Laboratory measurements of GCL shrinkage under cyclic changes in temperature and hydration conditions

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ABSTRACT: Recently, several geomembrane/geotextile-encased geosynthetic clay liner (GCL) composite liner systems have been exhumed where separation of GCL panel overlaps has been observed due to GCL shrinkage. All of the documented cases involved installations where the GCL was overlain by an HDPE geomembrane, which was exposed for a duration ranging from two months to five years with no soil cover. This paper presents the results of an original laboratory study of GCL shrinkage. The mechanism used in the laboratory testing program to induce shrinkage consists of cyclic changes in GCL water content and temperature. These cyclic changes are intended to simulate the conditions in the field, where bentonite hydration-drying cycles are related to day-night cycles. Samples of reinforced GCLs were tested with various types of cap and carrier geotextiles, various water contents, and various densities of needlepunch reinforcement. The results show that the test provides values of GCL shrinkage within the range of values observed in the field. The experimental data also quantify differences in the potential GCL shrinkage between different reinforced GCLs.

1 INTRODUCTION

Shrinkage of unreinforced geotextile-encased GCL panels in the field has been known and managed since the early 1990s. However, this problem has not been widely discussed. The current increased awareness of GCL panel shrinkage results from recently documented incidences of GCL panel shrinkage that occurred after the GCL was covered with a geomembrane. The first published acknowledgement of this issue was by Thiel & Richardson (2005). Then, Koerner & Koerner (2005a, 2005b) reported five cases of GCL panel separation due to GCL shrinkage dating back to 1993. An updated summary of field observations is presented in Table 1.

Table 1. Summary of field observations.

GCL Type (cap GT/carrier GT)		Slope	Maximum separation (mm)	Exposure duration (months)
W/W	unreinforced	22°	300	60
N/W	reinforced	18°	200	15
N/W	reinforced	4°	300	2
N/N	reinforced	34°	1200	36
N/N	reinforced	18°	300	5
N/N	reinforced	4°	450	2

Legend: GT = geotextile; W = woven; N = nonwoven

These observations are related to GCLs covered with a geomembrane which was left exposed from two months to five years prior to soil covering. In all cases, the side of the geomembrane in contact with the cap geotextile of the GCL was textured. Four of the five cases involved reinforced GCLs.

For various reasons, the owners of these facilities had to cut open or remove sections of the geomembrane, at which time they discovered that adjacent GCL panels had separated, exposing the underlying subgrade, where there had initially been overlaps of 150 mm between GCL panels. The GCL panels had shrunk in the widthwise direction by an amount ranging from 150 mm to more than 1350 mm. This magnitude of panel shrinkage translates into a decrease of 3.3% to 30% from the original panel width (typically 4.5 m). In all the documented cases, no decrease or increase was noted in the lengthwise direction of the GCL panels.

Thiel & Richardson (2005) and Koerner & Koerner (2005a, 2005b) surmised several possible reasons why GCL panel shrinkage could occur, without attributing the cause to any particular mechanism. The potential causes of panel shrinkage can be summarized as follows: (1) bentonite shrinkage due to desiccation, possibly exacerbated by hydration-drying cycles; (2) bentonite shrinkage due to cation exchange; (3) GCL panel necking due to Poisson's effect linked to tension in the longitudinal direction caused by gravity on slopes (or caused by the next mechanism in the longitudinal direction); (4) GCL panel lateral "gathering" due to repeated expansion-contraction of the overlying textured geomembrane that somehow dragged the GCL toward the center of the panel in the lateral direction; and (5) shrinkage of one or both of the geotextile components of the GCL.

The focus of this paper and laboratory testing is on potential shrinkage due to cyclical hydration-drying effects on reinforced geotextile-encased GCLs. Five tests were also performed to evaluate the contribution of geotextile components of the GCL on GCL shrinkage.

2 GCL HYDRATION AND DRYING

2.1 *GCL shrinkage due to drying*

For very high initial water content (e.g. $w_{initial}$ = 70%), non-reinforced GCL panel shrinkage by drying is not a new or surprising phenomenon. The primary author's firm has experienced this while performing construction quality assurance on projects with these types of GCLs, where significant shrinkage occurred from the beginning of the day to the end, resulting in complete loss of overlaps. Such shrinkage was also documented by Mackey (1997).

For reinforced GCLs, however, drying alone during GCL installation has not been observed to cause panel shrinkage. In fact, laboratory testing by the authors and by Koerner and Koerner (2005) indicate a maximum reinforced GCL shrinkage of approximately 2% with drying alone, while the separation of a 150 mm overlap in a 4.5 m wide panel would require a shrinkage of at least 3.3%. Thus, drying alone does not appear likely to explain the instances of overlap separation observed in the field.

2.2 *Hydration-drying cycles*

In contrast to drying only, cyclic hydration and drying can have a profound impact on GCL shrinkage, as demonstrated by the laboratory testing described in this paper, and could fully account for the overlap separation observed in the field. The specific situation evaluated is that of an installed geomembrane/GCL composite liner left exposed with no soil cover. During the daytime, the exposed geomembrane will increase in temperature due to the sun. A maximum temperature of approximately 70°C has been measured on black geomembranes exposed to the sun (Pelte et al. 1994; Koerner and Koerner 1995). This elevated temperature causes the GCL to dry during the day. As a result, water vapor becomes trapped between the GCL and the geomembrane.

During the night, when temperature decreases, the water vapor trapped below the geomembrane will condense into droplets. If there is an appreciable slope, the droplets may run down gradient and, after a number of day-night cycles, may gather at the toe of slope. This accumulation of water may saturate the GCL and underlying soil in the vicinity of the toe of the slope and/or form a water pillow beneath the geomembrane. If there is only a slight slope, the condensed water would be available to go back into the GCL.

During these cycles, the natural matric-suction of the bentonite in the GCL will always have a tendency to draw moisture from the subgrade. The rate at which a GCL will draw moisture from the subgrade will be site specific and depend on the subgrade moisture conditions and matric-suction characteristics of the subgrade soil. The subgrade moisture provides the GCL a water source for extended hydration-drying cycles.

Thus, this is the general mechanism for hydration/drying cycles of exposed geomembrane/ GCL installations. The magnitude of hydration and drying would vary substantially at different sites and under different exposures (e.g. south vs. north facing slope), as well as from day-to-day, week-to-week, and season-to-season.

3 EXPERIMENTAL PROGRAM

A laboratory testing program was developed to evaluate the amount of GCL shrinkage due to cyclical changes in temperature and water content. The laboratory testing program is described below. It includes tests on GCL samples and tests on geotextile samples.

3.1 *GCL testing*

The GCL samples were cut to a dimension of 350 mm (cross-machine direction, XD) by 600 mm (machine direction, MD). The samples were placed in a relaxed, stress-free state on aluminum pans with their as-received water content. The two small ends of the samples were clamped using a continuous bar-clamp screwed to the pan. This clamping is intended to simulate the conditions in the field where most geomembrane/GCL sloping installations include anchorage or ballast at both ends. After clamping, the distance between the bar-clamps was 550 mm.

Two marks were precisely located at mid-length of the sample and 25 mm from the long edges. The initial width between those marks was measured to the nearest 0.5 mm. This width was of the order of 300 mm. As a result, the aspect ratio of the relevant portion of the sample was 1.8 (i.e. 550/300).

Figure 1 shows the initial sample setup and the same sample after 20 test cycles. The central rectangle (500 mm by, initially, 300 mm) limits the area subjected to hydration.

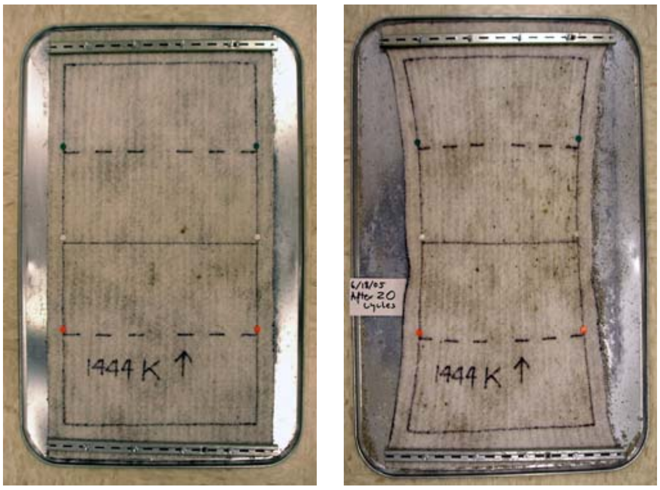

Figure 1. GCL sample (left) before test cycles and (right) after 20 hydration-drying test cycles.

The samples were then hydrated. To that end, a specified volume of water was evenly applied over the 500 mm by 300 mm central portion of the samples. The samples were then covered with a plastic sheet and allowed to hydrate at room temperature for approximately 8 hours. The volume of hydration water was 500 ml in most tests. However, in one test, a volume of 300 ml was used to evaluate the effect of the hydration water volume on the magnitude of shrinkage. A volume of hydration water of 500 ml equates to a GCL water content of approximately 65%. This water content is within the range of a typical bentonite water content equilibrium resulting from subgrade soil suction as documented by Daniel et al. (1993).

At the end of the approximately 8 hours of bentonite hydration, the sample width between the mid-point marks was measured and recorded.

The samples were then placed in an oven at 60°C and left to dry. This temperature was selected as representative of the temperature that is likely to exist beneath a black geomembrane exposed to the sun.

After approximately 15 hours of drying, the samples were removed from the oven, allowed to cool to room temperature for approximately 10 minutes, and the sample width between the mid-point marks was measured and recorded.

The samples were then re-hydrated for another cycle. Each cycle lasted 24 hours and consisted of a sequence of hydration (approximately 8 hours) and a sequence of drying (approximately 15 hours). Approximately one hour was used for measurements and handling samples. The GCL samples were subjected to 40 cycles. Figure 1 shows a GCL sample before and after 20 cycles.

3.2 *Geotextile testing*

To quantify the magnitude of cap and carrier geotextile shrinkage and its potential contribution to overall GCL shrinkage, samples of geotextiles representative of those used in the GCLs were tested. The testing protocol for sample preparation and for the cycles was the same as for the GCL samples. However, the number of cycles was lower.

4 MATERIALS TESTED

4.1 *GCLs tested*

Materials selected for GCL shrinkage testing included needlepunch reinforced geotextile-encased GCLs from two different manufacturers (A and B) with variations in geotextile carrier, bentonite source and granularity, water content, and density of needlepunch reinforcement as quantified by GCL peel strength per ASTM D 6496. Four of the GCLs included a heat-burnished carrier geotextile, which is sometimes used to improve internal shear strength. A summary of the geotextile-encased GCLs tested is presented in Table 2.

Table 2. Reinforced geotextile-encased GCLs tested.

GCL characterized by Cap GT/Carrier GT and by (manufacturer)	Initial water content	Peel strength kN/m (lb/in)
Nonwoven/Woven		
N/W1 (Manufacturer A)	20.9%	1.01 (5.8)
N/W2* (Manufacturer B)	11.8%	0.33 (1.9)
Nonwoven/Nonwoven		
N/N1 (Manufacturer A)	15.2%	2.15 (12.3)
Nonwoven/Scrim-Nonwoven		
N/S-N1* (Manufacturer B)	9.6%	2.00 (11.3)
N/S-N2* (Manufacturer B)	8.9%	0.79 (4.5)
Nonwoven/ Coated Woven		
N/W-C1* (Manufacturer B)	7.2%	2.61 (14.9)

* Heat-burnished carrier geotextile.

Samples N/W1 and N/N1 are representative of the reinforced GCL products which exhibited shrinkage in the documented field studies (see Table 1). The other tested GCLs have not been documented to shrink in field case histories.

In addition to the six geotextile-encased GCLs listed in Table 2, one geomembrane-supported GCL with 0.4 mm HDPE backing was tested. The geomembrane-supported GCL did not exhibit noticeable shrinkage, which is indicative of the proven dimensional stability of HDPE geomembranes.

4.2 *Geotextiles tested*

Five different woven and nonwoven geotextiles representative of those used in the GCLs were tested. These geotextiles are described in Table 2. As shown in Table 2, the geotextiles by themselves exhibited very little shrinkage and stabilized after few hydration-drying cycles. Therefore, geotextile hydration-drying shrinkage testing was terminated after seven cycles. Thus, it was determined that geotextile shrinkage by itself is relatively small and a minor contributor to overall GCL shrinkage.

Table 3. Shrinkage results for cap and carrier geotextiles.

Mass per unit area and Geotextile type	Function	Shrinkage (%)	
		1 cycle	7 cycles
200 g/m^2 nonwoven (light needling)	cap	1.1	2.4
200 g/m^2 nonwoven	carrier	0.1	0.3
100 g/m^2 woven (scrim)	carrier	0.8	0.9
200 g/m^2 scrim-nonwoven	carrier	0.4	0.5
400 g/m^2 nonwoven/ scrim-nonwoven	cap/carrier composite	0.3	0.5

5 RESULTS OF GCL SHRINKAGE TESTS

5.1 *Presentation of the results*

The measured changes in sample width at the mid-point of the sample are divided by the initial width of the sample and expressed as percent shrinkage. A graph of percent shrinkage as a function of cycle number is shown in Figure 2. This graph shows that a fraction of the shrinkage observed after drying is reversible, i.e. is recovered after hydration. However, there is a significant amount of residual shrinkage after hydration in all of the GCLs tested. For example, in the case shown in Figure 2, after 20 cycles, the shrinkage after drying is 15% and the residual shrinkage after hydration is 8%.

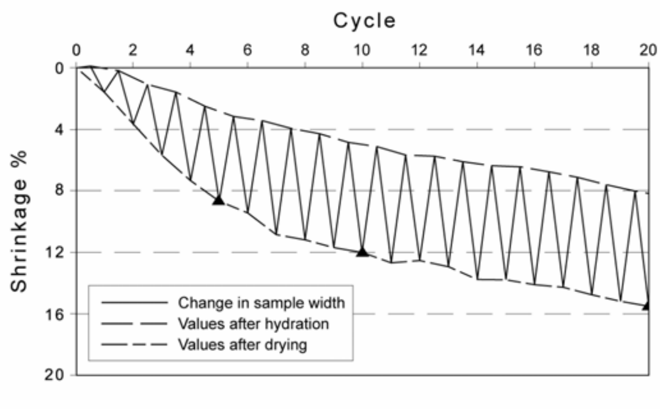

Figure 2. Change in sample width (expressed as percent shrinkage) vs. cycle number, for N/S-N2 with 500 ml of hydration water.
(Note: Only the first 20 cycles are shown for clarity.)

Shrinkage values at the end of the drying sequence of selected cycles are presented in Table 4. The same values are presented graphically in Figure 3. This figure shows that, after 40 hydration-drying cycles, some of the samples still exhibited a trend towards further potential shrinkage with additional cycles. More testing would be required to determine the limit of shrinkage for each product.

Given that the samples were clamped at both ends, shrinkage resulted in tension in the longitudinal direction of the samples, which might have contributed to the transverse necking through Poisson's effect.

Table 4. Summary of GCL shrinkage values after drying.

Product (Cap GT/Carrier GT)	Shrinkage (%) No. hydration-drying cycles				
	1	5	10	20	40
Nonwoven/Woven					
N/W1	3.7	11.8	15.2	18.7	20.6
N/W2*	2.7	7.6	10.0	11.1	14.5
Nonwoven/Nonwoven					
N/N1	5.8	16.5	19.3	22.2	23.0
Nonwoven/Scrim-Nonwoven					
N/S-N1*	1.4	5.3	7.8	10.4	12.9
N/S-N2*	1.6	8.7	12.0	15.5	19.2
N/W PP Coating					
N/W-C1	1.2	4.3	6.6	10.8	12.8

* Heat-burnished carrier geotextile.

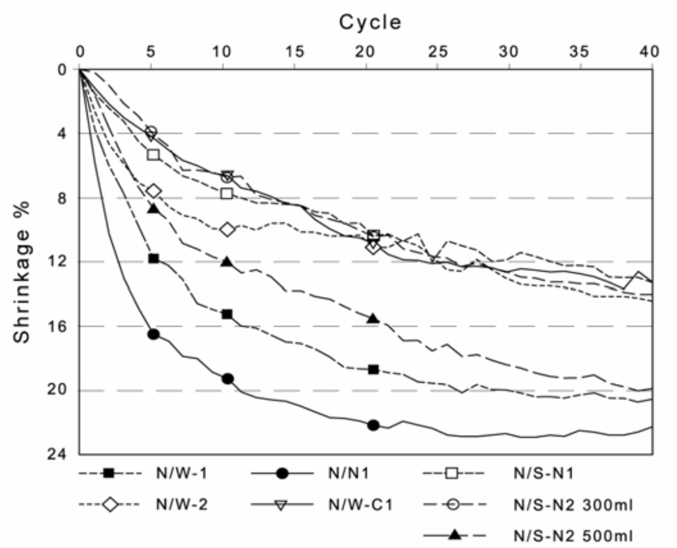

Figure 3. Shrinkage vs. cycle number for all geotextile-encased GCL samples tested (values after drying).
(Notes: (1) When the volume of hydration water is not indicated, it is 500 ml per cycle; (2) The curve for N/S-N2 with 500 ml is the curve for values after drying in Figure 2.)

5.2 *Comparison with field shrinkage*

The maximum shrinkage measured in the laboratory (23%) equates to a 1035 mm loss of panel width for a typical panel width of 4.5 m, or a panel separation of 885 mm assuming a 150 mm initial overlap. This is consistent with the maximum panel separation of 1200 mm observed in the field (Table 1). It may be concluded that the testing methodology presented in this paper is able to produce an amount of shrinkage of reinforced GCLs that is consistent with some of the field observations. However, more work would be needed to refine the testing methodology to ensure that it is representative of the field conditions. In particular, parameters, such as the amount of water used for hydration, the temperature used for drying, and the cycle duration, should be studied.

Also, it should be noted that the aspect ratio of the samples is different from the aspect ratio of the panels in the field. Typical geotextile-encased GCL panels are 30 to 45 m long (the typical roll length) and 4.5 m wide, hence an aspect ratio of 7 to 10. As mentioned in Section 3.1, the GCL samples utilized for this laboratory testing had an aspect ratio of 1.8. The influence of aspect ratio on shrinkage and necking due to hydration-drying cycles is not known. This should be a subject for additional testing.

5.3 *Effect of volume of water addition*

The results described above were obtained by adding 500 ml of water at each hydration sequence. To evaluate the effect of adding less water, Sample N/S-N2 was tested for two different volumes of water addition: 500 and 300 ml per cycle. The test results presented in Figure 3 and Table 5 show that the smaller water addition results in less shrinkage per cycle, with about one-fourth less shrinkage after 40 cycles. The difference in the limit of shrinkage is not known, and it would require additional cycles to determine if the ultimate shrinkage is less or the same with smaller water addition.

Table 5. GCL shrinkage for Sample N/S-N2 for two different volumes of water addition. (See also Figure 3.)

Water addition per cycle	Shrinkage (%) No. hydration-drying cycles				
	1	5	10	20	40
300 ml	0.2	4.1	6.8	10.4	14.4
500 ml	1.6	8.7	12.0	15.5	19.2

6 INFLUENCE OF GCL TYPE

Following is a discussion of the test results that is organized by the type of GCL characterized by the cap and carrier geotextiles (as in Table 2). In this discussion, the width reduction of the GCL panels observed in the field is obtained by adding 150 mm (the presumed initial overlap) to the panel separation values given in Table 1, and the percent shrinkage is derived from the width reduction using a panel width of 4.5 m.

6.1 *GCL with nonwoven/woven*

Sample N/W1 is representative of the nonwoven/ woven reinforced GCL which experienced shrinkage in two of the observations presented in Table 1, with a maximum width reduction of 450 mm (10% shrinkage). From Table 4, this correlates to four or five cycles of hydration-drying testing. Shrinkage after 40 cycles for Sample N/W1 was 20.6%, i.e. about twice the above mentioned 10% shrinkage observed in the field with a similar GCL.

Sample N/W2 exhibited about one-third less shrinkage than Sample N/W1 throughout the 40-cycle testing. Compared with Sample N/W1, Sample N/W2 had a lower initial water content (11.8% vs. 20.9%) and a heat-burnished carrier geotextile, two characteristics that could tend to reduce shrinkage. In contrast, Sample N/W2 had a smaller needlepunch density (as indicated by a lower peel strength), which may tend to increase shrinkage. Therefore, it is difficult to draw a conclusion regarding the difference in performance between Samples N/W1 and N/W2.

6.2 *GCL with nonwoven/nonwoven*

Sample N/N1 is representative of the nonwoven/ nonwoven reinforced GCL which experienced more shrinkage than the GCLs incorporating woven geotextiles in the documented field studies. In the tests also, this type of GCL experienced the highest shrinkage of all GCLs tested (23%).

6.3 *GCL with nonwoven/scrim-nonwoven*

The N/S-N samples incorporated a scrim woven fabric into the nonwoven carrier geotextile. It is generally suspected that the presence of a scrim reduces shrinkage when compared with the nonwoven-nonwoven product. In fact, incorporation of a scrim into a nonwoven carrier is discussed and recommended by Koerner and Koerner (2005a, 2005b), and also in the GRI-GCL3 standard specification for GCLs (GRI 2005).

Compared with Sample N/N1, Sample N/S-N1 had similar high peel strength, but included a heat-burnished carrier geotextile and had lower initial water content. Through 40 cycles of testing, Sample N/S-N1 exhibited significantly less shrinkage than Sample N/N1. Sample N/S-N1 also exhibited less shrinkage than the nonwoven/woven GCLs tested.

To evaluate the effect of needlepunch density, the results for Samples N/S-N1 and N/S-N2 can be compared. Sample N/S-N1 (with a peel strength of 2.0 kN/m) has a greater needlepunch density than Sample N/S-N2 (with a peel strength of 0.79 kN/m). Sample N/S-N1 exhibited about one-third less shrinkage than Sample N/S-N2. Thus, with heavier needlepunch density (i.e. greater internal strength), the GCL experienced less shrinkage.

6.4 *GCL with nonwoven/woven with PP coating*

Sample N/W-C1 comprised a heat-burnished nonwoven/woven carrier with a polypropylene (PP) geofilm coating. It exhibited the lowest shrinkage of all the GCLs tested through the first 10 cycles. Between 10 and 40 cycles, results for this sample were similar to the results for Sample N/S-N1. It is concluded that a PP geofilm coating improves geotextile and GCL stability through initial hydration-drying cycles.

7 CONCLUSION

7.1 *Conclusion on the causes of shrinkage*

The cyclic hydration-drying testing methodology presented in this paper produced shrinkage of reinforced GCLs within the magnitude of shrinkage observed in the field, whereas drying only does not cause significant shrinkage of reinforced GCLs. Therefore, it may be assumed that hydration-drying cycles play a key role in reinforced GCL panel shrinkage observed in the field. The test program also showed that geotextile shrinkage has only a small influence on GCL panel shrinkage.

Other mechanisms may contribute to GCL panel shrinkage. For example, GCL anchorage results in restrained shrinkage in the longitudinal direction, hence longitudinal tension, which can contribute to transverse necking (Poisson's effect) both in the field and in the laboratory tests. From this viewpoint, it is necessary to investigate the impact of the aspect ratio, which is 1.8 in the tests presented herein and typically 7 to 10 in the field.

It should be noted that the test program presented in this paper was not designed to find the reasons why hydration-drying cycles cause more shrinkage than drying alone. More research is needed to determine the root cause of GCL panel shrinkage.

7.2 *Conclusion on environmental conditions*

The test results indicate that less water supply per cycle reduces the amount of shrinkage in each cycle. It would be necessary to evaluate which amount of hydration water would properly simulate the field conditions. Another environmental condition that could have an impact, but which was not evaluated, is the drying temperature used in the test.

7.3 *Conclusion on testing*

Due to the important implications of GCL shrinkage, it may be appropriate to develop a standard test method to quantify the dimensional stability of GCLs subjected to hydration-drying cycles. The results of such tests could be useful to designers in specifying required GCL overlaps, and could help manufacturers in developing GCLs that better resist shrinkage. The experience gained in developing the testing program presented in this paper could be used for the development of a standard test method.

7.4 *Conclusion on manufacturing*

The test results presented in this paper show that the presence of a woven fabric in a GCL, whether it is a woven carrier or a scrim associated with a nonwoven carrier, reduces the amount of shrinkage. The test results also suggest that increased needlepunching results in a lower tendency for shrinkage. It also appears that a PP geofilm coating may have a beneficial effect on reducing shrinkage potential.

It is worth noting the difference in results between GCLs of the same type, but from two different manufacturers. At this point, it is difficult to determine the reason for the difference. Many variables would need to be considered, including type and granularity of bentonite, initial water content, type of geotextile fibers, methods of needle punching, tension on the geotextile components of the GCL during manufacturing and roll windup, etc.

7.5 *Conclusion for designers*

This paper should make more designers aware of GCL panel shrinkage, and should inform them that different GCLs may experience different amounts of shrinkage under similar circumstances. Also, it provides designers with a methodology for evaluating the potential shrinkage of GCLs, which should contribute to safer composite liners.

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