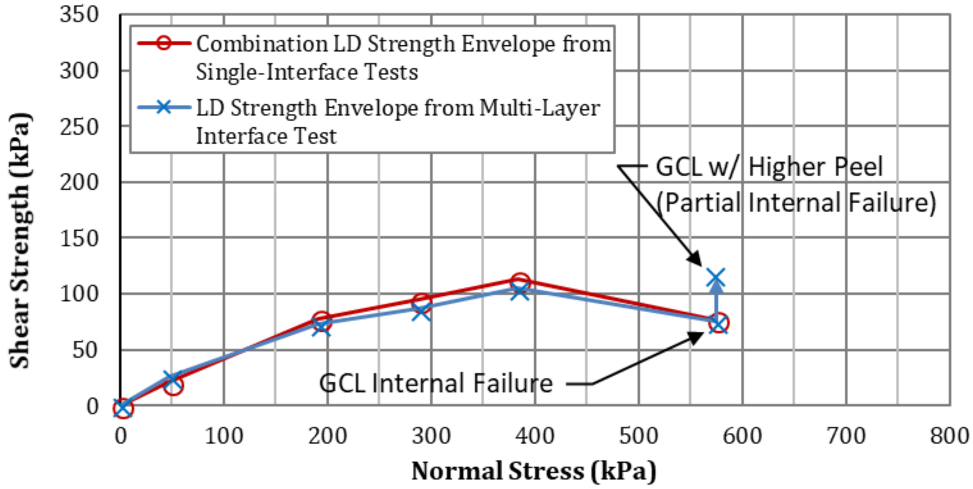

Figure 8. Site 2 – Unencapsulated GCL-Hydrated (Failure on GCL/DST GM)

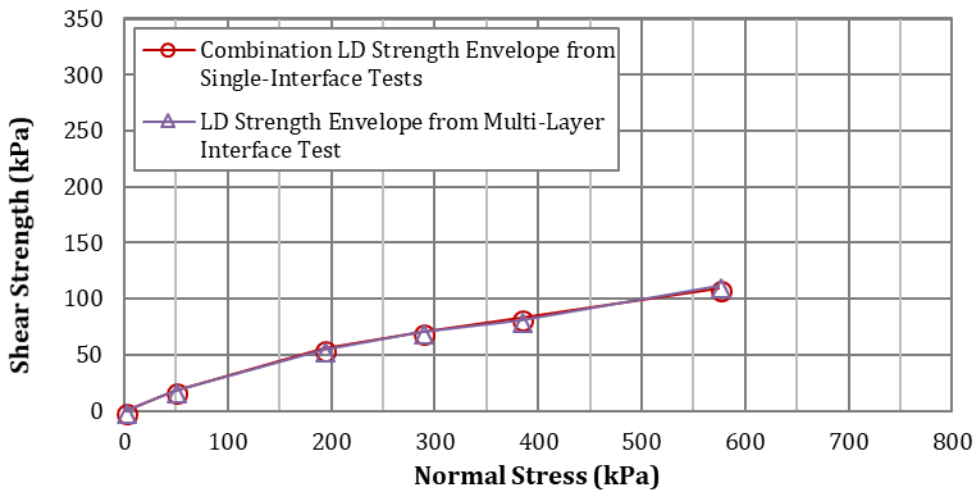

Figure 9. Site 2 – Unencapsulated GCL-Hydrated (Failure on DST GM/GC)

A detailed discussion of test configuration, load-shear displacement behaviors of interfaces, and interpretation of these results are presented in Khilnani et al. (2017).

In addition to the discussions of LD strengths above, we also reviewed the peak shear strengths for both single and multi-layer interface tests for the aforementioned two sites. The peak strengths of the critical interfaces were almost identical for the single and multi-layer tests. Based on the laboratory test observations at the completion of the multi-layer tests, there was no reported visible evidence of any relative displacements on other interfaces indicating excellent repeatability of test results between single and multi-layer tests.

SUMMARY AND DISCUSSION OF SINGLE AND MULTI-LAYER INTERFACE TESTS

The data for 14 projects involving over 300 data points discussed in this paper conclude that multi-layer interface tests, if performed using careful test setup and well-developed site-specific test procedures, provide reliable, consistent, and repeatable results for use in liner-refuse stability analyses. The failure interface and the lowest LD strength from the multi-layer tests compare extremely well with the results from single interface tests for two of the projects discussed in this paper where both types of tests were performed.

The authors are well aware of the opinions of various investigators regarding data interpretation from multi-layer interface shear tests. These opinions, as discussed in ASTM D7702, include:

1. *Shear strength parameters are only obtained for the failure surface and not for other materials or interfaces, some of which have moved or may have been close to failure* – This can generally be verified by the shape of load-shear displacement relationships and the rate of strength reduction near maximum (75 mm) displacement. If rate of strength loss is significant and stress-shear displacement relationship is not constant, the failure interface may be retested in single interface test to verify LD strengths at maximum (75 mm) displacement on that specific interface.
2. *Different interfaces will be the critical failure surface at different normal loads and the discernment of this may be difficult to interpret with multi-layer interface tests* – If the strength parameters are specified as discrete values of interface shear strengths at various normal stresses, which is the recommended practice, this factor is not important from practical stability considerations. In fact, the results of multi-layer interface tests are truly representative of field conditions where the critical interface may be different for interim refuse geometry (lower normal stress) and for maximum refuse height (highest normal stress). The results of multi-layer interface tests will automatically pick the correct strength regardless of what the weakest interface was. Where critical interface shifts at different normal stresses, such phenomenon was observed for both single and multi-layer tests.
3. *Issue of non-uniform normal stress distribution can significantly compound the problem for multi-layer interface tests* – The recommendation to place more compressible soil material in the upper half of shear box to minimize potential for plowing or lip effect minimizes the effect of non-uniform stress distribution. The authors have seen repeatable and consistent test results using this setup and examination of post-shear interfaces has not indicated any problems of uneven soil surfaces at the end of the test.
4. While the debate on the pros and cons of single and multi-layer tests will continue, in authors' opinion, the greatest benefit of multi-layer tests is that it represents the field condition of the composite liner system including the actual boundary conditions and confining effects of the overlying and underlying soil materials sandwiching the weak geosynthetics interfaces. The greatest drawback of single interface tests, on the other hand, is the influence of clamping of fixed interface and the potential for GM elongation under large displacements in the shear box.
5. Based on the limited data available from two case histories where both single and multi-layer tests were performed, slight increase in the lowest LD strengths on critical interface was observed for multi-layer interface tests compared to single interface tests. Using a compacted soil substrate, such as site-specific subgrade material or concrete sand, in single interface test appears to reduce this difference.

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