Comparison of Single and Multi-Layer Interface Strengths for Geosynthetic/Geosynthetic and Soil/Geosynthetic Interfaces

Kris Khilnani, P.E., G.E.[1]; Timothy D. Stark, Ph.D., P.E.[2]; and Taj M. Bahadori, P.E.[3]

[1]Advanced Earth Sciences, Inc., Irvine, CA 92618. E-mail: kkhilnani@aesciences.com
[2]Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana-Champaign, Urbana, IL 61801. E-mail: tstark@illinois.edu
[3]San Joaquin County, Dept. of Public Works, Stockton, CA 95205. E-mail: tbahadori@sjgov.org

Abstract

This paper presents a unique comparison of single and multi-layer interface shear strength tests for a recently constructed landfill liner system. The comparison includes peak and large displacement combination strength envelopes from single- and multi-layer interface direct shear tests for the same geomembrane (GM)/ drainage geocomposite (GC), geosynthetic clay liner (GCL)/geomembrane, and soil/GCL interfaces. This comparison shows excellent agreement between strength envelopes and critical interfaces derived from single- and multi-layer interface tests for the materials tested. Based on this comparison, it is recommended that multi-layer interface tests be used for composite liner system design and if there is an anomaly with the multi-layer interface test results, single interface tests can be conducted to verify the weakest interface and to clarify the test results. Alternatively, the liner system can be designed using single interface tests and multi-layer interface tests can be used to verify the combination strength envelope derived from the single interface tests as was done in this case.

INTRODUCTION

This paper summarizes the results of single and multi-layer interface shear strength tests performed on geosynthetic/geosynthetic and soil/geosynthetic interfaces for the composite liner system for a recently constructed municipal solid waste landfill expansion. The single and multi-layer interface tests were performed by SGI Testing Services, LLC (SGI) of Norcross, Georgia in accordance with test procedures specified in ASTM D5321 and D6243.

The liner systems for the sideslope and base liner for the landfill expansion are shown in Figure 1(a) and 1(b), respectively. They include the following layers:

Sideslope Liner (top to bottom)

- Operations layer soil
- Double-sided drainage geocomposite (GC)
- 1.5 mm thick double-side textured (DST) HDPE geomembrane (GM)
- Geosynthetic clay liner (GCL)
- Sideslope subgrade soil (SSS)

Base Liner (top to bottom)

- Operations layer soil
- Geotextile filter
- Granular drainage media (LCRS Gravel)
- 1.5 mm thick double-side textured (DST) HDPE geomembrane (GM)

- Geosynthetic clay liner (GCL)
- Foundation layer soil (FLS)

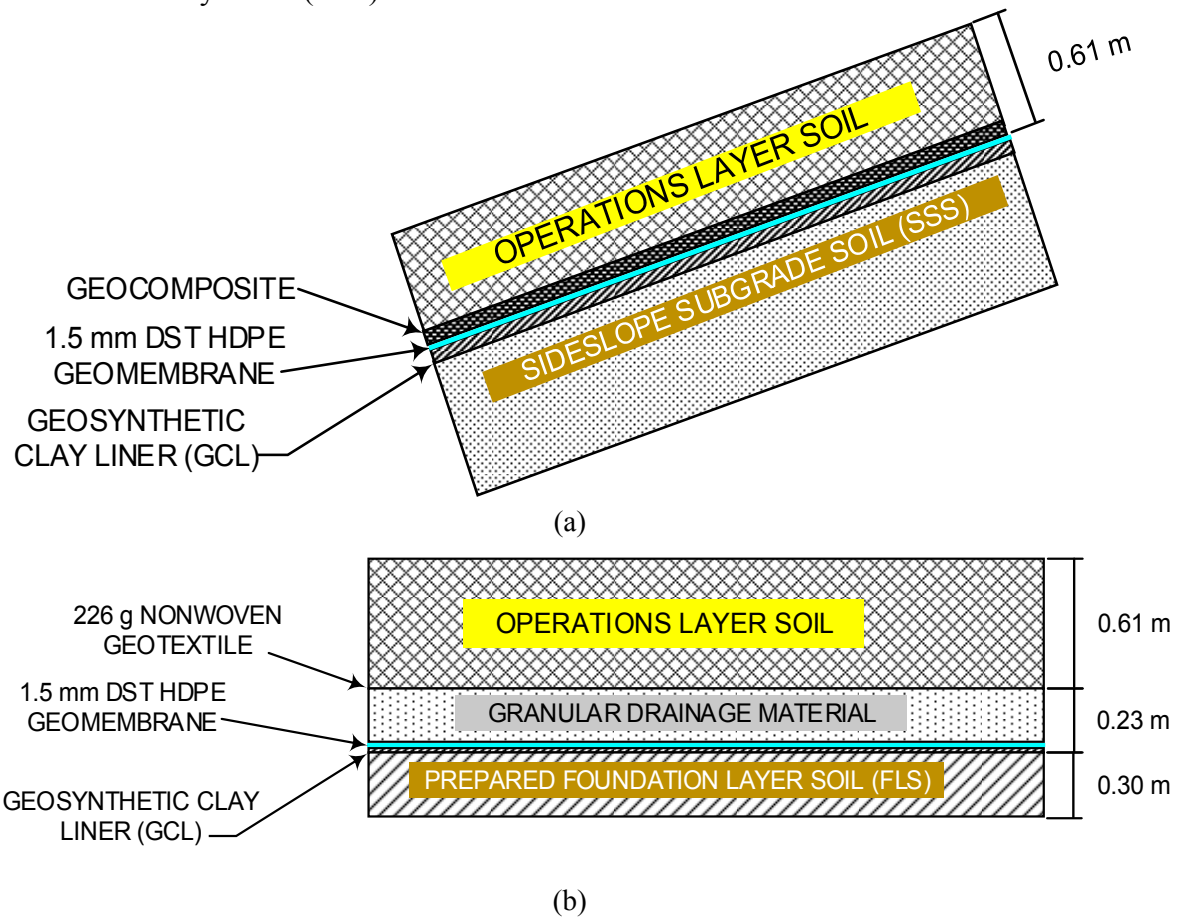

Figure 1. Landfill Liner System for: (a) sideslope and (b) base or bottom.

The project specifications required that the following four single interface strength test series be performed prior to geosynthetics materials acceptance, to verify compliance with design strengths:

- GCL/FLS
- GCL/SSS
- GM/GCL
- GM/GC

The on-site materials for the FLS and SSS were the same materials with no significant differences in material classification or compaction standards. Therefore, the first two test series would have been duplicate tests on identical materials and the following three single interfaces were tested. The numbering system used for these test series are as follows:

Single Interface Test Series	Interface Tested
1	GCL/FLS
2	GM/GCL
3	GM/GC

After Single Interface Test Series 1 through 3 shown above were completed, two additional multi-layer layer test series were conducted to confirm the single interface test results. These two test series numbered below, included multiple soil and geosynthetics layers for the base liner and sideslope liner shown in Figures 1(a) and 1(b).

Multi-Layer Interface Test Series	Test Configuration
4 - Base Liner System	Gravel/GM/GCL/FLS
5 – Sideslope Liner System	Operations Soil/GC/GM/GCL/FLS

The properties of geosynthetics and soil materials used in the testing are presented in Table 1 and are compared to the specified values. The interface strength test results for the three single and two multi-layer interface test series are summarized in Tables 2 and 3, respectively. These results are plotted below to assess the minimum interface strength envelope for the sideslope and base liner systems. The following sections discuss the measured, combination, and specified interface strength envelopes for the sideslope and base liner systems based on these single and multi-layer interface tests.

Table 1. Geosynthetic material properties for interpretation of geosynthetic interface test results.

Geosynthetic Property	Specified Property	Tested Property
GM Asperity Height	0.51 mm	0.76 and 0.79 mm
GCL Peel Strength	6.7 N (15 lbs) (ASTM D4632)	211.3 to 258.4 N (47.5 to 58.1 lbs) (D4632)
GCL Peel Strength	437.8 N/m (2.5 ppi) (ASTM D6496)	2084.0 to 2539.3 N/m (11.9 to 14.5 ppi) (D6496)
FLS Relative Compaction	90% of Modified Proctor (ASTM D1557)	90% Mod. Proctor (15.5 kN/m^3/98.5 pcf)
FLS Moisture Content	Optimum Moisture Content (OMC) to +4% (19 to 23%)	OMC + 4% or 23%

Sideslope liner interface test results. Figure 2 presents the single and multi-layer interface strength test results for the sideslope liner system that are presented in Tables 2 and 3. Each of the strength envelopes are keyed to the Test Series name in Tables 2 and 3. For example, Figure 2(a) presents the peak interface strengths for Test Series 1 through 3 because these single interface test series are used in the sideslope liner system. The GM/GCL interface test at a normal stress of 574.8 kPa (12,000 psf) was conducted twice with different GCL samples with peel strengths of 211.4 and 258.1 N (47.5 and 58 lbs), which explains the vertical increase in the peak envelope at a normal stress of 574.8 kPa (12,000 psf). The purpose of second test at a normal stress of 574.8 kPa was to determine if the internal GCL failure occurred in post-peak condition, even for GCL with the highest peel strength. The multi-layer interface test series for the sideslope liner system (Test Series 5 – Sideslope Multiple) are also included in Figure 2(a) for comparison purposes.

Table 2. Summary of single interface test results.

Normal Stress kPa (psf)	Series 1 - GCL/FLS Single Interface GCL/Foundation Soil		Series 2 - GM/GCL Single Interface GM/GCL		Series 3 - GM/GC Single Interface GM/GC	
	Peak kPa (psf)	Post-Peak kPa (psf)	Peak kPa (psf)	Post-Peak kPa (psf)	Peak kPa (psf)	Post-Peak kPa (psf)
0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
47.9 (1,000)	36.3 (757)	31.1 (649)	34.5 (720)	21.4 (445)	28.7 (599)	17.9 (372)
191.6 (4,000)	132.4 (2765)	112.8 (2354)	114.7 (2395)	77.9 (1625)	107.1 (2235)	55.3 (1154)
287.4 (6,000)	171.6 (3582)	29.5 (615)	167.1 (3489)	94.7 (1977)	144.3 (3013)	70.8 (1477)
383.2 (8,000)	220.1 (4596)	37.9 (791)	215.8 (4506)	112.8 (2355)	181.7 (3794)	83.1 (1735)
574.8 (12,000)	274.2 (5725)	46.4 (969)	271.5 (5670)	77.1 (1609)	251.1 (5243)	109.2 (2280)
574.8 (12,000)	340.2 (7104)	57.3 (1195)				

The single interface tests in Figure 2(a) show the weakest or critical interface for the sideslope liner system is the GM/GC interface. The critical interface is confirmed by Multi-Layer Interface Test Series 5, which shows shear displacement occurred along the GM/GC interface for all of the normal stresses tested, which matches the GM/GC interface being the critical interface in all of the single interface tests. In addition, the multi-layer interface tests yielded essentially the same peak strength envelope as the single interface tests, which is in agreement with similar findings in Stark et al. (2015). This agreement between single and multi-layer interface tests confirms the critical interface for the sideslope liner system materials tested is the GM/GC interface and should be used to create the post-peak strength envelope.

Using the design procedure set forth in Stark and Poeppel (1994) and refined in Stark and Choi (2004), geosynthetic lined slopes should be designed using the post-peak strength envelope for the critical interface. As a result, the post-peak strength envelope for the GM/GC interface in Figure 2(b) should be used for design of the sideslope liner system even though the post-peak envelope for the GCL/FLS interface is lower for normal stresses greater than about 239.4 kPa (5,000 psf). The GCL/FLS post-peak strength envelope should not be used for sideslope design because the GM/GC interface will fail before the GCL/FLS interface fails so a post-peak condition will not develop along the GCL/FLS interface before the GM/GC fails as described by Stark and Choi (2004). This strength envelope is referred to as post-peak, not residual, because the residual condition was not reached in the direct shear tests conducted by SGI even though the tests were continued to a displacement of about 75 mm (3 inches). The GCL/FLS post-peak strength envelope decreases in strength with increasing normal stress because the GCL failed internally and the measured strengths after a 383.2 kPa (see Figure 3(b)) corresponds to the shear resistance provided by the bentonite in the GCL. The GM/GCL post-peak strength envelope also decreased in strength at the highest normal stress (574.8 kPa) because the GCL also failed internally and the measured strengths corresponds to the shear resistance provided by the bentonite in the GCL (see Figure 3(b)).

Table 3. Summary of multi-layer interface test results.

Normal Stress kPa (psf)	Series 4 - Base Multiple Base Liner Interface Test		Series 5 - Sideslope Multiple Sideslope Liner Interface Test	
	Peak kPa (psf)	Post-Peak kPa (psf)	Peak kPa (psf)	Post-Peak kPa (psf)
0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
47.9 (1,000)	32.2 (672)	25.7 (535)	30 (625)	17.5 (365)
191.6 (4,000)	114.3 (2386)	73.2 (1527)	101.9 (2127)	54.4 (1135)
287.4 (6,000)	165.1 (3448)	86.8 (1811)	142.2 (2968)	70.2 (1465)
383.2 (8,000)	205.6 (4293)	105.1 (2195)	179.2 (3742)	81.3 (1696)
574.8 (12,000)	285.9 (5971)	114.5 (2391)	252.4 (5270)	111.2 (2322)
574.8 (12,000)	262.3 (5478)	75.5 (1575)	N/A	N/A

Table 4. Combination strength envelopes for the base and sideslope liner systems.

Normal Stress kPa (psf)	Base Liner – Combination Envelope		Sideslope – Combination Envelope	
	Peak kPa (psf)	Post-Peak kPa (psf)	Peak kPa (psf)	Post-Peak kPa (psf)
0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
47.9 (1,000)	28.7 (599)	21.4 (445)	34.5 (720)	17.9 (372)
191.6 (4,000)	107.1 (2235)	77.9 (1625)	114.7 (2395)	55.3 (1154)
287.4 (6,000)	144.3 (3013)	94.7 (1977)	167.1 (3489)	70.8 (1477)
383.2 (8,000)	181.7 (3794)	112.8 (2355)	215.8 (4506)	83.1 (1735)
574.8 (12,000)	251.1 (5243)	77.1 (1609)	271.5 (5670)	109.2 (2280)

The use of the post-peak strength envelope from the critical interface, i.e., GM/GC, is confirmed by Multi-Layer Interface Test Series 5, which yielded essentially the same post-peak strength envelope as the single interface tests on the GM/GC interface. In other words, the GCL/FLS interface did not fail before the GM/GC interface in the multi-layer interface test so the lower post-peak strength envelope for the GCL/FLS was not mobilized in the multi-layer interface tests as described above. As a result, the GCL/FLS interface strength envelope should not be used for sideslope liner design because it will be overly conservative as described by Stark and Choi (2004).

Figure 2(c) shows the combination post-peak strength envelope, which coincides with the post-peak strength envelope for the GM/GC interface because sliding occurred along this interface for all of the normal stresses tested in the single and multi-layer interface tests. For comparison purposes, Table 4 presents the normal stress and shear stress for the sideslope combination post-peak strength envelope. If the critical interface did change with increasing normal stress, the combination strength envelope would also change interfaces as described by Stark and Choi (2004) but this is not the case for this testing.

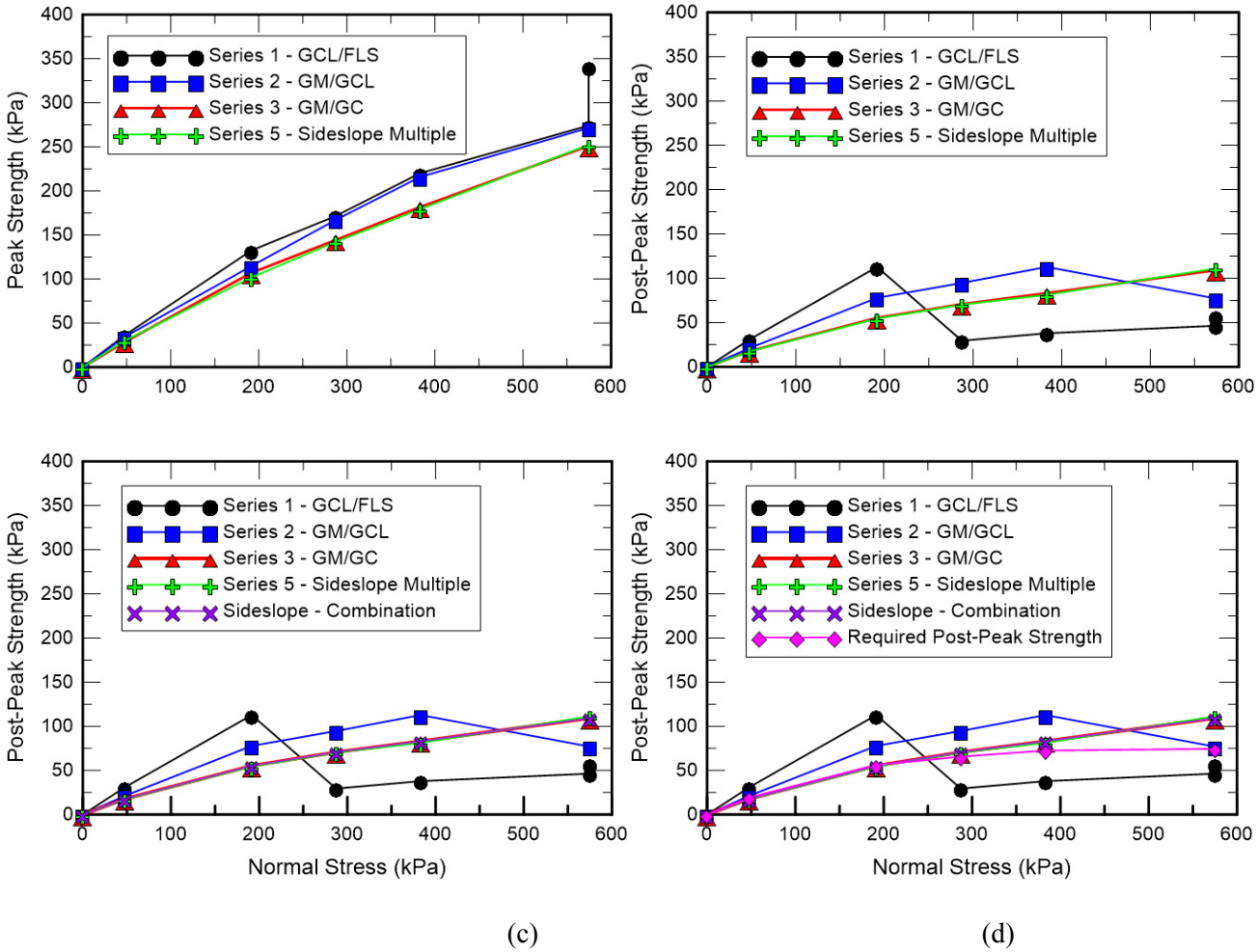

Figure 2. Sideslope Liner System: (a) measured peak strengths, (b) measured peak strengths, (c) combination post-peak strength envelope, and (d) comparison of combination post-peak strength envelope and design required post-peak strengths.

Finally, Figure 2(d) adds the project specified post-peak strength envelope to the strength envelopes in Figure 2(c) and in general shows the post-peak strength envelope of the GM/GC interface meets or exceeds the project specified strength envelope especially at normal stresses greater than 287.3 kPa (6,000 psf) based on both single and multi-interface test results. However, at normal stresses of 47.9 and 191.5 kPa (1,000 and 4,000 psf) the measured interface strength is slightly lower than the required post-peak values. However, this small difference between the measured and required post-peak strengths at normal stresses less than 191.5 kPa (4,000 psf) did not impact the factor of safety significantly so the geosynthetics tested were deemed suitable. If the geosynthetics and soils used during actual construction differ from the materials tested, the lowest post-peak strength envelope and critical interface could change and additional testing would have been performed.

In summary, the critical interface for the sideslope liner system materials tested is the GM/GC interface. The GM/GC post-peak strengths for the sideslope liner system meet or exceed the project specified post-peak strength envelope. This comparison illustrates the usefulness of conducting multi-layer interface tests.

Base liner interface test results. Figure 3 presents the interface strength test results for the base liner system that are presented in Tables 2 and 3. Each of the strength envelopes are keyed to the Test Series name in Table 2. For example, Figure 3(a) presents the peak interface strengths for Test Series 1 and 2 because the base liner systems does not contain a GC layer, like the sideslope liner system, so Test Series 3 is not relevant. In addition, the multi-layer interface test series for the base liner system (Test Series 4 – Base Multiple) with all of the interfaces tested in Test Series 1 and 2 is included for comparison purposes.

Figure 3(a) shows the weakest or critical interface of the base interfaces tested is the GM/GCL interface. The GM/GCL interface shows slightly lower strengths than the GCL/FLS interface for all normal stresses tested. There is not a large difference in the interface strengths for Test Series 1 and 2 so it is beneficial that a multi-layer interface test was conducted using the base liner system materials to further investigate the shear behavior of the base liner system.

The critical interface for the base liner system of GM/GCL was confirmed by Multi-Layer Interface Test Series 4, which shows shear displacement occurred along the GM/GCL interface for all of the normal stresses tested except 47.9 kPa (1,000 psf) where it occurred on the GM/gravel interface because of less gravel embedment into the GM as discussed below.

This confirms the critical interface for the base liner system materials tested is the GM/GCL interface and the single and multi-layer interface tests yield similar peak strengths, which is in agreement with Stark et al. (2015).

The use of the post-peak strength envelope for the GM/GCL interface, i.e., critical interface, is confirmed by Multi-Layer Interface Test Series 4, which showed shear displacement on the GM/GCL interface. However, the post-peak strength envelope for the GM/GCL interface from Multi-Layer Interface Test Series 4 is slightly lower than the single interface tests on the GM/GCL interface. Finally, the GCL/FLS interface did not fail before the GM/GCL interface so the lower post-peak strength envelope measured for the GCL/FLS interface (see Figure 3(b)) should not be used for base liner design because it will be overly conservative as described by Stark and Choi (2004). The GCL/FLS post-peak strength envelope decreases in strength with increasing normal stress because the GCL failed internally and the measured strengths after a 383.2 kPa (see Figure 3(b)) corresponds to the shear resistance provided by the bentonite in the GCL. The GM/GCL post-peak strength envelope also decreased in strength at the highest normal stress (574.8 kPa) because the GCL also failed internally and the measured strengths corresponds to the shear resistance provided by the bentonite in the GCL (see Figure 3(b)).

At a normal stress of 47.9 kPa (1,000 psf), shear displacement occurred on the GM/gravel interface instead of the GM/GCL interface although the resulting strength is in agreement with other normal stresses. This change in interface at low normal stresses is probably due to the gravel not embedding as deeply into the HDPE geomembrane as occurs at higher normal stresses. Nevertheless, the resulting post-peak strength (25.6 kPa; 535 psf) at 47.9 kPa (1,000 psf) exceeds the project required strength (19.3 kPa; 404 psf) so the base liner system geosynthetics tested are suitable. Being able to observe this interface change and interaction is another benefit of multi-layer interface testing.

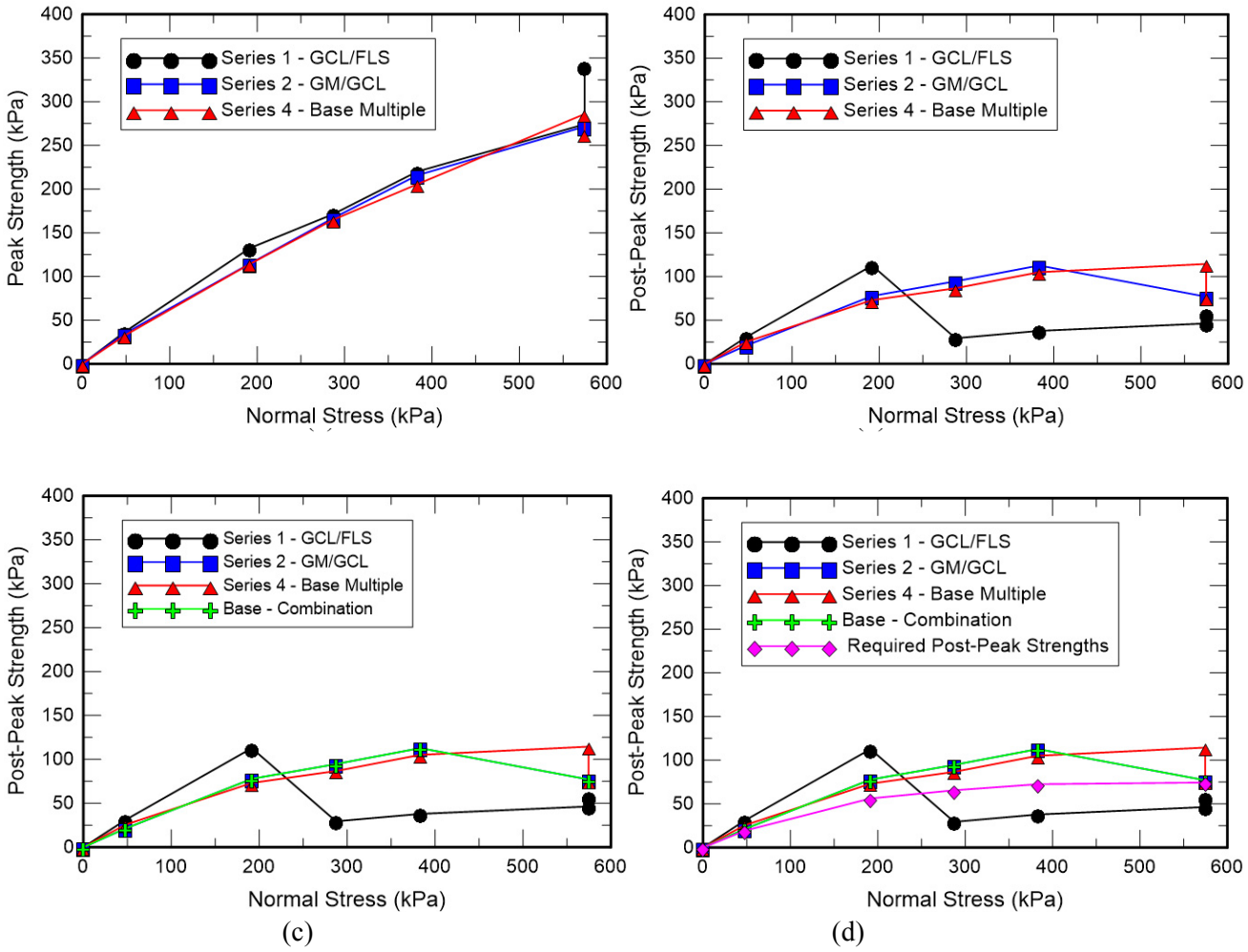

Figure 3. Base Liner System: (a) measured peak strengths, (b) measured post-peak strengths, (c) combination post-peak strength envelope, and (d) comparison of combination post-peak strength envelope and design required post-peak strengths.

Figure 3(c) shows the combination post-peak strength envelope, which essentially coincides with the post-peak strength envelope for the GM/GCL interface because sliding occurred at this interface for all of the normal stresses tested. For comparison purposes, Table 4 presents the normal stress and shear stress for the base liner combination post-peak strength envelope. Figure 3(d) adds the project specified strength envelope to the envelopes in Figure 3(c) and shows the post-peak strength envelope of the GM/GCL interface meets or exceeds the project specified strength envelope especially if a GCL peel strength greater than 211.4 N (47.5 lbs) (ASTM D4632) is used. A GCL peel strength of 211.4 N (47.5 lbs) (ASTM D4632) is the lowest peel strength for the GCL supplied for the project and the corresponding interface strength should be considered as the lower bound value for the materials used.

Another consideration in deciding that the GCL/GM interface is the critical interface and the post-peak strength of this interface should be used for design purposes is the field

compaction conditions versus the laboratory compaction conditions for the FLS. SGI compacted the FLS material to a relative compaction of 90% based on Modified Proctor compaction (ASTM D1557) and a moisture content of 23%, which corresponds to the optimum moisture content (OMC) +4% or the wettest condition allowed by project compaction requirements. The field compaction requirements for the FLS in the specifications are a relative compaction of greater than or equal to 90% based on Modified Proctor compaction (ASTM D1557) and a moisture content of OMC to +4% above OMC. Eighty-six (86) field compaction control tests show the following field compaction levels for the base liner system:

- Relative Compaction: 90 to 100% with an average of 95%
- Compaction Moisture Content: OMC – 0.3% to +4.3% with an average of OMC + 1.8%

As a result, it is anticipated the GCL/FLS interface will be as strong or stronger in the field than in the laboratory testing assuming a high GCL peel strength (> 211.3 kPa/47.5 lbs) is used for the GCL because a stronger GCL/FLS interface will force internal GCL shearing instead of failure along the GCL/FLS interface. A stronger FLS will result in a stronger GCL/FLS interface, which reinforces the conclusion above that the GM/GCL interface will be the critical interface for the base liner system especially if a GCL peel strength greater than 211.3 N (47.5 lbs) (ASTM D4623) is used.

SUMMARY AND RECOMMENDATIONS

The results of single and multiple geosynthetic interface shear strength tests performed on soil/geosynthetic and geosynthetic/geosynthetic interfaces for a landfill sideslope and base liner system for a landfill expansion project and resulted in the following observations and recommendations:

- Single and multi-layer interface direct shear tests yielded the same critical interface for the proposed sideslope liner system interfaces, which is the geomembrane/drainage composite (GM/GC) interface. In addition, the peak and post-peak strength envelopes measured from single and multi-layer interface direct shear test are in good agreement.
- Single and multi-layer interface direct shear tests also yielded the same critical interface for the proposed base liner system interfaces, which is the GM/GCL interface. In addition, the peak and post-peak strength envelopes measured from single and multi-layer interface direct shear test are in good agreement.
- Because the bottom and sideslope liners have different soil and geosynthetics components, it is recommended that different required strength envelopes be used for the two liner configurations because the critical interface is dependent on the components included and the applied normal stresses.
- If the project Specifications require single interface tests for various soil/geosynthetics and geosynthetics/geosynthetics liner interfaces, the specified strength should be a single peak strength envelope for the entire composite liner configuration rather than individual values for each interface. The specified post-peak envelope should be based on the peak interface strength of the weakest interface rather than the lowest post-peak strength.

- In practice, multi-layer interface tests are being used for liner system design and if there is an anomaly with the multi-layer interface test results, single interface tests can be conducted to clarify the test results. However, for this project, single interface tests were specified and multi-layer interface tests were used to verify the combination strength envelope from the single interface tests. Regardless, the multi-layer interface strength envelopes measured herein are in good agreement with the single interface test results.

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