Technical Developments related to the Problem of GCL Panel Shrinkage when placed below an Exposed Geomembrane

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ABSTRACT
The shrinkage of fabric-supported reinforced geosynthetic clay liner (GCL) panels covered by a geomembrane and left exposed with no overlying soil was openly documented as a potential problem in 2005. Laboratory and field testing has been conducted in an attempt to understand this problem. Various manufacturing, design, and construction measures have been suggested to mitigate the potential loss of GCL overlap due to shrinkage. These measures include increasing the GCL seam overlap, reducing the length of time that the geosynthetics remain uncovered by soil, use of a reflective surface on the geomembrane, supplying the GCL material with a lower initial water content, utilizing a thermally-locked scrim reinforcement, encapsulating the GCL between geomembranes, and applying a heat-tacking technique to the overlap. Ongoing studies continue to investigate the mechanisms of shrinkage so that other solutions to this problem can be confidently proposed.

1. INTRODUCTION

The shrinkage of fabric-supported reinforced GCL panels in the field has been known and managed since the early 1990s. This problem was not widely discussed, however, and, until 2005, the potential for this to occur with reinforced products was virtually unmentioned. Thiel and Richardson (2005) first publicly documented the potential problem of shrinkage of reinforced GCLs covered by a geomembrane (GM) and left exposed (i.e. with no overlying cover soil) in 2005. Thiel et al. (2006) summarized six cases (Table 1) in which GCL panels that reportedly had originally been overlapped by 150 mm had separated at their overlaps, leaving a gap between panels of between 200 and 1200 mm after periods of exposure of between 2 and 36 months. Koerner & Koerner (2005a, 2005b) noted two other examples in which GCL panels had either lost a portion of their original overlap or had completely separated. Examples from two projects are shown in Figure 1.

Table 1. Summary of field observations of reported GCL panel separation.

GCL Type (cap GT/carrier GT)		Slope	Maximum separation (mm) [approx % shrinkage]	Exposure duration (months)
W/W	unreinforced	22°	300 [7%]	60
N/W	reinforced	18°	200 [5%]	15
N/W	reinforced	4°	300 [7%]	2
N/N	reinforced	34°	1200 [28%]	36
N/N	reinforced	18°	300 [7%]	5
N/N	reinforced	4°	450 [11%]	2

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

The reasons for the separation of the GCL panels were not known and, quite frankly, are still not fully understood. Causes that have been postulated include (1) anisotropic-hysteretic expansion and contraction of the bentonite that occurs progressively through wetting-and-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 the slopes; (4) lateral "gathering" of GCL panels due to repeated expansion-contraction of the overlying textured geomembrane that then drags the GCL laterally toward the center of the panel; and (5) shrinkage of one or both of the geotextile components of the GCL.

The factor common to all the field cases in which shrinkage was observed is that the GCLs had been overlain by a geomembrane that was left uncovered (i.e. continuously exposed to meteoric conditions) for periods ranging from two months to five years. A likely reason that relatively few cases of this problem have been documented is that it is quite uncommon to cut open a geomembrane that has been installed and fully certified by a CQA program. In fact, in the primary author's 20 years of field experience with CQA, he has never once been called upon to perform this task, except for the edge tie-ins required for cell expansion. In all the case histories in which GCL panel separation was observed, there was some unique, non-typical cause that required the underlying GCL to be uncovered from the previously-installed geomembrane.

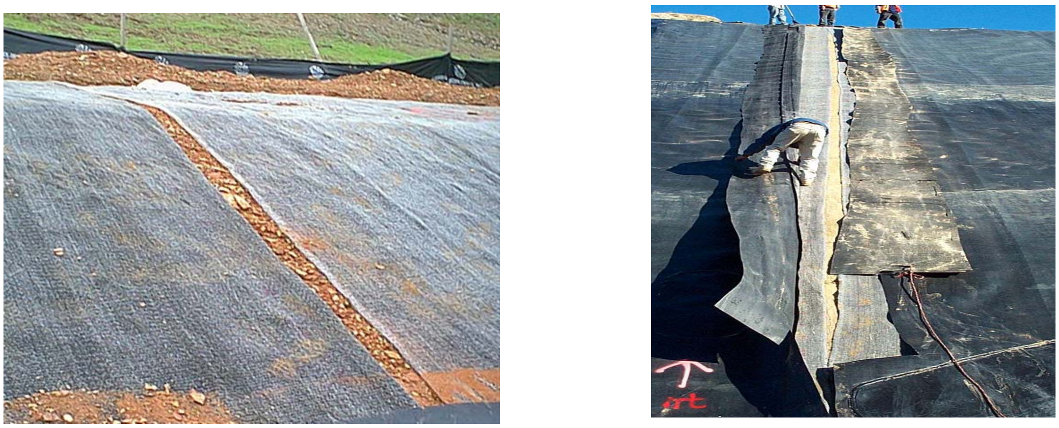

Figure 1. Photographs of actual GCL panel separation problems at two different projects in the USA.

The aim of this paper is to summarize the attempts that have been made since 2005 to understand and manage the issue of GCL panel separation. The paper focuses specifically on fabric-supported reinforced GCLs. This issue is not applicable to geomembrane-supported GCLs. This issue is even more extreme for fabric-supported non-reinforced GCLs, and the requirement for timely covering of those products with soil materials has been state-of-the-practice for many years for this reason.

2. LABORATORY STUDIES

Several initial laboratory studies (Thiel et al. 2006; Bostwick et al. 2007, 2008, 2010) have been able to replicate the magnitude of the GCL shrinkage phenomenon. These studies were accomplished by placing GCL samples that were cut to approximate dimensions of 350 mm by 600 mm 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 pans. The samples were then subjected to cycles of wetting and drying (generally at 60°C). The results indicated that shrinkage of up to approximately 25% could be induced in the laboratory by the application of cyclic wetting and drying, and that some products were more susceptible to shrinkage than others. Figure 2 shows a typical laboratory test sample. Figure 3(a) shows the cyclic progression of shrinkage and expansion through 20 cycles of wetting and drying, with a net unrecoverable shrinkage. Figure 3(b) shows a comparison of the results from several different GCL products after the 40th drying cycle.

Some of the conclusions drawn from the testing performed by Thiel et al. (2006) were: (1) needlepunched GCLs that have only nonwoven geotextiles exhibit the highest propensity for shrinkage, while those that contain a woven or scrim geotextile exhibit a lower shrinkage potential; (2) a greater intensity of needlepunching appears to result in a lower tendency toward shrinkage; and (3) less water supply in each wet/dry cycle reduces the amount of shrinkage that occurs in that cycle.

Koerner & Koerner (2005a, 2005b) considered three possible mechanisms for GCL panel shrinkage: (1) cyclic wetting and drying; (2) longitudinal steep slope tensioning of the GCL; and (3) GCL contraction on relatively flat slopes caused by "gathering" under textured geomembranes. Of these three possibilities they believed that Mechanism 2 (slope tensioning) is the major factor that contributes to the problem in the field. By performing laboratory tension tests, they demonstrated tension-necking due to a sort of "Poisson's effect" linked to tension in the longitudinal direction. An example of their testing-in-progress is presented in Figure 4. Inspection of Table 1, however, indicates that significant shrinkage and loss of overlap occurred in 2 months at locations where the slope was only 4^o. Furthermore, unpublished research from a field test site in Godfrey, Ontario (Brachman et al. 2007) suggests that shrinkage on the base (3^o slope) is not necessarily less than that on an 18^o slope under nominally similar conditions. Thus, while tensioning on a slope may contribute to panel separation, the authors do not consider it to be the primary mechanism that causes shrinkage and loss of overlap.

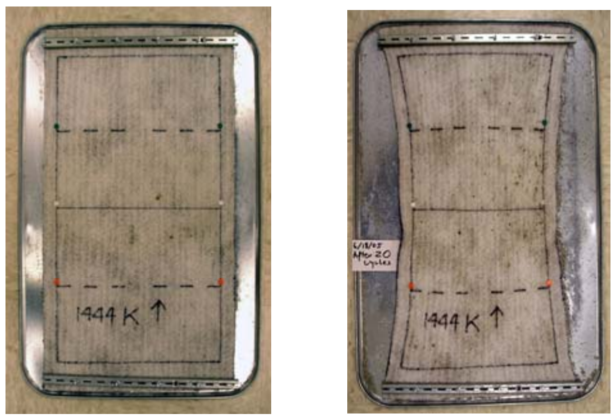

Figure 2. GCL sample (left) before testing and (right) after 20 wetting-drying test cycles.

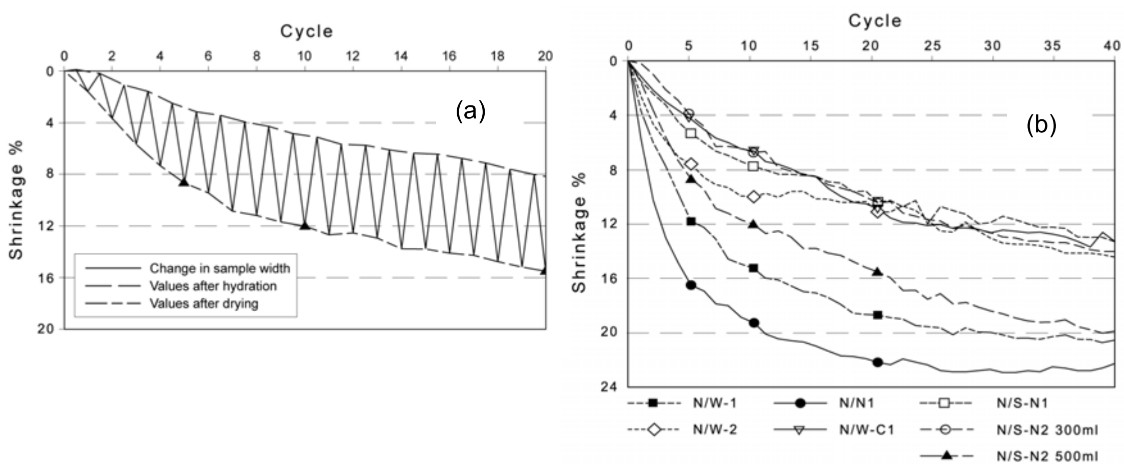

Figure 3. (a) Example of laboratory pan test results for change in sample width (expressed as percent of shrinkage) vs. cycle number. (b) Shrinkage vs. cycle number for different types of geotextile-encased GCL samples tested (values after drying). (from Thiel et al. 2006)

Rayhani et al. (2009) conducted large-scale experiments designed to investigate the effect of simulated daily thermal cycles on transient suctions for GCLs in an attempt to identify the relationship between initial hydration and subsequent shrinkage for GCLs placed on a soil substrate. Cyclic heating and cooling was found to cause up to about 4.5% of shrinkage in the GCL sample, which was much less than that reported for pan tests by Thiel at al. (2006) and Botswick et al. (2007). This difference is presumed to be primarily due to the lesser hydration of the GCL that could be achieved during cooling cycles when the only source of water for the GCL was that which could be taken up from the air and subsoil as it cooled, as compared to the substantial water added in each cooling cycle in the pan tests.

Bostwick et al. (2010) used an image analysis technique to measure strain distribution patterns in pan tests with cyclic wetting and drying of two types of reinforced GCL samples. Both restrained and unrestrained specimens of the same size were tested, as well as restrained specimens with different specimen sizes and aspect ratios. For unrestrained specimens, there was no apparent significant difference in shrinkage in the transverse and longitudinal directions. While there was no clear size effect, the degree of shrinkage appeared to increase with increasing aspect ratio, up to an aspect ratio of approximately 5. One important observation in this study was that specimens with an uneven bentonite distribution experienced much higher shrinkage than other specimens. Also, the areas of high shrinkage were visible early in the shrinkage process and intensified as the number of cycles increased. Low-bentonite areas were typically concentrated in zones parallel to the length of the roll. It was noted that if there is a wide distribution of low-bentonite areas, pinching of the geotextile can occur. These effects of low bentonite content were observed in both restrained and unrestrained specimens. This study thus appears to indicate that when specimens are subjected to wetting and drying cycles, the uniformity of the distribution of bentonite in the GCL in the field has an important impact on GCL shrinkage. The study also concluded that there is a high degree of variability in results for specimens in apparently similar test conditions in the same laboratory conducted by the same operator, which suggests that it may be difficult to develop a standard test method to evaluate a product's susceptibility to shrinkage. The Bostwick team also noted that different GCL products may have substantially different water retention curves and may therefore experience different water uptake histories on different subgrades in the field, which may in turn affect their field shrinkage performance. In this same vein, it has been reported to the authors that GCLs with sodium-activated bentonite exhibit higher shrinkage than those with natural Wyoming bentonite.

Figure 4. Example of laboratory tension-necking test. (courtesy of Koerner and Koerner, 2005a)

Rowe et al. (2009, 2010) conducted pan tests with cyclic wetting and drying on GCL samples with heat-tacked seams. Their results indicated that the heat-tacked seam that was tested had a strength comparable to that of the GCL adjacent to the seam, hence it is likely that the strength of the GCL itself would govern the failure of that particular GCL in applications where significant shrinkage may occur. The strength of a heat-tacked seam subjected to 40 wet-dry cycles was at least as high as that of virgin heat-tacked samples, suggesting that 40 wet-dry cycles did not weaken the heat-tacked seam. After 40 cycles, the samples remained heat-tacked, which suggests that the heat-tack technique (discussed in more detail in the next section) holds promise as a method of preventing panel separation of GCLs.

3. FIELD STUDIES

CETCO (2006) constructed test plots in Wyoming in July 2004. Full-width GCL panels were laid on 3H:1V slopes, and moisture sensors and movement telltales were installed in the GCL. The soil subgrade was a silty clay with a little fine sand and had a natural moisture content of approximately 5%. The GCL was then sprayed with water to increase its moisture content (Figure 5) and covered with a smooth geomembrane. Monitoring equipment was attached to stations. Measurements of the geomembrane surface temperature in the summer indicated temperatures that reached over 60°C

(140°F). The field instrumentation indicated that over the test period of 10 months, the GCL only went through a half cycle of moisture variation (from a high of over 40% to a low of 11%) and experienced a shrinkage of only 25-37 mm (0.6-0.9% strain), which is significantly less than the shrinkage observed in some of the case histories.

Figure 5.CETCO field study. (courtesy of CETCO, 2006)

Gassner (2009) reported on a field study conducted in Melbourne, Australia in which a W/NW needle-punched thermally-treated GCL was left on a 55m long 3H:1V soil slope for a period of 18 months, while covered with a black singled-sided textured geomembrane (textured side down) and an off-white geotextile. The GCL panels had a longitudinal seam with a 300 mm overlap, which was monitored at a position one-third of the distance down the slope by making a one-meter-long incision in both the geotextile and geomembrane at the end of the 18 months. The ambient air temperatures fluctuated between approximately 5 and 30°C during this exposure period. It was observed that the GCL overlap experienced between 50-80 mm of shrinkage during 18 months of exposure under the geomembrane and geotextile. Based on this result, Gassner concluded that an overlap of 300 mm was a sufficient and appropriate specification for this particular project.

Test plots were constructed at a confidential site in concert with the designer and owner of one of the sites on which severe GCL panel separation had been noted on relatively flat areas. Four different GCL test plots were constructed on a 40 m long 3H:1V slope. The GCLs were covered with a black textured geomembrane and their overlaps were periodically exhumed from below the geomembrane over a period of 7 months. While no GCL panel shrinkage was observed, high degrees of saturation, flowing water, and internal bentonite erosion due to the flowing water were observed. It appears that, as in the CETCO (2006) field study, the subgrade conditions were such that no cyclic wetting and drying occurred.

Thiel and Thiel (2009) reported a case history in which two types of reinforced GCL products (N/N and W/N) were installed with 150 mm seam overlaps and covered with a black textured geomembrane. The installer heat-tacked every GCL seam with the quick application of a flame torch that was immediately followed by the application of light but firm pressure. The heat tacking was continuous along all overlaps. Figure 6 shows the technician heat-tacking the seam with a torch, followed by the application of light pressure either in the form of a sand bag dragged along the seam, or the steady, intentional use of foot pressure. The technician could thus effectively seal the seam in a manner that added negligible material and labor cost. GCL seam exhumations were performed at mid-slope in six separate areas of the project between the months of February and June after 60 to 90 days of exposure. The air temperature during this period fluctuated from below 0°C to above 32°C. In every instance there was no evidence of any GCL shrinkage and the heat-tacked GCL seam remained intact. Samples of the heat-tacked seams were sent to Queen's University in Canada for laboratory testing, as described by Rowe et al. (2009, 2010), which confirmed the integrity of the heat-tacked seams.

Figure 6. Installer heat-tacking GCL edge seam with a 150 mm overlap.

4. DISCUSSION OF POSSIBLE MITIGATION MEASURES AGAINST GCL PANEL SEPARATION

GCL panel shrinkage and separation is an undeniable potential problem, as evidenced by both field case histories and laboratory testing. The current state of affairs is that we do not fully understand the mechanism of GCL panel shrinkage and separation. This is probably because panel shrinkage depends on the complex interaction of a number of factors, including the choice of GCL, the underlying soil and availability of moisture for hydrating the GCL, climatic conditions, and the interval before the cover soil is placed over the composite liner, an interval that invites possible shrinkage. Table 2 lists the conditions that we know, or suspect, either promote or inhibit GCL panel shrinkage and separation. These conditions and their surmised effects are then used to suggest general manufacturing, design, and construction strategies to control GCL panel separation at an acceptable level.

As noted in Table 2, a common strategy to counteract many of the conditions that promote GCL panel separation is to simply increase the overlap. The obvious question then, is how large an overlap is required for a given condition. This question is addressed in the next sections of this paper.

5. STATE OF THE PRACTICE

There is some difference in the GCL seaming practices that are recommended on the websites of the two primary GCL manufacturers in North America. One manufacturer recommends a 150 mm overlap, but provides qualifying language stating that cyclic wetting and drying, or tension, can cause seam separation. They also recommend the prompt placement of soil cover and covering the geomembrane with a white geotextile. In addition, they caution that if cyclic wetting and drying might occur in an unconfined condition, then the seam overlaps should be increased. The other manufacturer states that a 150 mm overlap is acceptable if the GCL product includes a scrim fabric in its construction; otherwise an overlap of 300 mm should be used.

The Geosynthetics Institute (2009) in the USA provides GCL Specification GCL-3; which addresses material procurement and is not necessarily applicable to installation. It alludes to the issue of panel separation in two passages. One is a note related to overlap-line markings, which states that “The overlap lines are minimally 150 mm (6.0 in.) from the edges of the GCL. Other design-related situations may require greater overlap distances to be printed on the GCLs, e.g., when not backfilled in a timely manner.” The other allusion to the shrinkage issue is in a footnote to the materials property table at the end of the specification, which states that “For both cap and carrier fabrics for nonwoven reinforced GCLs, one, or the other, must contain a scrim component of mass ≥ 100 g/m^2 for dimensional stability.”

The author's experience in reviewing designs and performing construction quality assurance on projects designed by others in North America indicates that the state of industry practice varies widely. At one extreme are those who either are not aware of the issue or choose to ignore it, believing that the traditional 150 mm overlap is adequate. At the other extreme are owners who, out of their great concern about compliance, require that there be a 450 mm overlap, that all exposed geomembranes have a white surface, and that the GCL be encapsulated between two geomembranes. A common compromise adopted by some is the requirement of a 300 mm GCL seam overlap, and that the geomembrane have a light-colored surface or an overlying geotextile, as in the case history presented by Gassner (2009). The requirement of a scrim geotextile as part of the GCL manufacturing has been less common, though it has been adopted by some designers.

Table 2. Summary of conditions that may promote or inhibit GCL panel separation, and strategies to control it.

	Possible strategies to control GCL panel separation
Conditions that may promote GCL panel separation	
Pulling on the ends of a GCL panel may cause tension-necking.	• Place cover soil as soon as possible. • Increase seam overlap.
Wet/dry cycling of GCLs may result in varying degrees of GCL panel shrinkage.	• Reduce maximum temperature extremes of geomembrane by providing a light-colored surface. • Place cover soil as soon as possible. • Encapsulate GCL between geomembranes to cut off moisture supply. • Increase seam overlap.
Non-uniform bentonite distribution exacerbates shrinkage potential.	• Improve manufacturing control to provide uniform bentonite distribution. • Increase seam overlap.
Different GCLs (e.g. having different bentonite minerology, granularity, additives, presence/absence of scrim reinforcement, etc.) may have different water-retention curves and different propensity for moisture uptake and shrinkage upon drying.	• Provide user awareness of shrinkage issue when selecting a GCL. • Place cover soil as soon as possible. • Increase seam overlap.
Higher initial water content will increase the degree of shrinkage on first drying cycle.	• Decrease initial water content during manufacturing.
Conditions that may restrict or inhibit GCL panel separation	
Greater amounts of needle-punching may reduce the propensity for shrinkage.	• Specify higher peel strength.
Incorporating a scrim or woven fabric with the nonwoven carrier geotextile, combined with thermal treatment, seems to reduce the shrinkage potential.	• Include a scrim or woven fabric in the GCL product in combination with thermal treatment.
GCLs seams that are heat-tacked together resist necking and shrinkage forces, even to the limits of the GCL strength.	• Specify that all GCL seams be heat-tacked together for those products where this treatment is possible.

Based on the experience of Thiel and Thiel (2009), as substantiated by the testing of Rowe et al. (2009, 2010), the primary author's practice has increasingly been to simply require that all GCL seams be heat-tacked together, when such products have geotextiles that allow this treatment. The use of this technique allows minimum overlap distances (150 mm on the sides, 300 mm on roll ends) and extended exposure time before the soil cover is placed. There are virtually no cost implications for such heat tacking, and the cost savings compared to greater overlap distances can be significant. The specific language used in his specifications is: "All overlapped seams are to be heat-tacked using a quick pass of a flame torch followed by quick application of appropriate pressure as provided by a roller, foot pressure, or other means." If the heat-tack seam is cyclically durable and as strong as the parent material, as was the case for the heat-tacked seam tested by the Rowe et al. (2009, 2010), then the only remaining question is whether there is a maximum stress-strain potential that could be caused by shrinkage in the field that would exceed the rupture strength of the material. This is a specific and practical question that can be answered by further laboratory and field studies.

Based on the available evidence gathered by the second author, an alternative may be the use of a GCL with a scrim reinforced carrier with thermal treatment. The authors are not aware of any case histories in which this type of product experienced significant panel shrinkage or separation. Unpublished research from a field test site in Godfrey Ontario (Brachman et al. 2007) indicates that this type of product has experienced negligible shrinkage under a geomembrane that was exposed for four years, while other products placed right next to it experienced significant shrinkage. Even so, while laboratory pan testing indicates that this type of product has the lowest propensity for shrinkage of any available product, it also indicates that there could be a maximum potential shrinkage of up to 12% strain. Thus the difference in the field performance of this type of GCL as compared to others may be related to its different water retention curve, and hence its moisture uptake and loss characteristics, compared to those of other commonly used GCLs (Beddoe et al., 2010).

Regardless of the approach used to mitigate GCL panel separation, it is widely agreed that the cover soil should be placed over the exposed geomembrane as quickly as is practicable. Although the emphasis of this paper is on reinforced fabric-supported GCLs, the same issues apply to unreinforced GCLs to an even greater degree. In general, the practice for the control of panel separation of unreinforced products is greater overlap and quick application of the soil cover (which means on the scale of hours, since even overnight exposure without cover has been observed to result in the substantial shrinkage of unreinforced products).

6. RECOMMENDATIONS FOR FUTURE STUDIES

In all cases, the sooner the liner is covered with soil, the smaller the risk of GCL panel separation. All the possible mitigation measures against GCL panel separation, however, are qualitative, and still involve a certain degree of educated guessing as to their effectiveness. Questions such as "How much overlap for a given soil subgrade, materials, exposure time, and climate will be adequate?", or "Is it possible that the rupture strength of a heat-tacked GCL could be exceeded due to shrinkage tensile forces?" have yet to be definitively answered. There thus remains considerable scope for additional studies.

Such additional research could profitably include the following:

- Establish a benchmark test, such as a pan test with uniform procedures, that can be used as an index to evaluate the propensity of various products to shrink in response to cyclic wetting and drying.
- Design a field study that can predictably replicate the field case-history problems that have been observed. If these can be faithfully replicated, then reliable solutions can be vetted.
- Perform laboratory testing to determine the minimum amount of cover soil needed to definitively inhibit GCL panel shrinkage.
- For those products that can be heat tacked, develop a test method to verify the minimum heat-tack requirements needed to develop either (a) the seam strength needed to resist the maximum shrinkage tension that might be generated in the field, and/or (b) the rupture strength of the parent material.
- For those products that can be heat tacked, perform laboratory and/or field testing to determine if the maximum combination of stress and strain that might be caused by shrinkage due to cyclic wetting and drying would exceed the rupture strength at the weakest point of full-scale field panels.
- The ideal goal would be to develop a set of index tests that would enable a designer to answer the following question: "How much overlap should be specified for a given maximum duration of exposure of an uncovered geomembrane, for a given site location and geometry, and for a given

set of products, so that the overlap at the time of soil covering is still at least 150 mm (or some other prescribed distance)?”

In an attempt to address these questions, research currently in progress by the second author and his colleagues includes the following topics (some of which will soon be published):

(a) examination of the water retention curve and the related moisture uptake/loss characteristics of different GCL products;
(b) extensive pan testing on a range of GCLs, examining factors such as type of GCL, type of bentonite, mass per unit area of bentonite, distribution of bentonite, GCL sample size and aspect ratio, amount of moisture added, time allowed for hydration and drying, temperature of drying etc.;
(c) studies of changes in the structure of bentonite within a GCL during cyclic wetting and drying in pan tests;
(d) laboratory and field examination of moisture uptake and loss of different GCLs on a soil foundation when subjected to different temperature cycles;
(e) laboratory studies of shrinkage when GCLs are placed on a subsoil, to assess shrinkage response when the only source of moisture is the soil below the GCL, and the GCL is subjected to simulations of both daily and seasonal thermal cycles; and
(f) a field test at a site near Kingston (ON, Canada) where four different commonly used GCLs were placed as part of an exposed composite liner (Brachman et al. 2007) on both a 3:1 (18.4^{o}) slope and a relatively flat base (3^{o} slope) on the same subsoil, to assess shrinkage over a period of four years.

7. SUMMARY AND CONCLUSIONS

There is no doubt that GCL panel shrinkage and separation poses a real potential problem, as evidenced by both field case histories and laboratory testing. The current state of affairs is that we do not fully understand the mechanism of GCL panel shrinkage and separation, which is likely the result of a complex combination of interactions between the GCL, adjacent materials (especially the foundation layer), climatic conditions, time of exposure, etc.

Several known conditions appear to exacerbate GCL panel separation, and there are several manufacturing and construction techniques that can be used to mitigate the problem. The best mitigative measure is to place the cover soil over the composite liner as soon as possible after placement of the composite liner. In many practical circumstances, however, this is not practical, and the composite liner may be left exposed to many daily, and in some cases, many seasonal cycles. Field evidence indicates that panel separation can occur in as little as two months under some circumstances, or after years of exposure in less extreme circumstances. Under other conditions, no panel separation (indeed negligible shrinkage) may be expected even after years of exposure. Other than the immediate covering of the liner with cover soil, all the potential mitigation measures against GCL panel separation are qualitative, and therefore involve a certain degree of educated guessing as to their effectiveness.

Additional research is needed in order for us to definitively understand how much overlap is adequate for a given soil subgrade, materials, exposure time, and climate.

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