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Field measurements of overlap reductions for two reinforced fabric-encased GCLs

R. Kerry Rowe¹, Richard W.I. Brachman² and W. Andy Take³

Abstract:

Two GCLs reported to have experienced significant shrinkage at other locations are examined on both a 3H:1V south facing slope and a relatively flat base on a silty-sand. The GCLs were overlapped by 300 mm with 400 g/m of supplemental bentonite and covered by a black 1.5 mm HDPE geomembrane to form a composite liner which was left exposed in a full-scale field test embankment for a period of almost five years. It is shown that despite the relatively uniform exposure conditions, shrinkage is highly variable with a maximum shrinkage of GCL A being 165 mm on the slope and 415 mm on the base while GCL B shrunk by up to 75 mm on the side slope and only up to 25 mm on the base. The dominant role played by variable overlap stick and heterogeneity to the locations where the overlaps are re-wetted are discussed. Based on this study of shrinkage and a related study of down-slope erosion at the same site, it is concluded that neither GCLs A and B should not be left in exposed composite liners when they can be subjected to thermal cycles that can lead to hydration and dehydration of the GCL.

Keywords: geosynthetics, composite liner; geosynthetic clay liner; overlap; shrinkage

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Introduction

Composite liners comprised of a geomembrane over a geosynthetic clay liner (GCL) are extensively used in landfills and increasingly in mining applications (Shackelford et al. 2000; Bouazza 2002; Rowe et al. 2004; Rowe 2005, 2012, 2014; Hornsey et al. 2010; Gates and Bouazza 2010; Scalia and Benson 2011; Bouazza and Gates 2014). Installation guidelines commonly recommend a minimum of 150 mm overlap of adjacent the GCLs panels (e.g., ASTM 2015) while some manufacturers recommend a minimum overlap of 300 mm (e.g., BIG 2015). Guidelines also often recommend that, whether the GCL is used alone or as part of a composite liner, the liner be covered with at least 0.3 m ballast soil (e.g., a drainage layer) in a timely manner. It has been demonstrated in a number of instances that when this recommendation is followed, and the liner is covered by ballast soil in a timely manner, there is no problem with panel shrinkage (e.g., Benson et al. (2010), Rowe et al. (2016), Scalia et al. (2017)) or downslope erosion (Rowe et al. 2016a,b) for the GCLs examined in this paper as well as a number of other GCLs. This paper addresses one of the potential consequences of not covering a composite liner in a timely manner.

Thiel and Richardson (2005) were the first to publically report cases of GCL shrinkage to the extent of a complete loss of the initial 150 mm overlap between adjacent GCL panels to the point where there was a 50-75 mm gap for 15-20 panel overlaps for a case where the composite liner had been left exposed for about 4 months. This was quickly followed by additional reported cases (Koerner and Koerner 2005a,b) and Thiel et al. (2006). Most of the reported cases were for two particular needle-punched GCLs denoted herein as GCLs A and B. Both had coarse granular bentonite and a nonwoven cover geotextile. GCL A had a nonwoven
carrier geotextile and GCL B a woven carrier geotextile. They were not thermally treated. The worst reported case of a 1200 opening between panels after 36 months was for GCL A on relatively steep (34°) slope (Table 1). On 3H:1V (18.4°) slopes, GCLs A and B experienced loss of 150 mm overlap and the formation of a gap between panels of 300 mm (after 5 months) and 200 mm (after 15 months), respectively. However, shrinkage was not restricted to slopes and in only 2 months GCLs A and B experienced loss of 150 mm overlap and the formation of a gap between panels of 450 and 300 mm, respectively, on a relatively flat (4°) base. These cases (Table 1) represented transverse shrinkage strains of between about 5-28%.

According to Thiel and Rowe (2010), in July 2004 the manufacturer of GCLs A and B constructed a test plot with full-width GCL panels on a silty clay subgrade (water content of approximately 5%) on 3H:1V (18°) slope in Wyoming, USA. To increase the GCL moisture content, the GCL was sprayed with water and covered by a smooth geomembrane. The geomembrane surface temperature was reported to have reached over 60°C. However, the GCL only experienced half a cycle of moisture variation from an as placed gravimetric water content of about 40% to a low of 11% and as a consequence experienced only minor shrinkage of 25 – 37 mm (0.6-0.9% strain). This case, contrasted with those reported by Thiel et al. (2006) suggest locations sensitivity with respect to the potential for panel shrinkage.

Gassner (2009) reported on a field study wherein a different needle-punched GCL with powdered bentonite encapsulated between a nonwoven cover and woven carrier geotextile and thermally treated was placed on a 55 m long 3H:1V (18°) soil slope and covered by a black singled-sided textured geomembrane (textured side down) and an off-white geotextile for a period of 18 months in Melbourne, Australia. During this period, the ambient air temperature

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ranged from about 5 and 30°C. The adjacent GCL panels, which were overlapped by 300 mm as recommended by the GCL’s manufacturer, only experienced a modest between 50 and 80 mm of shrinkage at mid slope after 18 months exposure and hence maintained most of the 300 mm overlap.

The field results discussed above suggest that the shrinkage of a GCL may depend on the local site conditions, product, and climate. Also, there has been speculation regarding the effect of slope and the effect of texturing of the geomembrane on shrinkage (Koerner and Koerner 2005a). However, in all cases, these reports only provide: (i) a one time of observation (mostly at very different times), (ii) data on different GCLs at different locations, (iii) no insight regarding the development of shrinkage over time, (iv) no data on the effect of slope under similar conditions, or (v) no insight regarding the effect for texturing of the geomembrane under similar conditions. Thus, the objective of this paper is to provide the first detailed documentation of the relative performance of GCLs A and B over time on both a 3H:1V (18.4°) and 3% (1.7°) base slope at one full scale field test embankment located just north of Kingston, Ontario, Canada over a monitored period of almost five years.

**Queen’s University Environmental Liner Test Site (QUELTS)**

The construction and purpose of Queen’s University environmental liner test site (located 40 km north-northwest of Kingston, Ontario at a latitude of 44°34’14”N and longitude of 76°39’44”W and referred to herein as QUELTS) has been described by Brachman et al. (2007) and only the essential details are repeated here. A 46-m-wide and 80-m-long earth

4 There are brief allusions to the current case in Thiel and Rowe (2010) and Brachman et al. (2014) but not the details presented here.
The embankment was built with the long axis of the embankment oriented in the east-west direction. The north and south slopes of the embankment were constructed at 3H:1V (18.4°) with a 5-m-wide flat crest between the two. Wrinkling of the geomembrane on the south slope and the performance of the GCLs covered by about 0.7m of local soil on the north slope have been reported by Rowe et al. (2012) and (2017), respectively. This paper is focused on shrinkage of two GCL products in the composite liner on the 3H:1V south-facing slope together with a 20-m wide and 80-m long (3% slope) base portion (Figure 1). The embankment fill and the base were native silty-sand (SM) with an average nonplastic fines content of 40% (i.e., % by mass passing the 0.075 mm sieve with dry sieving) with a range between 32 and 46% (Brachman et al. 2007), and a standard Proctor (ASTM D 698) optimum moisture content of 11.4% (Rayhani et al. 2011). The initial subgrade water content ranged between 12 to 21% and the dry densities between 1500 to 1700 kg/m³. The embankment fill was compacted to the same initial dry density as the native soil at the in-situ water content.

Immediately before placement of each GCL panel, the water content of the top surface of the foundation layer was recorded to a maximum depth of 50 mm and the average initial gravimetric water content of 215 grab samples was 14% (standard deviation of 4.4%), with the spot values varying between 6 and 20%. The GCL panels were covered by a black 1.5 mm-thick HDPE geomembrane within 4 hours of the GCL being placed.

**GCLs examined herein and monitoring details**

Based on 0.3 m square samples cut just after installation either at the toe of the southern slope or the southern end of the base, the two needle-punched GCLs examined in this paper (Table 2)
had an average mass of coarse granular bentonite of about 4000 g/m$^2$ (GCL A) and 4400 g/m$^2$ (GCL B) and average off-the-roll gravimetric water contents of 24% (GCL A) and 26% (GCL B) although considerable variability was noted (Table 2).

The GCL panels had a melted groove in the geotextile about 75 mm from the edge (Figure 2). This is intended to provide the bentonite for the “seal” between the overlapped panels. At the time the section was constructed in September 2006 the GCL was typically used with a seal from the small amount of bentonite at the melted groove and with a 150 mm overlap. Thus, a movement of 50-75 mm of the overlap could be sufficient to disengage the supplemental bentonite in the groove. This level of shrinkage could substantially reduce the effectiveness of the seal even if no gap formed, especially when the overlap coincided with a wrinkle (Joshi et al. 2017). For example, Brachman et al. (2016) showed that a 50 mm overlap with no engaged supplemental bentonite had a leakage a million-fold higher than that for a 150 mm overlap with engaged supplemental bentonite. Based on the magnitude of reported shrinkage (Table 1), it was decided that at QUELTS a more conservative approach would be adopted wherein all overlaps between adjacent panels were 300 mm (i.e., twice that usually used with these GCLs) and no reliance was placed on the melted groove but rather an additional 400 g/m of supplemental bentonite was placed at each overlap (Figure 2). The seams between the panel in the length-wise direction between the south slope and base panels were overlapped by at least 1 m.

The GCL panels were placed in groups of three, giving two overlaps to be monitored between three similar GCL panel arrangements. In total, three pairs of panel arrangements were examined. For GCL A, three panels were placed on the slope with an overlying textured
geomembrane [Section 1s] and the base with an overlying smooth geomembrane [Section 1b].

For GCL B, three panels were placed similarly on the slope with an overlying textured geomembrane [Section 2s] and the base with an overlying smooth geomembrane [Section 2b].

In addition, for GCL B, the effect of textured versus smooth geomembrane on the slope was examined with three panels being placed on both the slope [Section 3s] and the base [Section 3b] with an overlying smooth geomembrane.

Near the edge of each panel, small machine screws (with a nut and washers; Fig. 3) were placed as markers at a spacing of 2 m along the two edges of each panel from the anchor trench at the top of the slope top to the anchor trench at the south of the base. The initial distance between these markers on each adjacent pan was recorded ($S_0$ in Figure 2a).

Subsequently, with time, the distance $S$ between the markers was measured and the difference between the distance $S$ at some time $t$ and the initial value $S_0$ was the change in overlap that had occurred up to time $t$ (Figure 2b).

The first stage of monitoring involved periodic opening of the geomembrane by cutting a small window (inspection port) in the geomembrane (Fig. 3), taking measurements (Fig. 3), and then resealing. To minimise damaging the companion study of geomembrane wrinkling (Rowe et al. 2012), only a limited number of locations were inspected each time for the first 3 years. After completion of the wrinkle study, in the second stage of monitoring (starting at 3.6 years; spring 2010) and extending to termination of the QUELTS 1 field study at 4.8 years (summer 2011), the entire geomembrane was opened periodically to allow a full inspection of the overlaps and detailed inspection and monitoring (Fig. 4). It was at the first such opening (spring 2010) that the new mechanism of down-slope erosions was discovered (Take et al. 2015b).
Results of field monitoring of GCL A on the slope

The field monitoring data for GCL A on the 18.4° side slope for the two monitored overlaps (Fig. 5) show considerable variability with position along the length of an overlap. After 1 year (Sept. 2007) there was generally relatively small shrinkage on the slope (Fig. 5a) with the maximum shrinkage of 70 mm (Fig. 3a and 5a) at about mid slope (12 m from top; Fig. 5a). With a 300 mm overlap and added supplemental bentonite, 70 mm shrinkage would not be regarded as problematic. However, if the GCL A had in fact been placed, as this GCL was/is commonly placed in the field with only 150 mm overlap and relying on the melted groove for the supplemental bentonite, this represents about the limit of shrinkage before potential unacceptable performance could be expected. This is because the supplemental bentonite from the melted groove was only about 75 mm from the edge of the panel (Fig. 6a) and with 75 mm of movement of a 150 mm overlap (Fig. 6b) it would become disengaged (and possible at 70 mm since there is often very little bentonite in the last 5 mm from the edge of the roll). This suggest that at the QUELTS site in south-eastern Ontario, Canada, one winter, spring and summer of exposure would be enough for the shrinkage of GCL A to be problematic if only a 150 mm overlap had been used and there was reliance on the melted groove for supplemental bentonite. At QUELTS, with 300 mm of overlap and added supplemental bentonite, it was still in an acceptable condition.

With an additional 0.6 of a year (i.e., after a total of 20 months exposure of the composite liner; May 2008; Fig. 5a), the shrinkage of GCL A had increased to between 60 mm (at 16 m and approaching the toe of the slope with a line of sandbags) and 150 mm at midslope (at 12 m; Figs. 3b and 5a). At this time shrinkage of GCL A certainly would be problematic if only a 150
mm overlap had been used with reliance on the melted groove for supplemental bentonite. Again, with 300 mm of overlap and added supplemental bentonite, it was still in an acceptable condition. The shrinkage at the panel S11 to panel S12 overlap after increasing to about 150 mm after 20 months remained at just slightly more than that for the rest of the 4.8 years of monitoring (Figs. 5a and 7).

With further time of exposure, the shrinkage of the GCL A overlaps increased slightly along the slope but never exceeded about 165 mm even after 4.8 years of composite liner exposure at either overlap (Fig. 5). However, there was considerable variability in shrinkage with both location and time (Fig. 5) that begs explanation.

It is known that during the almost 5 years of monitoring, the geomembrane and the underlying GCLs were subjected to many thermal cycles (Take et al. 2015a). These thermal cycles resulted in evaporation of moisture which migrated as water vapour to the areas with the largest air volume (i.e., wrinkles; e.g., Fig. 8). It was the condensation of this moisture on cooling of the geomembrane that resulted in the formation of rivulets on the GCL (Take et al. 2015b; Rowe et al. 2016). Thus, although the moisture content of the subgrade and the GCL on first hydration may have been relatively uniform, with time the level of hydration varied significantly with location even over a relatively small area (i.e., with is a distance of 0.3 m there could be both very well hydrated and poorly hydrated bentonite). In particular, there was a migration of moisture from the slope to the base with time. Early in the morning there were some small pools of water in local low spots between the GCL and geomembrane on the base near the toe of the slope and occasionally elsewhere on the base. These disappeared due to
evaporation once the geomembrane heated in the sun but would often reappear at the same locations the next morning.

A significant factor in the variability of the shrinkage and in the relatively low level of shrinkage observed over the 4.8 years for GCL A compared to that reported in Table 1, and in particular the behaviour evident in Fig. 7, was the 300 mm overlap and use of 400 g/m of additional supplemental bentonite not called for in the manufacturer’s installation guidelines. When the bentonite in the overlap hydrated, it formed a gel and then on drying it was observed that the bentonite effectively glued the panels together.

Brachman et al. (2010) showed that supplemental bentonite in the overlaps can interact with the fibres of the upper and lower geotextiles of the GCLs at the overlap and provide in-plane shearing resistance (i.e., adhesion; referred to a “overlap stick” in this paper), if the supplemental bentonite was allowed to hydrate and then subsequently dry (e.g., Fig 3b) and remain dry. For example, a mean resistance (overlap stick) of 1.8 kN/m (standard deviation of 0.2 kN/m) developed for GCL A. However, this resistance could be lost when the GCL was rehydrated. Thus, the variability in the shrinkage and the limits on shrinkage (e.g., Figs. 5 and 7), can be explained by local hydration eliminating resistance from this overlap stick (especially beneath wrinkles; Fig. 8).

The overlap stick observed for GCL A on the slope would not be expected from the bentonite extruded from the melted groove in GCL A and if the overlap had relied on that groove and had only been 150 mm, it would have experienced at least 70 mm of shrinkage and hence have been compromised after 20 months along essentially the entire 20 m of the eastern overlap S11/12 (Fig. 5a) and about 14 m of the western overlap S10/S11 (Fig. 5b).
Results of field monitoring of GCL A on the base

On the gently sloping (3%; 1.7°) base, GCL A experienced substantially more shrinkage (Fig. 9) than on the 18° slope (Fig. 5) with the maximum shrinkage of 415 mm resulting in a complete loss of overlap despite the 300 mm of initial overlap and the formation of a gap up to 115 mm at 4.8 years (Figs. 4, 9 and 10). In fact, for the central panel (of three similar GCL A panels in Section 1b) on the base, a gap appeared over a distance of 5 m on the east overlap (B11/B12; Fig. 4) and 1.3 m on the west overlap (B10/B11; Fig. 4). Had the overlap only been 150 mm it would almost certainly have been lost over a distance of more than 7 m at the eastern overlap and 9 m at the western overlap and if reliance was placed only on the melted groove, the overlap would have been compromised over a distance of more than 8 m at the eastern overlap and 10 m at the western overlap.

Results of field monitoring of GCL B on the base

The shrinkage of GCL B was substantially less than that of GCL A at QUELTS where there was 300 mm overlap with 400 g/m of supplemental bentonite (Fig. 9) with the maximum shrinkage after 4.8 years of only 25 mm. It appears that there was more overlap stick in this case. There was no statistically significant difference in the measured 1.6 kN/m (Std dev. 0.4 kN/m) overlap stick developed for GCL B (Brachman et al. 2010) compared to GCL A. Despite having a woven geotextile, the appearance of the upper slit-film woven geotextile in GCL B was more like a nonwoven surface because the needle-punched fibres from the lower nonwoven geotextile protruded above the upper woven. Hence GCL B developed resistance similar to the 1.8 kN/m (Std dev. 0.2 kN/m) of GCL A. Thus, the difference must have been related to the distribution of moisture to the seams (wrinkling pattern) although nothing was obvious. On conclusion of the
experiment, physical inspection of the overlaps showed significant stick along essentially the entire GCL B overlaps (unlike those of GCL A).

**Results of field monitoring of GCL B on the slope**

Contrary to the findings for GCL A, where there was more shrinkage on the base than the side slope, the opposite was true for GCL B where there was somewhat more shrinkage on the side slope (Fig. 11) than the base (Fig. 9) although the maximum value of 75 mm was still well below that observed for GCL A. There was generally more shrinkage below the textured geomembrane (Fig 11a) than the smooth geomembrane on the slope (Fig. 11b). The possibility of some effect of the interface roughness of the geomembrane/GCL interface cannot be excluded, however given the significant role placed of overlap stick and moisture distribution related to wrinkling pattern, it is hard to attribute any difference in shrinkage to the interface roughness.

**Discussion**

The two GCLs examined had each been reported to have experienced 600 mm (GCL A) and 450 mm (GCL B) of shrinkage in as little as 2 months on a flat slope (Thiel et al. 2006) at different locations. The exposure of the same two GCLs at the same location in south-eastern Ontario reported herein differed from previous reported cases in terms of the climatic conditions and, likely, the foundation conditions but also in that, contrary to typical practice for these GCLs, in this case they were overlapped by 300 mm (instead of the usual 150 mm) and 400 g/m of supplemental bentonite was placed at each overlap (compared to the usual minor amount extruded from a melted groove).
It is known that the uptake of moisture by a GCL is dependent on the initial water content of the subgrade (Rayhani et al. 2011; Benson 2013; Siemens et al. 2013), the subgrade particle size distribution and mineralogy which both affect the subgrade water retention characteristics (Anderson et al. 2012; Sarabian and Rayhani 2013; Bouazza et al. 2016), the hydraulic conductivity of the subgrade (Chevrier et al. 2012), the water retention characteristics of the GCL (Beddoe et al. 2011), and the nature of thermal cycles (Rowe et al. 2011b). At this site the soil had a relatively uniform mineralogy, particle size, and initial water content although there was some variability from location to location (with the western half of the site being a little siltier with higher initial water contents than the eastern half of the site which was generally sandier with lower initial water contents; Rowe et al. 2016) however since GCL B was placed at both the eastern and western ends of the site and GCL A was located toward the centre of the site, this variability does not appear to offer an explanation for the observed behaviour.

It is known from other field sites (Table 1) and from laboratory tests on the samples of GCLs A and B used in the field that both had considerable potential to shrink (Bostwick et al. 2010; Rowe et al. 2011a). This shrinkage was very sensitive to the water content at the time that a thermal cycle causes loss of moisture (Rowe et al. 2013) and the rate of drying (Brachman et al. 2014). Thus, shrinkage is complex even if the GCLs had been installed with only 150 mm of overlap and no supplemental bentonite as was, and is, common. However, in this case the most interesting finding was that increasing the overlap and adding 400 g/m of supplemental bentonite appears to have resulted in considerable overlap stick which reduced, and in some cases suppressed, shrinkage at some locations but not at all locations. Tests by Brachman et al. (2010) have shown that a resistance of 1.6-1.8 kN/m could be developed due to overlap stick
and that there was no statistically significant difference between GCLs A and B in this respect. In both cases (but more effectively for GCL B) the overlap stick appears to have suppressed shrinkage on the 3H:1V slope, almost from the start of testing for GCL B and after about 1.7 years for GCL A. But the difference in the performance of the two GCLs on the base was stark. In one case a maximum of 25 mm shrinkage in 4.8 years and in the other up to 415 mm of shrinkage and loss of overlap over a considerable distance. There was no evidence that GCL A was wetter than GCL B on base. There was no obvious difference in wrinkles observed over these two GCLs, and the differences in the subgrade and water retention characteristics of the two GCLs are not sufficient to explain the different performance. Thus, there is an apparent heterogeneity to how the moisture concentrates and distributes, which in the case of GCL A resulted in sufficient wetting of the supplemental bentonite that it did not provide enough overlap stick to prevent shrinkage, whereas for GCL B the seam remained dry enough after an initial hydration and drying cycle to suppress significant shrinkage. This does not mean there was no moisture on the base of GCL B; on the contrary, there was sufficient moisture to cause downslope erosion (Take et al. 2015; Rowe et al. 2016) but it was not at the overlaps.

The study of downslope erosion indicated that while the location of where moisture tends to accumulate on condensation were mostly heterogeneous (a notable exception being wrinkles in the roll direction at the quarter points on blown film geomembranes and at some weld locations; Rowe et al. 2012, 2016; Take et al. 2015) they were also repeatable (i.e., the water tended to condense in the same places in different cycles). This partly explains why in some cases the GCL overlaps were subjected to cyclic wetting and drying and in other cases not.
Thiel and Thiel (2009) sought to provide an alternative “stick” between GCL panels by heat-tacking the overlap. Rowe et al. (2010) examined the behaviour of heat-tacked GCL seams under cyclic wetting and drying. After 40 wet-dry cycles the strength of the heat tacked seam was as high as that of virgin heat-tacked samples, suggesting that the strength of the heat-tack had not weakened due to the shrinkage testing. This shows that heat tacking has some promise; however, all published tests have been on small-scale specimens under idealized conditions, whereas the field may be different due to both variability of the bond (for which there is no field control) and the larger forces that could be developed on a field scale. For example, the conditions that gave rise to the large panel separations reported by Koerner and Koerner (2005a, b) and Thiel et al. (2006) can be expected to develop much larger forces than were developed at QUELTS or in the laboratory tests reported by Rowe et al. (2010) and Allen et al. (2017). Neither Rowe et al. (2010) nor Allen et al. (2017) performed test at sufficient scale to show that heat-tacking would provided an adequate resistance to prevent panel separation under adverse field conditions. Thus, although overlap stick or heat-tacking may reduce the risk of panel separation (as it did for GCL B at QUELTS) it does not alter the need to cover composite liners in a timely manner after placement. Even if panel shrinkage could be avoided, as was for GCL B at QUELTS, there was still unacceptable downslope erosion for both GCLs A and B (Take et al. 2015; Rowe et al. 2016) due to exposure of a composite liner subjected to thermal cycles.

Conclusions

Two GCLs reported to have experienced significant shrinkage at other locations were examined on both a 3H:1V (18°) south facing slope and a relatively flat (2°) base on a silty-sand (SM) with
an average 40% nonplastic fines and initial average water content of 14% (SD 4%). The GCLs were overlapped by 300 mm with 400 g/m of supplemental bentonite was placed at each overlap. Then they were covered by a black 1.5 mm HDPE geomembrane to form a composite liner. The composite liner was left exposed and the GCLs were monitored for shrinkage. Based on almost five years of monitoring the following conclusions were reached for the GCLs used under the conditions at the QUELTS site between 2006 and 2011.

- Despite the relatively uniform exposure conditions, shrinkage was highly variable.
- GCL A shrank by up to 165 mm on the slope and 415 mm on the base. This would have been sufficient to have eliminated effective panel overlap in about 1 year with complete loss of panel overlap on the side slope in less than 1.7 years if the usual 150 mm overlap and reliance on the melted groove for overlap bentonite had been adopted for the slope. However, with supplemental and a 300 mm overlap was enough to maintain adequate overlaps for almost 5 years on the slope at QUELTS. On the base, even the supplemental bentonite and 300 mm overlap was not sufficient. There was complete loss of overlap for a distance of 5 m on one and 1.3 m on the other monitored overlap.
- In contrast to GCL A, GCL B shrunk by up to 75 mm on the side slope (probably sufficient to have lost effective panel overlap if the usual 150 mm overlap with reliance on the melted groove for overlap bentonite had been adopted for the slope) and only up to 25 mm on the base.
- The difference in the seam performance was attributed to variable overlap stick, where the supplemental bentonite was hydrated and then dried relatively quickly forming an adhesive bond between the upper and lower GCL panels with a strength of the order of
1.6-1.8 kN/m. When rewetted this bond was lost and overlap shrinkage could occur.

The distribution of moisture due to evaporation from the GCL into the airspace between the GCL and geomembrane and subsequent condensation (especially below wrinkles) redistributes water. There is some heterogeneity to the locations where the overlaps were re-wetted which had a positive benefit for GCL B and negative effect if GCL A. The difference between the performance of these two GCLs was unlikely to have been related to the particular GCL and was more likely related to the heterogeneity of the moisture distribution as discussed in the context of the study of down-slope erosion of these GCLs at this site. Although GCL B performed generally well with 300 mm overlap and 400 g/m of supplemental bentonite, this was likely due to overlap stick which should not be relied upon.

Thus, the field study reported here at QUELTS and in the companion paper on downslope erosion (Take et al. 2015b) shows that GCLs A and B should not be left exposed when they can be subjected to thermal cycles that can lead to hydration and dehydration of the GCL. Neither heat tacking nor overlap stick is a sufficient solution. There is documented evidence that covering the GCL with a ballast layer of 0.3 m or more in a timely manner (i.e., before it has had a chance to significantly hydrate) eliminated the problem of shrinkage and down-slope erosion for both GCLs examined in this paper (as well as others forming part of the borderer studies at QUELTS). Alternatively, if a composite liner must be left exposed, serious consideration should be given to the use of a white geomembrane (Rentz et al. 2016, 2017) together with a GCL that largely prevents the moisture-cycle mechanism (as will be demonstrated in a subsequent paper) causing shrinkage or downslope erosion.
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Thiel, R., Giroud, J.P., Erickson, R., Criley, K., and Bryk, J. 2006. Laboratory measurements of GCL shrinkage under cyclic changes in temperature and hydration conditions, 8th International Conference on Geosynthetics, Yokohama, Japan 1: 21-44.

Figure Captions

Fig. 1. Cross section through south facing composite liner test site. Modified from Brachman et al. (2007).

Fig. 2. (a) GCL overlapped seam showing as-built configuration for GCLs A and B at test site. (b) Illustration of reduced GCL overlap from exposure when covered only by a black geomembrane. S0 = initial indicator screw separation, S = screw separation after exposure, SSo= reduction in GCL overlap.

Fig. 3. Views through inspection windows cut in geomembrane showing indicator screw separation for GCL A overlap S11/S12 at distance 12 m from top of slope after: (a) 1.07 and (b) 1.66 years exposure. Initial indicator screw separation = 130 mm.

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**Fig. 9.** Reduction in overlap on both sides of centre panel on base after 4.8 years.

**Fig. 10.** Close-up of GCL A panel separation along overlap B11/B12 on base after 4.8 years. Maximum gap = 190 mm. View looking north.

**Fig. 11.** Overlap reductions for GCL B on side slope for Overlaps: (a) S5/S6 beneath textured geomembrane and (b) S16/S17 beneath smooth geomembrane. Nov. 2008 is first data for both plots. No significant change in overlap between dates plotted.
Table 1. Reported cases of GCL overlap loss for needle-punched GCLs (Thiel and Richardson 2005; Koerner and Koerner 2005a,b; Thiel and Rowe 2010)

<table>
<thead>
<tr>
<th>GCL</th>
<th>Cover/Carrier GTX</th>
<th>Slope (°)</th>
<th>Gap (mm)</th>
<th>Shrinkage (%)</th>
<th>Time (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>NW / NW</td>
<td>34</td>
<td>1200</td>
<td>28</td>
<td>36</td>
</tr>
<tr>
<td>A</td>
<td>NW / NW</td>
<td>18</td>
<td>300</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>A</td>
<td>NW / NW</td>
<td>4</td>
<td>450</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>NW / W</td>
<td>18</td>
<td>200</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>B</td>
<td>NW / W</td>
<td>4</td>
<td>300</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

W = woven; NW = nonwoven


**Table 2. Summary of GCLs A & B Tested at QUELTS 1**

<table>
<thead>
<tr>
<th></th>
<th>GCL A</th>
<th>GCL B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier geotextile</td>
<td>NW</td>
<td>W</td>
</tr>
<tr>
<td>Cover geotextile</td>
<td>NW</td>
<td>NW</td>
</tr>
<tr>
<td>Detail</td>
<td>NP</td>
<td>NP</td>
</tr>
<tr>
<td>Mass of bentonite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average (g/m$^2$)</td>
<td>4040</td>
<td>4390</td>
</tr>
<tr>
<td>Std dev. (g/m$^2$)</td>
<td>600</td>
<td>440</td>
</tr>
<tr>
<td>No. of 0.15-m-square samples</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Initial gravimetric water content</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average (%)</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>Std dev. (%)</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Minimum (%)</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>Maximum (%)</td>
<td>27</td>
<td>46</td>
</tr>
<tr>
<td>No. of 0.3-m-square samples</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Reference water content* (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>195</td>
<td>215</td>
</tr>
<tr>
<td>Std dev.</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

NW = nonwoven needle-punched; W = slit-film woven; NP = needle-punched

* Water content after 2 months hydration under 2 kPa confining stress with DI water. Maximum water content to which these GCLs will hydrate at the stress without a backpressure to dissolved air bubbles and hence as close to 100% saturation that the GCLs are likely to reach in a composite liner before loading.
Table 3. GCL Panel arrangement

<table>
<thead>
<tr>
<th>Section</th>
<th>GCL</th>
<th>Location</th>
<th>Geomembrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>1s</td>
<td>A</td>
<td>Slope</td>
<td>Textured</td>
</tr>
<tr>
<td>1b</td>
<td>A</td>
<td>Base</td>
<td>Smooth</td>
</tr>
<tr>
<td>2s</td>
<td>B</td>
<td>Slope</td>
<td>Textured</td>
</tr>
<tr>
<td>2b</td>
<td>B</td>
<td>Base</td>
<td>Smooth</td>
</tr>
<tr>
<td>3s</td>
<td>B</td>
<td>Slope</td>
<td>Smooth</td>
</tr>
<tr>
<td>3b</td>
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<td>Base</td>
<td>Smooth</td>
</tr>
</tbody>
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