

Effect of GCL Properties on Shrinkage When Subjected to Wet-Dry Cycles

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Abstract: The potential shrinkage of eight different geosynthetic clay liners (GCLs) subjected to wetting and drying cycles is examined. It is shown that the initial (e.g., off-the-roll) moisture content may affect the initial shrinkage but did not notably affect the final equilibrium shrinkage. For GCLs with granular bentonite and wetted to a moisture content of about 60% (or greater) in the hydration phase, the actual moisture content did not appear to affect the magnitude of the final equilibrium shrinkage. However, it did affect the rate of shrinkage. Specimens brought to about 100% moisture content in each cycle reached a constant shrinkage value much faster than those brought to about 60% in each wetting cycle. GCLs containing powdered bentonite generally shrank more than those containing granular bentonite. All of the powdered bentonite specimens continued a slow accumulation of strain with increasing cycles, even up to 75 cycles. The shrinkage of a needle-punched GCL with a thermally treated scrim-reinforced nonwoven carrier geotextile and granular bentonite was less than that for a needle-punched GCL with a simple nonwoven carrier and granular bentonite. For some products, there was considerable variability in GCL shrinkage for specimens from the same roll and tested under nominally identical conditions, whereas for other products, the variability was relatively small. The shrinkage strain required to cause the loss of a 150–300 mm panel overlap is shown to be able to be mobilized in about five wet-dry cycles in the experiments reported. DOI: 10.1061/(ASCE)GT.1943-5606.0000522. © 2011 American Society of Civil Engineers.

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Introduction

The primary function of a geosynthetic clay liner (GCL) in a composite liner is to minimize leakage through any holes in the overlying geomembrane (Rowe 2005; Saidi et al. 2008). Many factors can affect the performance of GCLs used alone or as part of composite liners (e.g., Benson et al. 2010a; Dickinson and Brachman 2010); however, one aspect that has received very little attention is the effect of overlaps of GCL panels. Historically, the GCL has typically been installed in panels with a 150 mm overlap of the panels with powdered bentonite between the overlaps to ensure good hydraulic behavior (Cooley and Daniel 1995; Benson et al. 2004). The overlying geomembrane is typically covered with soil once installed, but sometimes it is left exposed to the atmosphere for operational reasons for periods ranging from months to years. Leaving composite liners uncovered has resulted in five reported cases of needle-punched GCL panel movement in which the initial 150 mm overlap had been lost and significant gaps between

panels have been observed (Thiel and Richardson 2005; Koerner and Koerner 2005a, b; Thiel et al. 2006). These cases corresponded to composite liners both on side slopes and the landfill base and exposure periods of 2 months to 5 years. Panel separations of 300 and 450 mm were observed after only two months of exposure for two needle-punched GCLs on a base with 4° slope. In another case, a separation of 1,200 mm occurred after 36 months of exposure on a 34° slope (Thiel et al. 2006). However, there is also a published case (Gassner 2009) in which a needle-punched GCL experienced only 50 mm of shrinkage during 18 months of exposure on a 18° slope. Instances of panel separation in the field occurred over a range of environmental conditions (such as temperature, humidity, and type of subsoil).

The objective of this paper is to examine the effect that the type of GCL may have on the magnitude of shrinkage in an experimental program that represents a significant extension of the work of Thiel et al. (2006). The various features of different products, such as the type of carrier geotextile and the type and granularity of the bentonite, were systematically examined to assess the role the effect that these variables may have on GCL shrinkage when subjected to wet-dry cycles in the laboratory.

Background Information

There has been relatively little research into the shrinkage of GCL panels. Although the problem of field shrinkage of high-moisture-content, unreinforced GCLs has long been known, it was not expected to occur with reinforced (i.e., needle-punched) products (Mackey 1997; Thiel et al. 2006). Indeed, Koerner and Koerner (2005a, b) stated that field drying alone of a high-moisture-content reinforced GCL was not known to cause shrinkage. Following the recognition of the panel separation issue, a laboratory

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Table 1. Properties of Needle-Punched GCLs Examined

Product	Average dry mass (g/m ²)	Range of dry mass (g/m ²)	Range of initial moisture contents (%)	Cover GT	Average cover GT mass (g/m ²)	Carrier GT	Average carrier GT mass (g/m ²)	Bentonite granularity and type	Thermally treated?
GCL1	4970	4880–5060	< 1–7	NW	240	W	120	Fine, A	Yes
GCL2	4380	3690–5010	3–65	NW	230	NWSR	260	Fine, A	Yes
GCL3	5550	5100–6030	0–19	NW	280	W	130	Coarse, A	No
GCL4	4870	4510–5170	5–72	NW	260	NW	230	Coarse, A	No
GCL5	5380	5360–5410	10	NW	410	NWSR	500	Powdered, A	Yes
GCL6	4740	4710–4780	11	NW	310	NWSR	440	Powdered, B	Yes
GCL7	4860	4860–4870	11–12	NW with bentonite	410	W	220	Powdered, C	Yes
GCL8	4680	4670–4690	9–10	NW	240	W	140	Powdered, B	Yes

Note: NW, nonwoven; W, woven; NWSR, scrim-reinforced nonwoven; GT, geotextile.

testing program was initiated by Thiel et al. (2006). In their experiments, GCLs nominally similar to GCL1–GCL4 examined in this study (Table 1) were subjected to wet-dry cycling and their shrinkage monitored. Following this study, it was concluded that wet-dry cycling had the potential to cause shrinkage in the GCL to the degree observed in the field. Thiel et al. (2006) also showed that geotextiles alone exhibit very little shrinkage (maximum of 2.4%). However, with one exception, the study by Thiel et al. was limited to one specimen per product.

Thiel et al. (2006) did test one product type (GCL2) twice, although these tests were not strictly identical because they were on two versions of the product with one having a much greater needle-punching density and significantly higher peel strength than the other. After 40 cycles in these tests, there was substantial variation in the accumulated shrinkage (12.9 and 19.2% for GCLs with construction similar to GCL2 but peel strengths of 2 and 0.8 kN/m, respectively). However, it is not possible to tell from these data whether this difference was due to the significantly different peel strengths or was a reflection of potential sample variability because, in general, there was a poor correlation between the amount of shrinkage and the peel strength of the different products. For example, the maximum shrinkage (23%) was for a product similar to GCL4 having a peel strength of 2 kN/m, followed by 20.6% for a product similar to GCL3 (peel strength 1 kN/m), then 19.2% for a product similar to GCL2 with peel strength of 0.8 kN/m, then 14.5% for a product similar to GCL1 (peel strength 0.3 kN/m), and the lowest was 12.9% for a product similar to GCL2 with peel strength of 2 kN/m. Thiel et al.'s tests focused primarily on illustrating that wet-dry cycles could accumulate sufficient shrinkage to explain panel separation. The test for the GCL4 gave 23% shrinkage (equivalent to just over 1,000 mm in the field), which could explain all but one of the field cases of panel separation observed for that product.

Testing Program

Materials

It is well known that the type of bentonite can affect its swelling (and shrinkage) and interaction with different permeants (e.g., Rowe et al. 2004; Katsumi et al. 2008; Benson et al. 2010b; Gates and Bouazza 2010; Hornsey et al. 2010; Lange et al. 2010; Rosin-Paumier et al. 2010; Shackelford et al. 2010). Thus, eight different GCL products were examined in this study. Four (two containing coarse granular bentonite and two containing fine granular bentonite) were manufactured for the North American market, while four others, consisting of powdered bentonite, were

manufactured in Europe. The four North American products used in this study have been previously examined for GCL shrinkage (Thiel et al. 2006; Bostwick et al. 2007, 2008, 2010; Rowe et al. 2010), with a comparison between test results provided for GCLs without heat tacking in Bostwick et al. (2010); to the writers' knowledge, the powdered European products have not previously been examined in cyclic wet-dry shrinkage tests. This study also reports a far more extensive study than that reported in conference papers by Thiel et al. (2006) or Bostwick et al. (2007, 2008). A summary of the products examined is given in Table 1 and details of bentonite grain size classification are given in Fig. 1. Peel test and swell index values are given in Table 2.

Three different types of bentonite were examined. Bentonite type A was a Wyoming sodium bentonite used in both the North American and the European products, in all three granularities (Table 1). As reported by the supplier, bentonite type B was also sodium bentonite but not Wyoming sodium bentonite, and C was a blend of sodium bentonites from different sources (including Wyoming sodium bentonite). The swell indexes are given in Table 2 for the bentonite used in each GCL. The swell index of the type A bentonite used in the various GCLs was fairly consistent for a given roll of GCL but varied between 23 and 32 mL/g from product to product (probably reflecting variability in the bentonite provided from nominally the same source from time to time). The swell index for bentonite B was 24–25 mL/g and C was 28 mL/g.

Test Specimens

Both restrained (R) and unrestrained (UR) specimens were tested. Preliminary tests by Bostwick et al. (2008) demonstrated that this factor does not significantly impact the final maximum shrinkage.

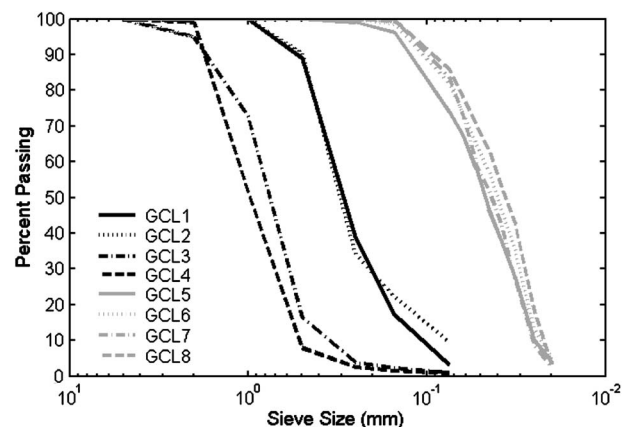


Fig. 1. Grain-size analysis of bentonites from various GCL products

Table 2. Peel Strengths of Needle-Punched GCLs Examined and Swell Index

Product	Average peak peel strength (N)	Standard deviation of average peak peel strength (N)	Average bonding peel strength (kN/m)	Standard deviation of average bonding peel strength (kN/m)	Mean swell index (mL/2 g)	Standard deviation of swell index (mL/2 g)
GCL1	93.8	16.5	0.66	0.09	25.3	0.4
GCL2	260	16.8	2.37	0.12	22.6	0.5
GCL3	204	35.7	1.51	0.26	32.2	0.3
GCL4	219	29.6	1.78	0.28	23.2	0.3
GCL5	207	33.7	1.51	0.19	27.1	0.3
GCL6	224	16.9	1.71	0.09	24.3	0.6
GCL7	97.0	14.2	0.73	0.06	27.7	0.3
GCL8	54.0	4.2	0.41	0.04	25.3	0.6

Each specimen, whether restrained or unrestrained, had a testing area of 550 by 350 mm; this was further reduced to an area of interest of 500 by 300 mm by drawing a 25 mm border on all sides of the specimen. By analyzing only the area of interest, edge effects were avoided.

After specimens were cut and prepared, they were placed on individual smooth aluminum baking pans. Unrestrained specimens were allowed to move freely on the pan, while restrained specimens were held down with 25-mm-wide clamps at either end. Circular control markers, used for calibration during photogrammetric analysis, were also added to the pans. An example of a restrained specimen is shown in Fig. 2.

Testing Process

Once the initial conditions of each specimen were recorded (e.g., water content, mass per unit area, and measurements at grid lines), the specimens were wet with a specified amount of water. An 8 L commercial garden sprayer was used to apply the water in a uniform manner across the specimen. The amount of water varied according to the specimen being tested, as noted subsequently.

In test series I, 500 g of water was added to reproduce the base-case test conditions adopted by Thiel et al. (2006), which was selected on the basis of a target moisture content of about 65% because this was reported by Daniel et al. (1993) to be a typical water content reached through moisture uptake from soil. However, because the mass per unit area of the specimens tested varied widely, the application of a constant mass of water meant that, in fact, moisture content varied and generally was not 65%. Thus, in test series II, the amount of water was selected to give a target water content of 60% of specimen dry mass after moisture uptake. Two additional test series (III and IV) examined the effect of adding extra water during the hydration phase; these test series were conducted concurrently with test series I and II. In test series III, specimens

were wet with 1,000 g of water. In test series IV, the amount of water added was selected such that it would bring the specimens to a target water content equal to 100% of specimens' dry mass.

Following the wetting process, specimens were allowed to hydrate for 8 h in a temperature-controlled room at 20°C. During this period, the specimens were covered with moisture-barrier plastic to prevent moisture loss to the atmosphere.

The subsequent drying phase, which lasted 15 h, took place in ovens set to 60°C. This temperature was on the basis of that used by Thiel et al. (2006) to approximate the temperature that can be reached by a black geomembrane exposed to solar radiation. Pelte et al. (1994) measured a maximum geomembrane temperature of 70°C in the field. At the completion of the drying phase, the samples had reached an average moisture content of slightly less than 1%. The handling phase took approximately 1 h, resulting in a total cycle length of 24 h.

The described experiments were not intended to give the expected shrinkage strains under field conditions, but rather to indicate the effect of variables examined on the maximum amount of shrinkage that might be expected under extreme exposure conditions. For the GCL to shrink, it must first uptake moisture, lose it, and then uptake it again. In this paper, the GCLs were wetted with spray from a water bottle. However, in the field, GCL moisture uptake will be partly because of uptake from the soil and partly because of condensation of water evaporated from the GCL. The experiments reported herein approximate the latter mechanism. The uptake of moisture from the soil and its dependence on the water-retention curve and the water content of the foundation soil as well as the water-retention curve for the GCL is not examined in the present study.

Strain Measurement

Definition of Specimen Strain

For restrained specimens, the restraint caused specimens to neck (Thiel et al. 2006; Bostwick et al. 2007, 2008), and hence, the maximum strain occurred near the midpoint of the specimen. To minimize the risk of a single point measurement giving excessive and unrepresentative strain, strain in restrained specimens was expressed as the average strain on the basis of measurements 100 mm to either side of the maximum individual value. This is termed the maximum strain.

For unrestrained specimens, the lack of restraint meant that no necking occurred; therefore, all shrinkage on unrestrained specimens was expressed as the average shrinkage along the entire length of the specimen for the transverse (across-roll) direction and across the entire width of the specimen for the longitudinal (roll) direction.

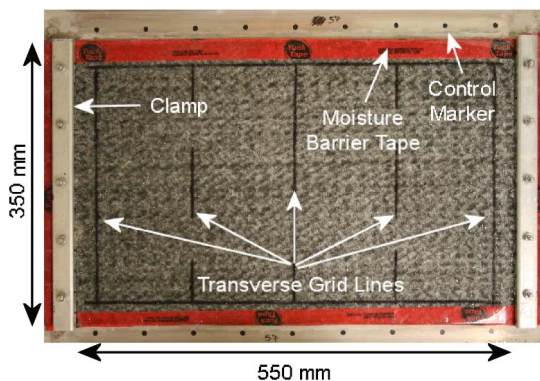


Fig. 2. Setup of restrained pan tests

This paper does not specifically address the possible effect of anisotropic shrinkage on overall shrinkage behavior. Bostwick et al. (2010) demonstrated that there is no apparent variability in longitudinal and transverse shrinkage for GCL2. GCL4 often exhibited preferential shrinkage in the longitudinal direction; however, this was not always the case and this was likely due to the considerable variability in the distribution of bentonite within a single sample of GCL4.

Hand Measurements

During testing, hand measurements were taken of each of the specimens following every drying cycle. Measurements were taken at each of the grid lines, and were only taken within the area of interest; this resulted in five measurements per cycle for restrained specimens, and 10 measurements per cycle for unrestrained specimens. This allowed an approximate measurement of strain as testing progressed. These measurements were only used as a check on the primary method of measurement—image analysis as is subsequently discussed. Final hand measurements are given by Bostwick (2009).

Image Analysis

A 10 megapixel (MP) digital SLR camera was used to capture digital images of each specimen at the end of both the hydration and the drying portions of the imposed moisture cycles. These images were used to calculate shrinkage deformation using the program GeoPIV (White et al. 2003).

The first stage of the image-based deformation measurement analysis is the definition of the regions to be tracked. In the software GeoPIV, these regions (or patches) consist of a small portion of the original matrix comprising the initial image. These 64 × 64 pixel square patches were selected to form 51 pairs on each specimen, coincident with the border lines. Each patch consists of its own unique distribution of pixel color intensity; to enhance the contrast on products with white geotextiles, black paint was applied to the specimen. The uniqueness of each patch made it traceable throughout the series of images, thus allowing movement to be calculated. A series of control markers was drawn on each pan to provide static reference points, which allowed precise calibration of the pans using close-range photogrammetry.

According to White et al. (2003), GeoPIV is capable of a precision up to 0.1 pixels. Thus, the error in an analysis is dependent on the resolution of the photograph taken. Photographs taken with a 10 MP camera, with dimensions of 3,588 × 2,592 pixels and, thus, a resolution of approximately 0.17 mm/pixel, have an approximate error of 0.02 mm. The conversion of this error to percent strain depends on the gauge length being studied. For a transverse-strain measurement with a gauge length of 300 mm, the approximate error would be 0.006%.

Discussion of Test Results

Effect of Initial Moisture Content

One of the differences between different GCL products is the initial off-the-roll moisture content. For example, for GCL2, a typical value is less than 10%, whereas GCL4 is typically 15–30%. The initial moisture content for some specimens used in these tests was around 5–7%, which indicates that some drying occurred during storage; these specimens may have undergone an unintended first drying relative to the off-the-roll moisture content prior to being cut.

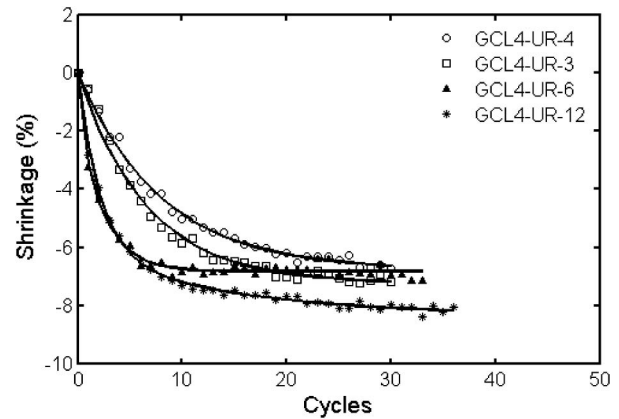


Fig. 3. Effect of initial moisture content on shrinkage of GCL4

To examine the effect of the initial water content at the start of the first wetting/drying cycle for GCL4 (which typically has a relatively high off-the-roll moisture content), water was added prior to testing to artificially raise the moisture content from the off-the-roll value stored in the lab (5% for GCL4-UR-4) to initial values of 19% (GCL4-UR-3), 64% (GCL4-UR-12), and 72% (GCL4-UR-6) to cover an extreme range of possible initial conditions. These specimens were allowed to equilibrate prior to the addition of 500 g of water used in the wetting phase. Fig. 3 and Table 3 demonstrate that although there was a wide range in observed shrinkage values for these four samples, there does not appear to be any strong correlation on the basis of the initial moisture content (at least for GCL4, which came with the highest off-the-roll moisture contents). As shown in Table 3, the average moisture content following drying was independent of the initial moisture content. Thus, in these experiments, the drying portion of the cycle is sufficient to negate the effects of initial moisture content, returning the specimens to the same moisture content for the second and subsequent cycles. While a higher initial moisture content might increase the shrinkage in the very first cycle (as is evident from Fig. 3) and, hence, the accumulated strain in the first few cycles, after a number of cycles, the effect is lost and at equilibrium there is no apparent effect. Indeed, the highest strain (8.2%) was not for the specimen with the highest initial water content, and the lowest final equilibrium strain (6.6–6.8%) was for specimens with the lowest and highest initial water contents (Table 3). However, the difference in the first few cycles could be of practical importance for GCLs only left exposed for a few wet/dry cycles. The strain after five cycles was 3.2–3.8% for the specimens with low initial water content and 6.1–6.2% for the specimens with higher initial water contents.

To put the noted strains in context, for typical 4.4–4.7 m wide GCL rolls, and assuming adjacent rolls shrink in a similar manner, a shrinkage of 3.2–3.4% would give panel separation for a 150 mm overlap and shrinkage of 6.4–6.8% would give panel separation for a 300 mm overlap. Thus, for a 150 mm panel overlap, separation of GCL4 could occur after only a couple of cycles if the GCL had developed a water content above 100% prior to the first drying cycles, or after as few as five cycles if the moisture content was in the range of 50–80%. This may be a contributing factor to the fact that GCL4, which starts with a higher initial water content, has shown panel separation after only a few months exposure on a flat (4%) slope in the field (Thiel et al. 2006).

Effect of Extra Added Water

Thiel et al. (2006) noted that reducing the amount of water added from the original 500 to 300 mL resulted in approximately 25% less

Table 3. Effect of Initial Moisture Content on Final Shrinkage Magnitude

Sample	Dry mass per unit area (g/m ²)	Initial moisture content (%)	Target moisture content—first cycle (%)	Average moisture content after drying (%)	Final shrinkage (%)	Shrinkage after five cycles (%)
GCL4-UR-4	4,960	5	58	0.6	6.6	3.2
GCL4-UR-3	4,510	19	77	0.6	7.2	3.8
GCL4-UR-12	5,100	64	115	0.5	8.2	6.2
GCL4-UR-6	4,870	72	125	0.5	6.8	6.1

Note: For typical range of panel widths, shrinkage required for loss of 150 and 300 mm panel overlap would be 3.2–3.4% and 6.4–6.8%, respectively.

shrinkage for GCL2. To examine this issue further, a series of experiments was undertaken in which more water was added during the hydration process. For series III, 1,000 g was added instead of 500 g (series I); in series IV, the water content was raised to 100% of the dry mass compared to the usual 60% in series II (Table 4).

For GCL1 (Fig. 4), the extra water did not cause a change in the final magnitude of shrinkage. It did, however, increase the rate of shrinkage in the early cycles—the specimen hydrated with extra water reached its shrinkage equilibrium much faster than those hydrated with the standard 500 g.

There did not appear to be a change in either the rate or the magnitude of shrinkage for GCL2 (Fig. 5). This is the same product tested for the effect of water content by Thiel et al. (2006), and they concluded that less water resulted in less shrinkage. These two findings may both be valid [i.e., reducing the wet-cycle water content from about 60% to 35–40% (at or below the typical plastic limit) resulted in less shrinkage, but increasing it to about 100% did not increase shrinkage relative to that for 60%] because 300 mL of

water may not have been sufficient to uniformly hydrate the entire specimen to 35–40%. The experience gained during testing has shown that it is more difficult to uniformly apply smaller amounts of water to a specimen. Bostwick (2009) showed that for identical amounts of hydration water, a specimen that had been wetted unevenly, leaving areas unhydrated, can experience less shrinkage than a specimen that has been wetted evenly.

For GCL4 (Fig. 6), the effect of additional moisture was examined for both unrestrained and restrained specimens. Bostwick (2009) showed that longitudinal restraint does not greatly affect final shrinkage (as is also confirmed in Fig. 6 with the UR specimens only giving slightly less final shrinkage than the R specimens). There appeared to be an increase in both the initial rate of shrinkage and the final equilibrium shrinkage with extra water, although there was considerable difference in final shrinkage among the specimens with 60% water added even though they were tested under nominally identical conditions. Thus, it is possible that the difference in equilibrium strain between the control specimens and the specimens with extra water added could be a result of specimen variability, although the increase in shrinkage from 60% to 100% water content for early cycles is significant. As was found when examining the effect of initial water content (Table 3 and Fig. 3), the initial rate of shrinkage for the specimens with extra water appears to be higher than for those wetted with the standard amount of water.

Application of the Student *t*-test to the data on the percentage of total shrinkage after five cycles shows that the addition of extra hydration water does increase the rate of shrinkage at the 0.025 significance level. This could be important in field applications in which the number of cycles is limited. The shrinkage after five cycles ranged from 4.8 to 9.1%, depending on the GCL and water added in these experiments. This would, theoretically, be sufficient to give panel separation for a 150 mm overlap in all cases and panel separation for a 300 mm overlap in about 40% of the cases examined (Table 4) after five wet-dry cycles. That said, care should be exercised in interpreting the results given in Table 4. Even when

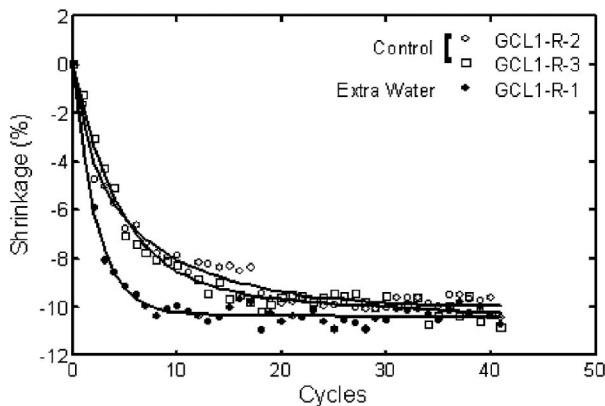
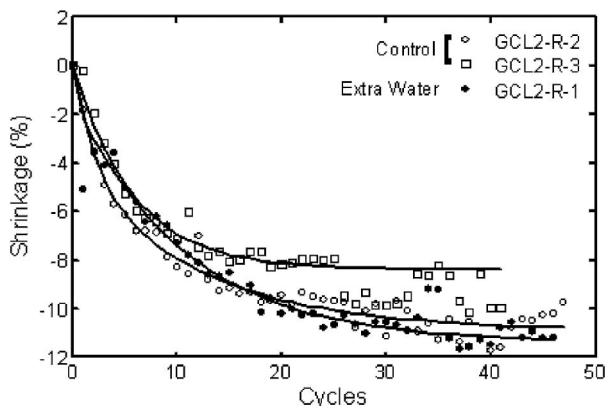
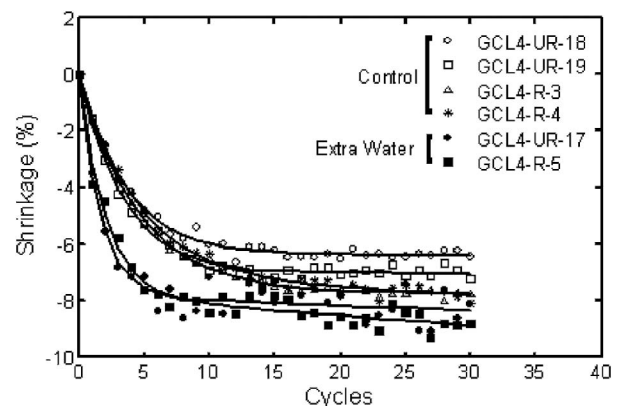
**Fig. 4.** Effect of additional hydration water on GCL shrinkage (GCL1)**Fig. 5.** Effect of additional hydration water on shrinkage of GCL2**Fig. 6.** Effect of additional hydration water on shrinkage of GCL4

Table 4. Effect of Extra Hydration Water on GCL Shrinkage

Sample	Type of test—series	Dry mass per unit area (g/m ²)	Water added (% dry mass)	Final transverse shrinkage (%)	Transverse shrinkage after five cycles (%)	Percentage of final shrinkage after five cycles (%)
GCL1-R-2	Control—I	5,060	51	10.0	6.4	64
GCL1-R-3	Control—I	4,880	53	10.2	6.4	63
GCL1-R-1	Extra water—III	4,970	105	10.4	9.2	88
GCL2-R-2	Control—I	4,610	58	10.8	6.1	56
GCL2-R-3	Control—I	4,800	59	8.4	4.9	58
GCL2-R-1	Extra water—III	4,200	123	11.3	5.1	45
GCL4-UR-18	Control—II	4,570	60	6.4	4.8	75
GCL4-UR-19	Control—II	4,640	60	7.0	5.4	77
GCL4-R-3	Control—II	4,890	60	7.8	5.2	67
GCL4-R-4	Control—II	5,080	60	7.8	4.9	63
GCL4-UR-17	Extra water—IV	4,850	100	8.3	7.5	90
GCL4-R-5	Extra water—IV	4,910	100	8.9	7.3	82

they have consistent initial conditions in terms of moisture content, different GCLs will experience different suction cycles because of their different water-retention curves. Beddoe et al. (2010) provided a methodology for establishing the water-retention curve for GCLs, which was used by Beddoe (2009) and Beddoe et al. (2011) to examine the water-retention curves under both wetting and drying conditions for GCLs 1–4.

The findings of Beddoe et al. (2011) indicate that GCL2 had a substantially different gravimetric water-retention curve than the other three products. The water-retention curves of Beddoe et al. (2011) measured along a wetting path indicate that 60% gravimetric moisture content corresponds to a suction of 150–300 kPa, depending on the GCL product. The much higher target gravimetric moisture content of 100% corresponds to an equilibrium suction of approximately 5–60 kPa, again depending on the GCL product. Thus, as a result of the practical testing decision of applying consistent gravimetric moisture cycles for all samples in this study, GCL2 will be more fully hydrated during the swelling phase of each cycle, and therefore subjected to a larger suction cycle than the other GCLs at the same water content. Thus, in these tests, GCL2 is subject to the most severe conditions in which, as in the field with similar foundation conditions, GCL2 is likely to be at a lower water content than the other GCLs and, hence, is likely to experience less shrinkage in wet-dry cycles.

Effect of Bentonite Granularity and Type

The GCLs tested in this study contained bentonite with three different granularities (Fig. 1)—coarse granular (two products), fine granular (two products), and powdered (four products). The granular bentonite specimens all had Wyoming bentonite and were produced in North America. Of the four powdered bentonite specimens produced for the European market, only one was a Wyoming bentonite (denoted as type A), although the other bentonites (types B and C) were also sodium bentonite. These bentonite types were compared to see what effect, if any, this variable had on shrinkage. The comparisons were grouped by carrier geotextile type so that this variable did not influence the interpretation of the results. To simplify graphs, only the results for specimens showing the greatest and least shrinkage are plotted for granular products.

For the scrim-reinforced products (Fig. 7), the initial shrinkage over the first five cycles was very similar for all cases. However, after about five cycles, GCL6 (powdered bentonite type B, test series III) exhibited much greater shrinkage than GCL5 (test series III) and GCL2 (test series I). After about 10–15 cycles, GCL5 (powdered Wyoming bentonite) exhibited greater shrinkage than GCL2 (fine granular Wyoming bentonite). Nominally, GCL5 and

GCL6 have the same cover and carrier geotextiles, differing only in the type of bentonite (although the average mass per unit area of the geotextile for GCL5 was greater than for GCL6).

For the GCLs with nonwoven/woven cover/carrier geotextiles (Fig. 8), GCL7 (powdered type C bentonite with extra bentonite impregnated in the complete cover layer, resulting in a higher geotextile weight; test series III) initially gave the lowest shrinkage. For GCL1 (test series I) and GCL3 (with the granular Wyoming bentonite, test series I), the shrinkage leveled off after about 25 cycles;

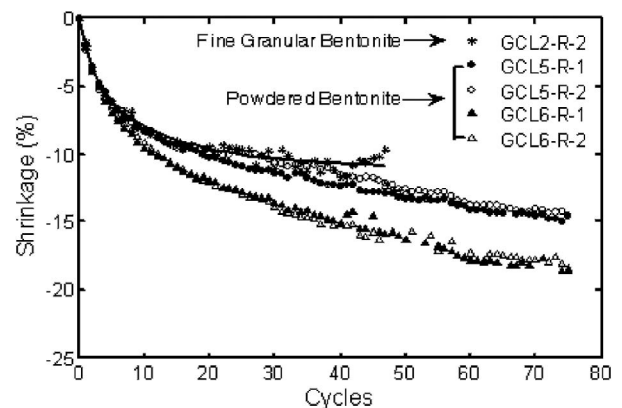


Fig. 7. Effect of bentonite particle size on shrinkage (nonwoven/nonwoven scrim-reinforced cover/carrier)

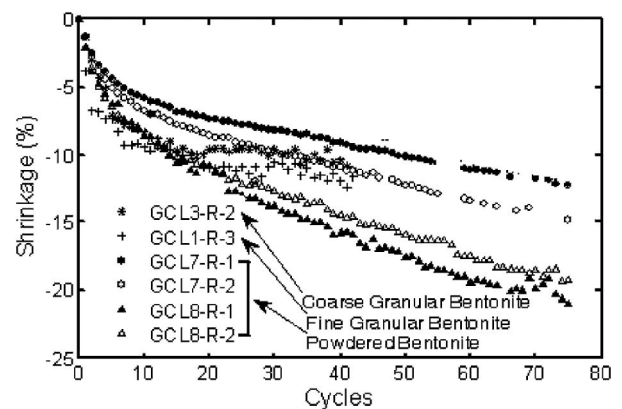


Fig. 8. Effect of bentonite particle size on shrinkage (nonwoven/woven cover/carrier)

Table 5. Summary of Properties and Final Shrinkage for GCLs with Powdered Bentonite

Sample	Bentonite type	Carrier GT	Cover GT	Maximum transverse shrinkage (%)	Average (%)	Shrinkage after five cycles (%)
GCL5-R-1	A	NWSR	NW	14.8	14.8	6.2
GCL5-R-2				14.7		6.6
GCL6-R-1	B	NWSR	NW	18.8	18.5	7.0
GCL6-R-2				18.1		6.6
GCL7-R-1	C	W	NW with bentonite	12.3	13.6	4.4
GCL7-R-2				14.8		5.0
GCL8-R-1	B	W	NW	20.5	19.9	6.2
GCL8-R-2				19.3		6.5

however, for GCL7, shrinkage kept increasing. GCL8 (type B bentonite, test series III) initially exhibited shrinkage similar to GCL1 and GCL3, but after about 15 cycles, it continued to accumulate shrinkage strains at a significant rate, whereas for the other two GCLs, the shrinkage accumulation began to level off. Thus, after many cycles, the GCLs with powdered bentonite exhibited very different total shrinkage behavior than that observed with either the fine or coarse granular bentonite (Figs. 7 and 8). The GCLs with granular bentonite reached a relatively constant shrinkage by about 30 cycles, whereas the GCLs with the powdered bentonite had not reached a relatively constant shrinkage after 75 cycles. As a consequence, the GCLs with the powdered bentonite also experienced much higher shrinkage, up to 20% in some cases. Although powdered bentonite specimens tend to shrink more than granular bentonite specimens, there is still a large variability even among products with the same bentonite grain size (Table 5).

Although it is of scientific interest to observe the difference in the behavior between the different GCLs after many cycles, the relevance of this to actual field situations must be questioned unless the composite liner is left uncovered for very considerable periods of time. Because it will generally take considerable time for the GCL to rehydrate to 60% moisture content after drying, the first 5–10 cycles are likely most relevant to field situations for GCLs resting on typical foundation soils. At 10 cycles, the magnitude of the shrinkage for the powdered and granular bentonite products were similar.

GCLs 5 and 6 have very similar properties except for the type of bentonite. Bentonite type A (Wyoming bentonite) in GCL5 gave less shrinkage than bentonite type B in GCL6. GCL6 experienced less shrinkage than GCL8, which also contained bentonite type B (although it had a different carrier geotextile). GCL7 (bentonite type C) had additional bentonite impregnated into the cover layer. After the completion of 75 cycles, GCL8 exhibited the highest shrinkage of all the GCLs examined; however, there did not appear to be a great difference between GCLs 6 and 8, which had similar shrinkage curves and contained the same type of bentonite (type B).

Effect of GCL Type

Although all products contained a nonwoven cover geotextile, the carrier geotextile ranged from woven (W), nonwoven (NW), and nonwoven scrim reinforced (NWSR). A comparison between the otherwise similar GCL2 (NW/NWSR) and GCL1 (NW/W) is given in Fig. 9. To simplify the graphs, only the results for specimens showing the greatest and least shrinkage for each of the products are included; in addition, individual data points have been removed for clarity. In these specific tests, there is no statistically significant difference between the product with the nonwoven scrim-reinforced geotextile and the product with the woven geotextile (Bostwick 2009), on the basis of the results of a Student *t*-test. However, this does not necessarily mean that they will perform

the same in the field, and this observation should be viewed with considerable caution as will be subsequently explained.

There does not appear to be a statistically significant difference (Bostwick 2009) between GCL3 (NW/W) and GCL4 (NW/NW), as may be appreciated from Fig. 10. This is consistent with instances of field shrinkage because both Thiel and Richardson (2005) and Koerner and Koerner (2005a, b) reported that both GCL3 and GCL4 had suffered loss of panel overlaps.

There is high variability between specimens from the same GCL roll (which was especially significant for GCL4), even when care is taken to only compare specimens tested under as near-identical conditions as practical. Also, the dry unit weights of the various geotextiles in each of the products differs, which may affect shrinkage.

In investigating possible solutions to the problem of GCL panel separation, Koerner and Koerner (2005a, b) recommended that if a

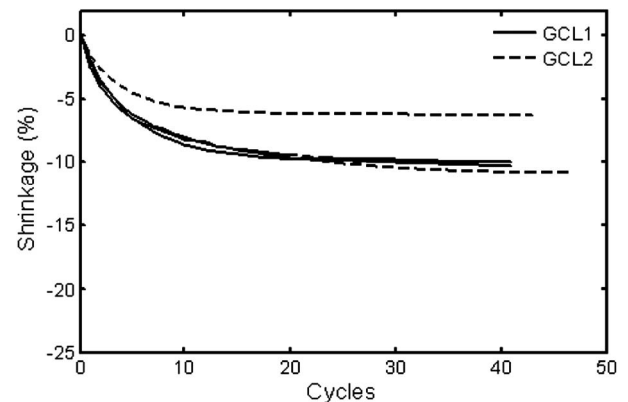


Fig. 9. Comparison of maximum and minimum shrinkage curves—fine granular bentonite

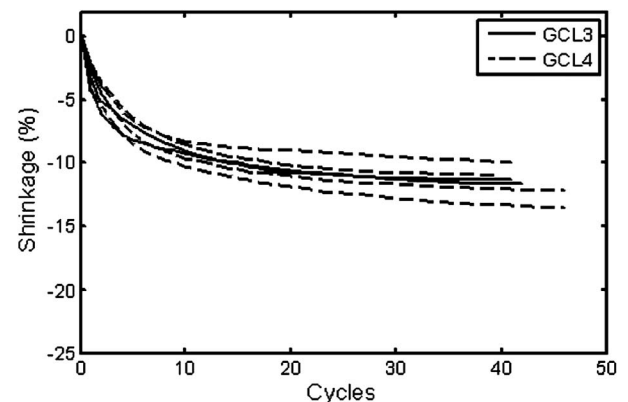


Fig. 10. Comparison of shrinkage curves—coarse granular bentonite

Table 6. Effect of Scrim Reinforcement on GCL Shrinkage

Sample	Water added (% dry mass)	Transverse shrinkage (%)	Shrinkage after five cycles (%)	Sample	Water added (% dry mass)	Transverse shrinkage (%)	Shrinkage after five cycles (%)
GCL2-R-2	58	10.8	6.1	GCL4-R-1	45	13.5	8.4
GCL2-R-3	59	8.4	4.9	GCL4-R-2	49	12.1	7.6
GCL2-R-4	64	10.7	4.1	GCL4-UR-1	51	10.0	6.6
GCL2-R-5	60	10.0	5.1	GCL4-UR-2	55	11.0	6.4
GCL2-R-6	59	9.8	5.3				
GCL2-UR-1	60	9.1	3.7				
GCL2-UR-2	70	10.5	4.0				
GCL2-UR-3	52	6.2	4.5				
Average	60	9.4	4.7	Average	50	11.7	7.3
Standard deviation	5	1.5	0.8	Standard deviation	4	1.5	0.9

Note: Each sample had 500 g of water added to it; differences in water content as a percentage of dry mass is a result of the differences in sample dry mass.

NW/NW product is used, it should be accompanied by scrim reinforcement. In addition, laboratory shrinkage tests by Thiel et al. (2006) showed that a GCL with scrim reinforcement shrank less than a simple NW/NW product. The results of a comparison between GCL2 and GCL4 tested under nominally identical conditions are given in Table 6. Although there is a large range of shrinkage for both products, on average, GCL4 shrank more than GCL2 (the scrim-reinforced, thermally treated product). A one-tailed Student *t*-test confirmed that this result is statistically significant (Bostwick 2009). However, the maximum shrinkages of 10.8% (GCL2) and 13.5% (GCL4) are less than those found by Thiel et al. (2006) of 12.8% (GCL2) and 23.0% (GCL4) for tests that were nominally identical. The difference for GCL2 is modest (10.8% versus 12.8%), but for GCL4 it is large (12.8% versus 23%), suggesting that there is much greater variability from roll to roll for GCL4 than for GCL2.

Both GCL1 and GCL3 had a woven carrier geotextile, with the major differences being the bentonite granularity (GCL1 with fine granules, GCL3 with coarse granules) and the heat treatment of GCL1. On the basis of the data, GCL3 did shrink more than GCL1 at a statistically significant level (Bostwick 2009), indicating that either the bentonite granularity or the heat treatment may play a factor in GCL shrinkage.

Conclusions

Shrinkage of eight different GCLs subjected to wetting and drying cycles was examined. On the basis of specific experiments conducted and GCLs tested, the following conclusions were reached:

1. Higher initial moisture content results in higher initial shrinkage and accumulated shrinkage during the first five cycles. The effect of the initial moisture content diminished with number of cycles and did not notably affect the magnitude of the final equilibrium shrinkage after many cycles.
2. For GCLs with granular bentonite and wetted to a moisture content of about 60% (or greater) in the hydration phase, the actual moisture content did not appear to affect the magnitude of the final equilibrium shrinkage (i.e., after many cycles). However, it did affect the rate of shrinkage. Specimens brought to about 100% moisture content in each cycle reached a constant shrinkage value much faster than those brought to about 60% in each wetting cycle.
3. The difference in the accumulation of shrinkage strain in the first five cycles because of higher initial water content (conclusion 1 above) or higher hydrated water content (conclusion 2 above) could have important implications in the field

where the number of cycles is limited. The former will depend on the moisture content of the as-delivered GCL (with it being much higher for some GCL products than for other GCLs). For the same thermal exposure conditions, the latter will depend on the initial moisture content of the underlying foundation layer, the water-retention curve of the foundation layer, and the water-retention curve of the GCL, which may vary from product to product (Beddoe et al. 2011).

4. For GCLs with Wyoming bentonite, the bentonite particle size affected the magnitude of the shrinkage, with the GCLs containing fine granular bentonite shrinking the least and those with powdered bentonite the most. All the powdered bentonite specimens continued to show a slow accumulation of strain with increasing cycles up to at least 75 cycles, although the strains in the most critical early stages were similar to those with granular bentonite. Thus, over the range examined, the bentonite grain size will not significantly affect the GCL performance with respect to panel separation unless the GCL is subjected to a very large number of wet-dry cycles.
5. The shrinkage of a needle-punched GCL with a thermally treated scrim-reinforced nonwoven carrier geotextile and granular bentonite was less than that for a needle-punched GCL with a simple nonwoven carrier and granular bentonite.
6. For some products, there was considerable variability in GCL shrinkage for specimens from the same roll and tested under nominally identical conditions, whereas for other products, the variability was relatively small. For example, a comparison of results from this study with those reported by Thiel et al. (2006) for nominally identical experimental conditions and products showed that while the difference for one product was modest (10.8% versus 12.8%), for another it was large (12.8% versus 23%).
7. The shrinkage strain required to cause the loss of 150–300 mm panel overlap could be mobilized in about five wet-dry cycles in the experiments reported.

The results from the experiments reported in this paper should not be viewed as expected values of shrinkage strains under field conditions, but rather as an indication of the effect of certain variables and the maximum amount of shrinkage that might be expected under extreme exposure conditions. For the GCL to shrink, it must first uptake moisture, lose it, and then uptake it again. In these laboratory tests, this was achieved by wetting from a spray water bottle. However, in the field, GCL moisture uptake will be from (1) the soil and (2) possible condensation of water evaporated from the GCL. The uptake of moisture will depend on the water-retention curve and the water content of the foundation soil at the time the GCL is placed and the water-retention curve for the GCL.

Beddoe et al. (2011) showed that in terms of moisture uptake, there is a significant difference between the water-retention curves of different products. The effect of this is not reflected in the current study in which all GCLs were brought to a similar nominal water content or had a similar amount of moisture added in the same time period. Because the rate of cyclic accumulation of shrinkage strains was observed to be a function of the moisture content cycle imposed on a GCL sample, it is therefore likely that the magnitude of shrinkage achieved in the field will be a function of (1) the water-retention characteristics of the GCL and subsoil and (2) the magnitude, duration, and number of moisture cycles. When these factors are considered, there may be greater differences between the shrinkage observed for different products than is evident from this study. In addition, although the temperature of the ovens was chosen to correspond to temperatures measured in the field beneath a geomembrane, the testing process could not exactly replicate the water-vapor pressure experienced by field-installed GCLs.

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