Technical Paper by P.J. Fox, E.J. Triplett, R.H. Kim and J.T. Olsta

FIELD STUDY OF INSTALLATION DAMAGE FOR GEOSYNTHETIC CLAY LINERS

ABSTRACT: Field tests were conducted to assess installation damage for an adhesive-bonded, and a needle-punched, geosynthetic clay liner (GCL). GCL panels were laid on a prepared subgrade and covered to varying thicknesses with clean angular sand and clean angular gravel. After hydration, bulldozers were driven over the test plots. GCL samples were then carefully exhumed and laboratory tests were performed to assess damage according to product type, cover soil type, cover soil thickness, bulldozer type, and number of bulldozer passes after hydration. Visual observations and laboratory test results indicated that the products generally performed well during installation. Damage to the geosynthetic components of the GCLs was minor for a cover soil thickness of 305 mm or greater. Mass per unit area measurements indicated that bentonite migration was insignificant for nearly all specimens; the only exception was the adhesive-bonded GCL covered with gravel and subjected to 10 passes of a medium-weight bulldozer after hydration. No failures were observed for installation conditions that met the guidelines of ASTM D 6102 and the manufacturer. Compared to similar investigations for other geosynthetic materials, installation damage studies for GCLs are unique because of the sensitivity of these products to hydration and overburden stress conditions and the need to quantify bentonite migration due to stress concentrations.

KEYWORDS: Geosynthetic clay liner, Installation damage, Survivability, Bentonite, Cover soil.

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1 INTRODUCTION

Geosynthetic clay liners (GCLs), like any geosynthetic product, can be damaged during installation. Primary concerns for the installation of GCLs are tearing and puncturing, hydration prior to placement of cover materials, and stress concentrations from construction equipment. Proper construction quality control/construction quality assurance procedures can greatly reduce the likelihood of accidental GCL puncture and premature hydration during construction. However, concern still exists with regard to GCL damage resulting from stress concentrations, especially for GCLs placed over rough subgrades or covered by coarse soils (Koerner 1997). Depending on the product type and hydration conditions, such stresses may damage the carrier geosynthetics, damage the reinforcement, or cause bentonite migration and consequent reductions in local mass per unit area of the product. Case histories have demonstrated that unexpectedly coarse soils may be encountered during the installation of GCLs (Schmidt 1995; Stewart and von Maubeuge 1996), further underscoring the need for information on potential installation damage for these products.

Although manufacturers' recommendations have varied with regard to the maximum permissible particle size for a subgrade or cover soil in direct contact with a GCL, a new standard guideline for GCL installation, ASTM D 6102, represents general agreement on this issue in the United States. Where a GCL is placed over an earthen subgrade, ASTM D 6102 recommends that, at a minimum, the surface should be rolled with a smooth-drum compactor such that it is firm and unyielding, with no abrupt elevation changes, voids, or cracks. Furthermore, the subgrade surface should be free of vegetation, standing water, ice, debris, and any protrusions greater than 12 mm in height. With regard to cover soils, ASTM D 6102 recommends any such soil should be no coarser than a well-graded gravel with a maximum particle size of 25 mm. Cover soils should be free of sharp-edged particles or other foreign objects that could damage the GCL. In addition, it is recommended that cover soils be placed using construction equipment that minimizes stress on the GCL, with a minimum of 300 mm of cover maintained between equipment tires/tracks and the GCL at all times. ASTM D 6102 further recommends the construction of field-scale test pads to assess possible GCL damage for cover soils containing more than 50% of aggregate larger than 20 mm and for frequently trafficked areas such as roadways.

Based primarily on field observations during construction, ASTM D 6102 is the most complete guideline for GCL installation currently available. There is need, however, for controlled field studies to substantiate and strengthen the recommendations of ASTM D 6102. Furthermore, neither ASTM D 6102 nor ASTM D 5818 provide details regarding field and laboratory procedures needed to conduct a controlled field test of GCL installation damage. Although field studies of installation damage have been conducted for geotextiles and geogrids (see summary by Allen and Bathurst 1994) and for geomembranes (Heerten 1993; Darilek et al. 1995; Reddy et al. 1996; Richardson 1996; Guglielmetti et al. 1997), and laboratory studies have investigated GCL bentonite migration under concentrated loads (Koerner and Narejo 1995; Fox et al. 1996) and areal loads (Anderson 1996; Stark 1998), a controlled field study of GCL installation damage has not been reported.

The objective of the current paper is to present the results of a installation damage field study for an adhesive-bonded, and a needle-punched, geotextile-supported GCL. GCL panels were installed on a prepared subgrade and covered to varying thicknesses with two soils. After hydration, bulldozers were driven over the test plots. GCL samples were then carefully exhumed and laboratory tests were performed to assess damage according to product type, cover soil type, cover soil thickness, bulldozer type, and number of bulldozer passes after hydration. The materials and field procedures are first described, followed by the laboratory testing program, results, discussion, and conclusions. The findings of the study provide information to manufacturers, designers, and installers who have concerns regarding possible installation damage for GCLs placed against natural soils.

2 MATERIALS

2.1 Geosynthetic Clay Liners

Two commercial GCL products were used in the study. GCL-1 (Claymax 200R, Colloid Environmental Technologies Co. (CETCO), Arlington Heights, Illinois, USA) is an unreinforced, adhesive-bonded GCL in which granular bentonite is held between one woven, slit-film polypropylene geotextile with a mass per unit area, μ = 109 g/m^2 and a nonwoven polypropylene geotextile with μ = 50 g/m^2. GCL-2 (Bentomat ST, CETCO) is a reinforced GCL in which granular bentonite is held between a woven, slit-film polypropylene geotextile (μ = 109 g/m^2) and a nonwoven, needle-punched polypropylene geotextile (μ = 204 g/m^2). To provide reinforcement, polypropylene fibers from the nonwoven geotextile are needle-punched through the bentonite and the woven geotextile.

2.2 Subgrade and Cover Soils

Figure 1 shows the particle size distributions for the subgrade and two cover soils used to construct the test plots. The subgrade had a liquid limit of 45, plastic limit of 26, and is classified as CL (lean clay with sand) according to the Unified Soil Classification System. The cover soils were clean and cohesionless and were classified as SP (poorly graded sand) and GP (poorly graded gravel). Both cover soils were obtained from a local quarry and were composed of crushed granite with sharp angular particles.

3 PROCEDURES

3.1 Subgrade Preparation

The study was conducted behind the CETCO manufacturing plant located in Fairmount, Georgia, USA, over a two week period in August 1997. The test site is shown schematically in Figure 2. The subgrade was prepared by scraping the grass and topsoil off the site and rolling the surface at natural water content (10 to 15%) with a 108 kN smooth drum roller. Prior to GCL installation, the subgrade met the criteria of ASTM D 6102. A sand cone test of the prepared subgrade yielded a dry unit weight of 16.7 kN/m^3, which is slightly higher than the corresponding standard Proctor maximum dry unit weight of 16.5 kN/m^3 for this soil.

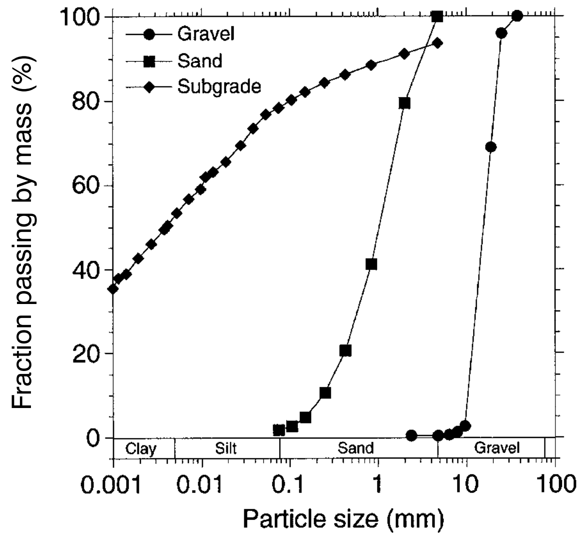


Figure 1. Particle size distributions for subgrade and cover soils.

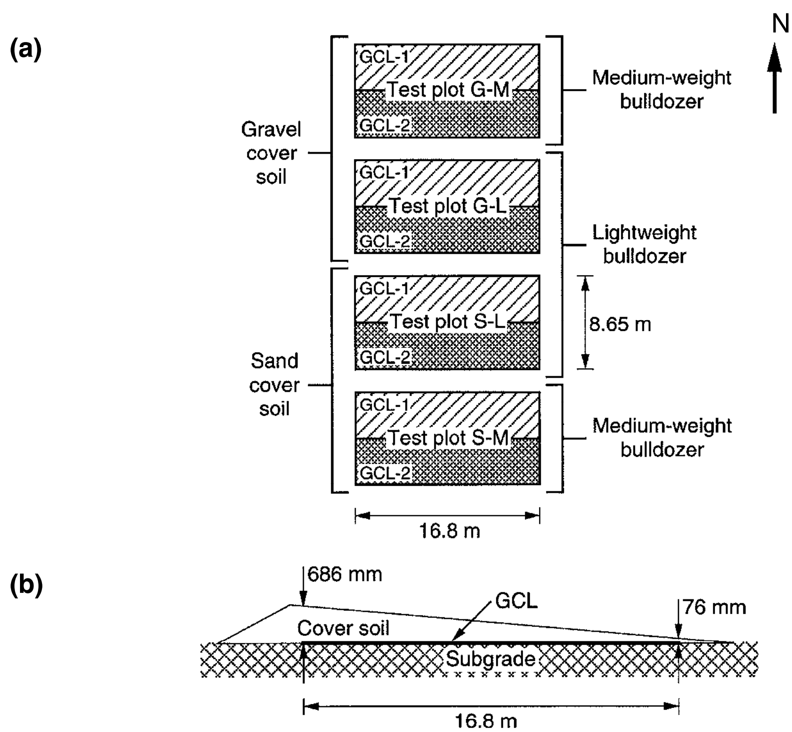


Figure 2. Test site: (a) plan view; (b) cross section.

3.2 Installation and Hydration

Four test plots were constructed at the site, each consisting of one panel of GCL-1 (4.2 m × 16.8 m) and one panel of GCL-2 (4.6 m × 16.8 m) laid side-by-side with an overlap of approximately 150 mm (Figure 2a). Test plots S-L and G-L were installed on 4 August using panels cut from one roll of GCL-1 and one roll of GCL-2. The panels were unrolled by hand on the prepared subgrade and covered with soil the same day. Both GCL-1 and GCL-2 were placed with the woven geotextile facing up. The panels for plot S-L were covered with sand, and the panels for plot G-L were covered with gravel. The cover soils were deployed using a Case model 550E (Long Track) bulldozer with 406 mm wide tracks. This lightweight bulldozer weighed 67 kN and had a total ground contact area of 1.82 m^2, giving an average ground contact pressure of 37 kPa. The cover soils were piled at the east end of the plots (not on the GCLs) and pushed toward the west end such that their thickness was progressively increasing. Once completed, the thickness of each cover soil increased from 76 mm at the east end of the panels to 686 mm at the west end (Figure 2b). Care was taken during installation to ensure that the bulldozer did not drive over the GCL panels with less than the final thickness of cover soil under its tracks. After the cover soils were deployed, the test plots were hydrated using a fire hose. Water (4,320 liters) was applied as uniformly as possible to the top of the cover soils for each test plot (equivalent to a 25 mm storm event). The plots were covered with geomembranes overnight and during rainy days to prevent further hydration from rain. The geomembranes were removed during the day if it was not raining.

Test plots S-M and G-M were constructed on 8 August using panels cut from two rolls of GCL-1 and one roll of GCL-2. The method of construction and hydration was identical to that for plots S-L and G-L except that a Caterpillar D5H-XL bulldozer with 610 mm wide tracks was used to deploy the cover soils. This medium-weight bulldozer weighed 165 kN and had a total ground contact area of 3.34 m^2, giving an average ground contact pressure of 49 kPa.

3.3 Curing and Trafficking

Test plots S-L and G-L were permitted to cure for two days after hydration. The weather during this time was hot and sunny, and the plots were uncovered during the daytime. As a result, the cover soils dried considerably for test plots S-L and G-L. On 6 August, the same Case model 550E bulldozer was used to make 10 single passes (i.e. five up-and-back cycles) over one side of each GCL panel. For the first 10 passes, one bulldozer track was driven directly above the overlap between the panels and the other track was driven over the GCL-1 panel. Ten more passes were made with one bulldozer track directly above the overlap and the other track over the GCL-2 panel. The bulldozer moved in a single lane without turning or braking for each set of 10 passes. Using this procedure, one side of each GCL panel received 10 passes, and the other side (i.e. toward the outside of the test plot) received no passes. Thus, the effects of installation and hydration could be studied separately from the effects of installation, hydration, and trafficking.

Test plots S-M and G-M were permitted to cure for three days after hydration. The weather was overcast and rainy for the first two days and the plots remained covered. Although skies cleared on the third day and the geomembranes were removed, the cover soils for test plots S-M and G-M did not dry as much as those for test plots S-L and G-L.

On 11 August, the Caterpillar D5H-XL bulldozer was driven over test plots S-M and G-M in the same manner as was done previously for plots S-L and G-L. Figure 3 shows the medium-weight bulldozer driving over test plot G-M.

3.4 Exhumation

Exhumation of GCL samples from each test plot began immediately after bulldozer trafficking was completed. A total of 80 GCL samples were collected for laboratory testing, the locations of which are shown in Figure 4. For each GCL panel, two samples (0.3 m × 0.5 m) were exhumed for index tests at cover soil depths, *H*, of 152, 305, 457, and 610 mm, one sample directly underneath the bulldozer track, and one approximately 1.5 m away from the bulldozer track (Figure 5). Three large GCL-2 samples (0.5 m × 1.5 m) were collected for direct shear tests from each test plot under the bulldozer track at average depths of 203, 381, and 559 mm. The direct shear samples were cut with the long sides parallel to the product machine direction. In addition, two samples of GCL-1 and two samples of GCL-2 (0.2 m × 0.2 m) were collected, at a depth of 330 mm under the bulldozer tracks, from test plots S-M and G-M for hydraulic conductivity tests.

Samples at cover soil depths of 381 mm or less were exhumed entirely by hand. Shovels were used to dig through the upper part of the cover soils. The excavations were then completed using garden hoes and hand spades. Extreme care was taken not to damage the GCL samples during exhumation. The cover soils were removed using predominantly horizontal motions to avoid applying stress concentrations to the GCLs below. If a sample was accidentally damaged during excavation, which happened on occasion, the location of the sample was moved to avoid the damaged area (not indicated in Figure 4). Once the cover soil was cleared away, a photograph was taken, and the sample was cut from the panel using scissors and sharp utility knives. Oversized samples were cut in the field so that the disturbed area around the edges could be trimmed off in the laboratory. Exhumed samples were labeled, sealed in plastic bags, placed on plywood

Figure 3. GCL trafficking for test plot G-M.

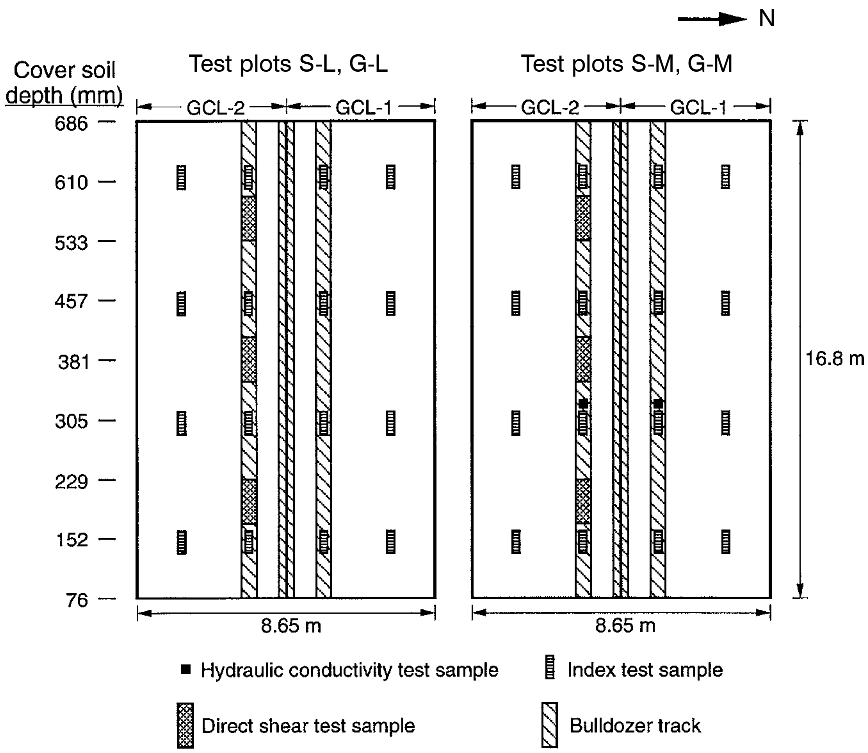


Figure 4. Locations of the exhumed GCL samples.

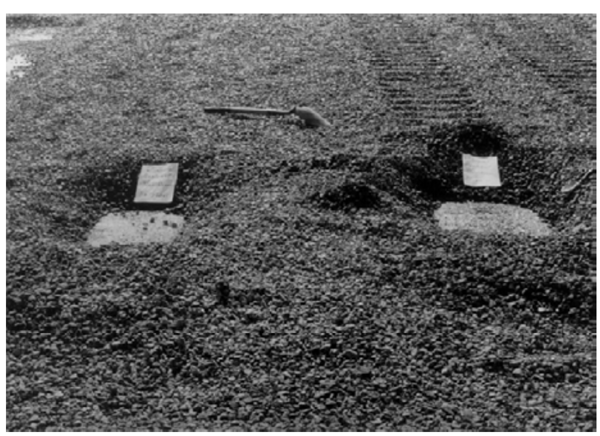


Figure 5. Exhumed GCL-2 specimens under the bulldozer track and 1.5 m away from the bulldozer track for test plot G-M (H = 152 mm).

sheets, and stored in the plant for later testing. Only the direct shear samples were stacked during storage.

Once the shallow samples ($H \leq 381$ mm) were exhumed, a front-end loader was used to excavate the cover soil from each test plot moving from east to west. When the loader approached the locations of the deeper samples ($H > 381$ mm), the bucket was raised to a height of 0.3 m and the loader only removed the upper part of the cover soil. Samples were then exhumed by hand as previously. In this way, the wheels of the loader did not drive within approximately 1.5 m of the samples prior to excavation.

3.5 Control Samples

Control samples were collected from the same GCL rolls that were installed in the field (i.e. three rolls of GCL-1 and two rolls of GCL-2). Five samples (0.3 m × 0.5 m) were taken across the width of each roll prior to installation for index tests. In addition, two samples of GCL-2 (0.5 m × 1.5 m) were taken from each roll for direct shear tests. Control samples are designated as: Control-L (test plots S-L, G-L), Control-S-M (test plot S-M, GCL-1), Control-G-M (test plot G-M, GCL-1), and Control-M (test plots S-M and G-M, GCL-2).

3.6 Laboratory Testing

The laboratory testing program was designed to detect three types of GCL specimen damage: (i) damage to the carrier geotextiles; (ii) damage to the reinforcement (for GCL-2); and (iii) bentonite migration. Index tests (grab tensile strength, grab peel strength, thickness, mass per unit area, and water content) were performed at the CETCO plant within two days after exhumation of each test plot. Internal shear strength and hydraulic conductivity performance tests were conducted at Purdue University and the CETCO Arlington Heights testing laboratory, respectively, over subsequent months. Identical tests were performed for field and control specimens. Each type of laboratory test was performed by one person in order to minimize operator-dependent variability in the results.

Damage to carrier geotextiles was measured using grab tension tests. The tests were performed on field specimens in the hydrated state and on control specimens in the as-manufactured state (i.e. without hydration). The procedure was identical to that specified by ASTM D 4632 for the grab tensile strength of geotextiles. Two tension test specimens (102 mm × 254 mm) were die cut from each index test sample with the long sides parallel to the machine direction. The geosynthetics at both ends of each specimen were clamped to 25 mm × 51 mm testing grips, and the specimen was failed in tension at a displacement rate of 305 mm/minute. The tensile strength, F_t , of the material was calculated as the average peak tensile force measured from the two corresponding tension tests.

Damage to the reinforcement of GCL-2 was measured using grab peel tests and direct shear tests. Peel tests were conducted on field specimens in the hydrated state and on control specimens in the as-manufactured state. Two peel test specimens (102 mm × 254 mm) were cut from each index test sample with the long sides parallel to the machine direction. The geosynthetics at one end of each specimen were separated and clamped to 25 mm × 51 mm testing grips, and the specimen was peeled apart at a displacement rate of 305 mm/minute. The peel strength, F_p , of the material was calculated as the average peak tensile force from the two corresponding peel tests. Direct shear tests were performed on large rectangular GCL specimens (406 mm × 1067 mm) using the pullout shear machine described by Fox et al. (1997). The testing procedure was identical to that used by Fox et al. (1998) for measuring GCL internal shear strength. Both field and control specimens were hydrated using a four-day, two-stage procedure and sheared under a normal stress, σ_n , of 24.0 kPa to a final displacement of 195 mm at a horizontal displacement rate of 0.1 mm/minute. A thin, stainless steel needle was used to measure pore pressure at the failure surface (woven geotextile/bentonite interface) during shear.

Bentonite migration (i.e. vertical or lateral bentonite displacement) was assessed by measuring water content, w, and mass per unit area, μ, as well as the variability of thickness and local μ within the specimens. Water content and μ values were calculated using the weight of oven-dry bentonite (i.e. minus the weight of geosynthetics). Two GCL specimens (102 mm × 254 mm) were cut from each index test sample for this purpose. Soil particles and extruded bentonite were carefully removed from each specimen. One-half of the first specimen (102 mm × 127 mm) was used to obtain w and μ according to ASTM D 5993, while the other half was labeled and stored in a plastic bag for archival purposes.

A detailed procedure was used to measure the distributions of local thickness and local μ values for the second specimen. Three "thick" and three "thin" locations were identified by manual inspection. If no perceptible differences in thickness could be found, six arbitrary locations were selected. Six thickness measurements were obtained at these locations using a caliper with C-shaped jaws. At the same locations, six measurements of local μ were obtained using miniature sampling tubes (Figure 6). Each tube consisted of a thin-walled, stainless steel or brass cylinder (diameter = 10 mm, height = 25 mm), which was sharpened at one end. To penetrate the geotextiles without squeezing the bentonite, an auxiliary tube was heated with a propane torch and used to melt a circular ring through the top geotextile (but not through the clay) at the six loca-

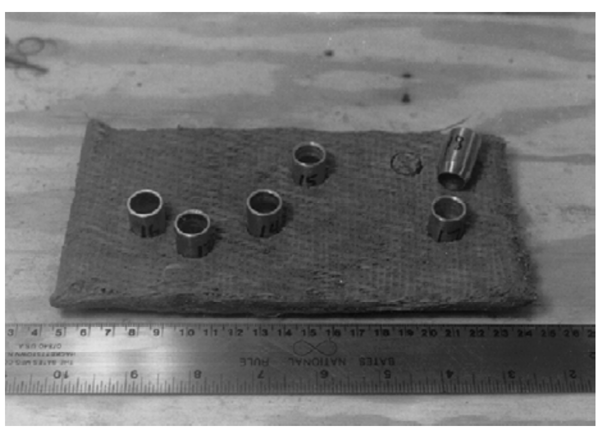


Figure 6. Sampling local bentonite mass per unit area using miniature tubes.

tions. The sampling tubes were then pushed into the bentonite, the GCL specimen was turned over, and the auxiliary tube was again used to melt the bottom geotextile such that each tube could be removed with a small specimen of the GCL inside. The tubes were then placed in moisture content tins and oven dried overnight. Knowing the tare weight and cross-sectional area of each tube, six values of local mass per unit area were obtained for each GCL specimen. Control specimens from each roll were slightly hydrated and subjected to the same procedure.

The GCL μ values were not greatly affected by embedded subgrade and cover soil particles because the nonwoven geotextiles were placed adjacent to the subgrade. The subgrade was cohesive and relatively dry and, as a result, only a few small pebbles and soil fragments were embedded in the nonwoven geotextiles. These were easily removed. The majority of sand and gravel particles were also easily removed from the woven geotextiles by light scrapping with a metal spatula. Although this process was largely effective, it was not possible to remove all of the soil particles from the geotextiles (especially for specimens exhumed from under the sand cover soil).

The hydraulic conductivity, k, and index fluid flux, v, of four GCL specimens (diameter = 102 mm) were measured using flexible-wall permeameters according to ASTM D 5887. Each specimen was cleaned of cover and subgrade soil, placed between two porous disks, and hydrated under an effective confining stress of 35 kPa for 2 days (back pressure = 517 kPa, cell pressure = 552 kPa). The flow rate of de-aired tap water was measured at steady state under a differential pressure of 14 kPa. The thickness of the GCL specimens was measured before and after testing according to ASTM D 5199.

4 RESULTS

Test results for field specimens are reported according to GCL type, cover soil type, bulldozer type, cover soil thickness, and number of passes after hydration. Corresponding results for control specimens are also reported for comparison. Measured values are presented versus cover soil thickness in each figure.

4.1 Damage to Carrier Geotextiles

Grab tensile strengths for GCL-1 and GCL-2 are plotted in Figures 7 and 8, respectively. Values for the control specimens, which are independent of H, are shown as horizontal lines. Each data point represents the average of two tests and each control value represents the average of five tests. Although the data in these plots (and the ones to follow) show significant scatter, some trends are evident. The average measured tensile strength for nearly every pair of field specimens is significantly less than that of the corresponding control specimens. However, for several test series (e.g. GCL-1, G-M, 10 passes), F_t shows relatively small variation for H = 305 mm. In addition, visual inspection of the specimens exhumed from deeper cover soils revealed no perceptible damage to the carrier geotextiles of either GCL product. It is therefore concluded that the reduced values of F_t resulted, at least in part, from the different hydration condition of the field and control specimens. Compared to the control specimens, the hydrated field specimens were thicker, softer, and covered with a thin layer of moist bentonite. As a result, a higher clamping pressure was needed for the testing grips to prevent the field

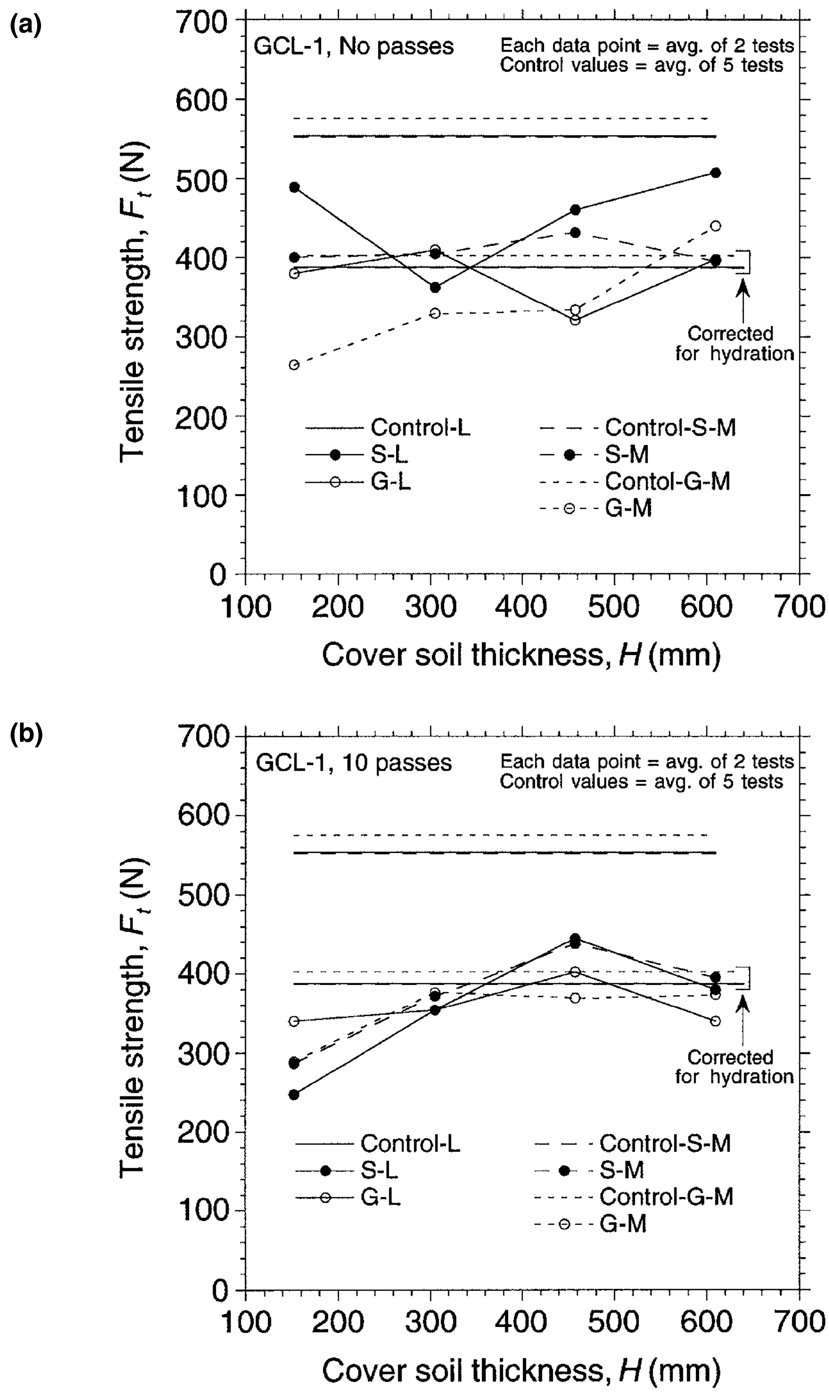


Figure 7. Grab tensile strength of GCL-1 for: (a) no passes; (b) 10 passes after hydration.

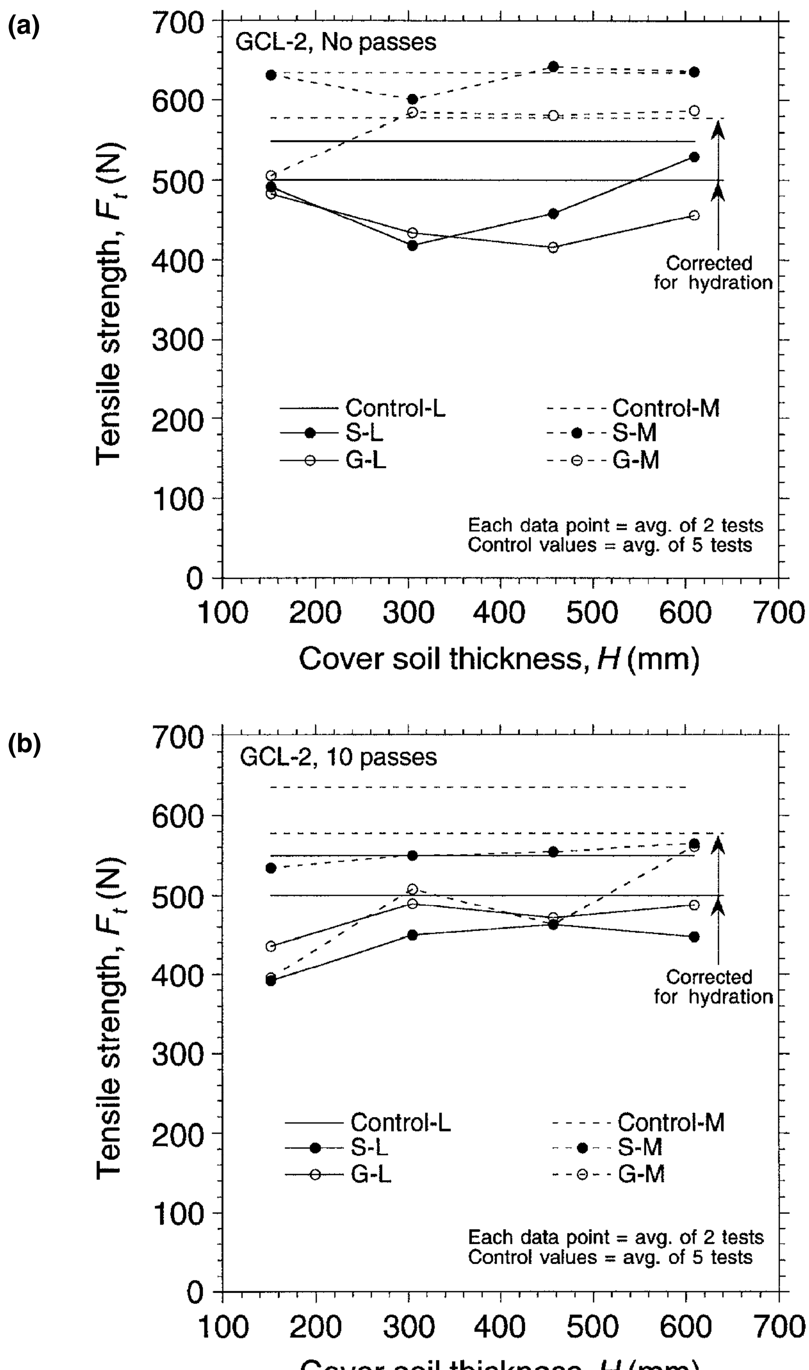


Figure 8. Grab tensile strength of GCL-2 for: (a) no passes; (b) 10 passes after hydration.

specimens from slipping during the tension tests. This likely produced higher stress concentrations in the geotextiles near the testing grips, which consequently reduced the peak tensile force.

In a subsequent series of tests performed on 30 specimens, grab tensile strengths of GCL-1 and GCL-2 were reduced after hydration in the laboratory for two days under a normal stress of 3 kPa. The average tensile strength decreased by 30% for GCL-1 (average w = 245%) and 9% for GCL-2 (average w = 113%). Grab tensile strength values for the control specimens were corrected for hydration using these results as a guideline. The corrected values, also shown in Figures 7 and 8, are in closer agreement with the field data.

Figures 7a and 8a suggest that F_t values for the S-L, G-L, and S-M specimens of both GCL products with no bulldozer passes after hydration does not significantly decrease as a result of installation. Considering that essentially no reductions were measured for H = 152 mm, differences between field and corrected control values likely reflect product variability. For the G-M specimens at H = 305 mm, F_t decreases by 18% for GCL-1 and –1% for GCL-2. Corresponding decreases at H = 152 mm are 34% for GCL-1 and 12% for GCL-2. These reductions are attributed to installation damage.

Grab tensile strengths of field specimens that received 10 passes after hydration are shown in Figures 7b and 8b. The plots suggest the carrier geosynthetics of GCL-1 experienced minimal damage for H = 305 mm. GCL-2 follows a similar trend with the exception of G-M, which showed F_t reductions of up to 20%. For H = 152 mm, F_t has the lowest value for each test series. The maximum reduction in tensile strength is approximately 34% for both GCL products, which is consistent with typical strength reduction factors of 1.1 to 1.5 for the installation of geotextiles in slope stabilization applications (Koerner 1998).

4.2 Damage to Reinforcement of GCL-2

4.2.1 *Peel Strength*

Grab peel strengths of GCL-2 specimens are presented in Figure 9. A subsequent series of tests performed on eight GCL-2 specimens showed that F_p was reduced, on average, by 8% after hydration in the laboratory for two days under a normal stress of 3 kPa. Figure 9 also provides control values that were corrected for hydration based on these results. The grab peel strength of field specimens that received no passes after hydration show substantial variability (Figure 9a) but little indication of damage to the reinforcement of GCL-2. Similarly, Figure 9b suggests little reinforcement damage for H = 305 mm and 10 passes after hydration. Considering H = 152 mm, 10 bulldozer passes reduces the peel strength of GCL-2 (except for S-M) by as much as 38%.

4.2.2 *Internal Shear Strength*

Figure 10 shows peak internal shear strengths, τ_p , for GCL-2 specimens. Compared to the plots for tensile and peel strength, the data in Figure 10 exhibit less variability, possibly because of the large size of the direct shear test specimens. Similar to previous studies of GCL-2 (Gilbert et al. 1996; Fox et al. 1998), the specimens failed at the woven geotextile/bentonite interface and not within the hydrated bentonite. In addition, mea-

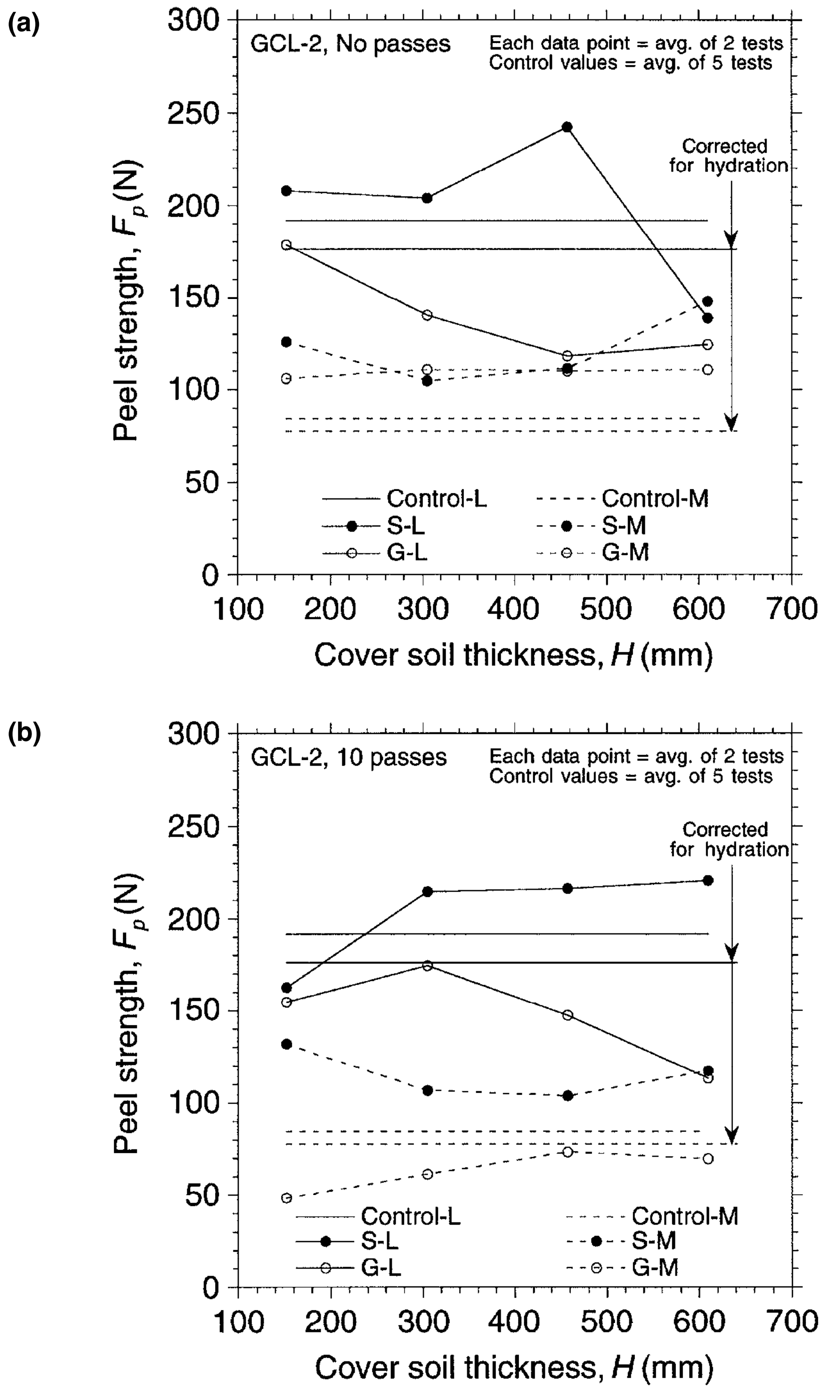


Figure 9. Grab peel strength of GCL-2 for: (a) no passes; (b) 10 passes after hydration.

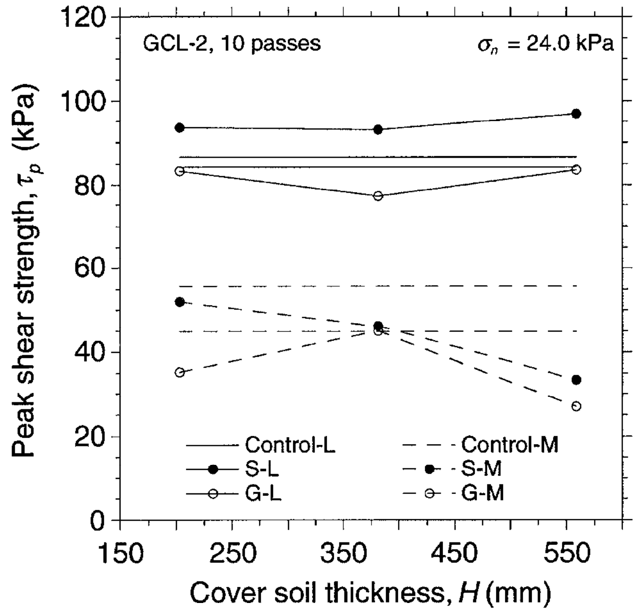


Figure 10. Peak internal shear strength of GCL-2 for 10 passes after hydration.

sured values of excess pore pressure on the failure surfaces were small during shear (± 0.7 kPa). Figure 10 indicates that τ_p was not significantly reduced as a result of installation and trafficking. A possible exception is the G-M test at H = 203 mm, in which τ_p is 32% less than the corresponding S-M value.

4.3 Bentonite Migration

4.3.1 *Water Content*

Bentonite water contents for the 102 mm × 127 mm field specimens are shown in Figure 11a for GCL-1. Water contents for test plots S-M and G-M are generally higher than those for test plots S-L and G-L, providing direct evidence of the different hydration conditions for the two phases of the current study. In addition, w generally increases with decreasing H due to the lower effective overburden stress. Most GCL-1 specimens that received 10 passes after hydration have a lower water content than corresponding specimens, which received no passes after hydration (especially for $H \leq$ 305 mm). This trend cannot be explained by changes in GCL mass per unit area (Figure 12). It may be that, despite the short duration of trafficking, limited consolidation of the bentonite was responsible for the lower measured water contents.

Water contents for GCL-2 (Figure 11b) are more consistent and generally lower than that for GCL-1 due to the additional confinement provided by the needle-punched reinforcement. As H decreases, w generally decreases for the S-L and G-L specimens (due to desiccation) and generally increases for the S-M and G-M specimens (due to lower

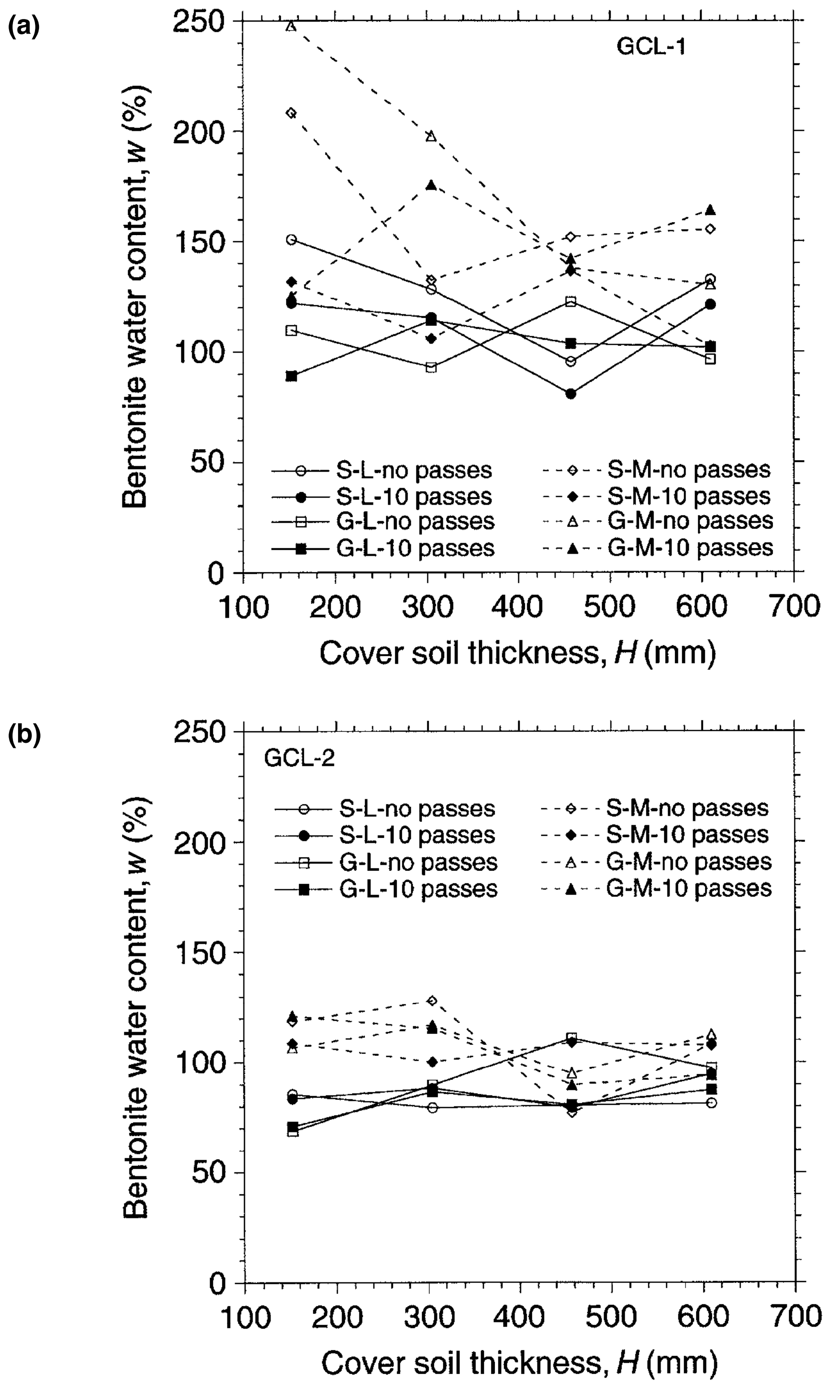


Figure 11. Bentonite water content for: (a) GCL-1; (b) GCL-2.

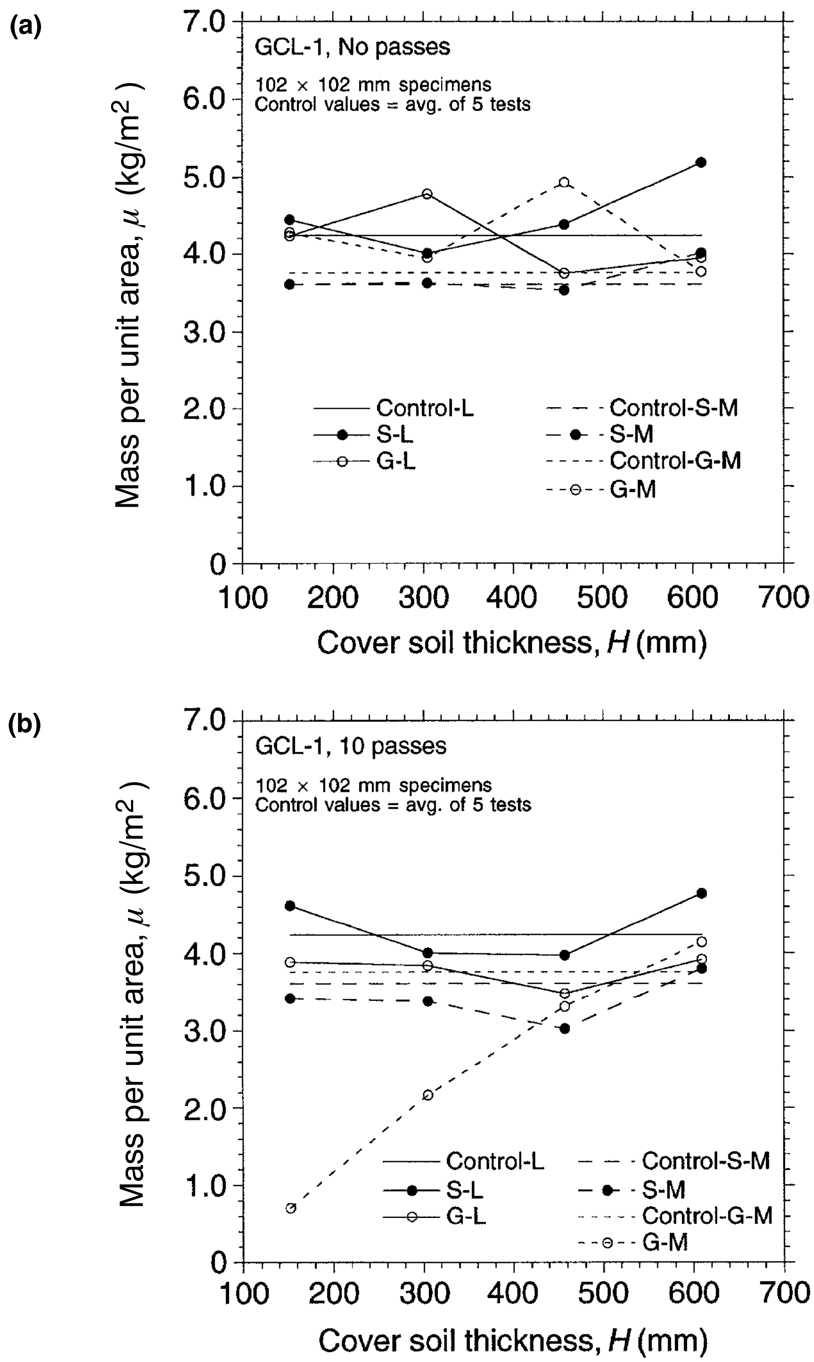


Figure 12. Bentonite mass per unit area values of GCL-1 for: (a) no passes; (b) 10 passes after hydration.

overburden stress). No significant difference in *w* was measured for specimens subjected to zero passes and 10 passes after hydration. Water contents for GCL-2 do not exceed 128%, whereas values as high as 248% were measured for GCL-1 under similar conditions.

4.2.3 *Mass Per Unit Area*

Values of μ for the 102 mm × 127 mm GCL-1 specimens are shown in Figure 12. With no passes after hydration (Figure 12a), field specimen values are in relatively close agreement with those for the control specimens. No significant variation was found with cover soil type, cover soil thickness, or bulldozer type.

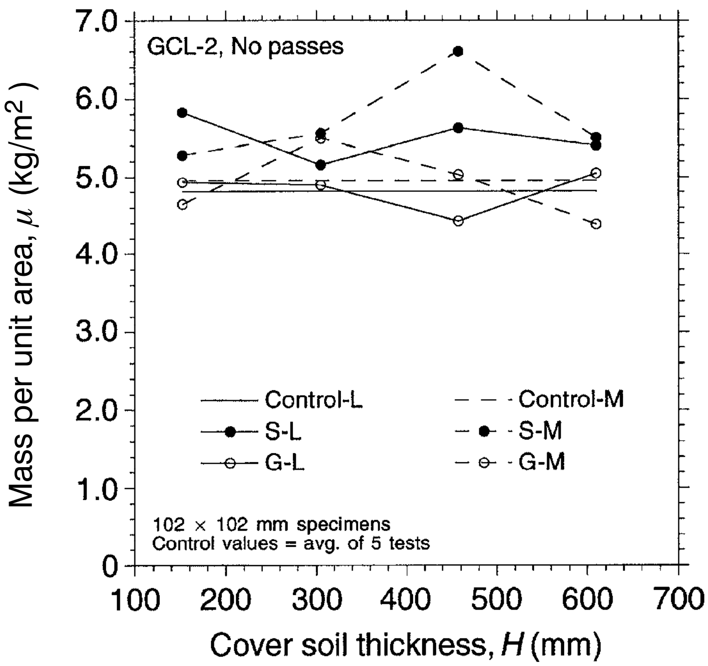
Figure 12b shows μ values for GCL-1 with 10 passes after hydration. Values for S-L, G-L, and S-M reveal no clear trends, whereas values for G-M decrease significantly with decreasing cover soil thickness. Upon exhumation of the G-M specimens, severe bentonite migration was observed for H = 152 mm. In this case, bentonite extruded vertically through the upper geotextile into the gravel layer, with the upper geotextile remaining intact. At some locations, the geotextiles of GCL-1 were in contact and, once the gravel particles were carefully picked away, the underlying subgrade could be seen through the geotextiles. G-M specimens of GCL-1 showed progressively less vertical bentonite migration for thicker cover soil layers. Compared to the control specimens, the percent reduction in μ for the G-M specimens is 81, 42, 12, and -10% for H = 152, 305, 457, and 610 mm, respectively. Specimens of GCL-1, when covered with clean angular gravel and subjected to 10 passes of the medium-weight bulldozer after hydration, failed for H = 152 mm and 305 mm. Values of μ are not significantly reduced for H = 457 mm and 610 mm.

Corresponding plots of μ for field and control specimens of GCL-2 are shown in Figure 13. GCL-2 shows essentially no loss of bentonite for all conditions. On the contrary, values of μ for the field specimens are generally larger than those for the control specimens. This presumably resulted from the difficulty of scraping the cover soil particles out of the woven geotextiles (with protruding needle-punched fibers) prior to drying the specimens.

4.2.4 *Local Mass Per Unit Area*

Values of $(\mu_{max} - \mu_{min}) / (\mu_{avg})$ for GCL-1 specimens are presented in Figure 14, where μ_{max}, μ_{min}, and μ_{avg} are the maximum, minimum, and average values of six measurements of local mass per unit area for each specimen. The values give an indication of the relative variability of GCL mass per unit area. Interestingly, GCL-1 field specimens, which received no passes after hydration, show lower variability of local mass per unit area values than the corresponding control specimens. For 10 passes, local mass per unit area variability for the G-M specimens increases significantly with decreasing *H*. Values of $(\mu_{max} - \mu_{min}) / (\mu_{avg})$ approach 2.0 for H = 152 mm, suggesting that bentonite was nearly absent from the thinnest locations of these specimens. This is consistent with field observations. Corresponding plots of $(\mu_{max} - \mu_{min}) / (\mu_{avg})$ for GCL-2 (Figure 15) indicate that bentonite migration was insignificant for each field installation condition, which is also consistent with field observations.

(a)



(b)

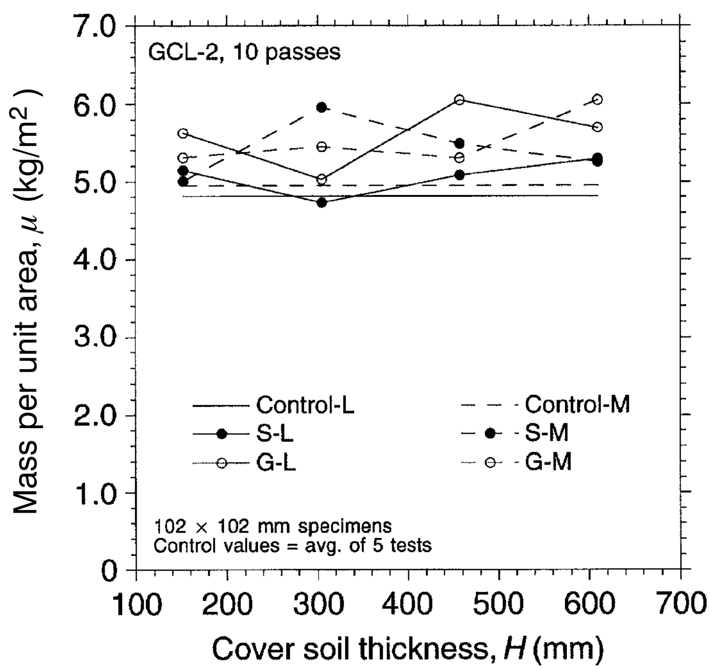


Figure 13. Bentonite mass per unit area values of GCL-2 for: (a) no passes; (b) 10 passes after hydration.

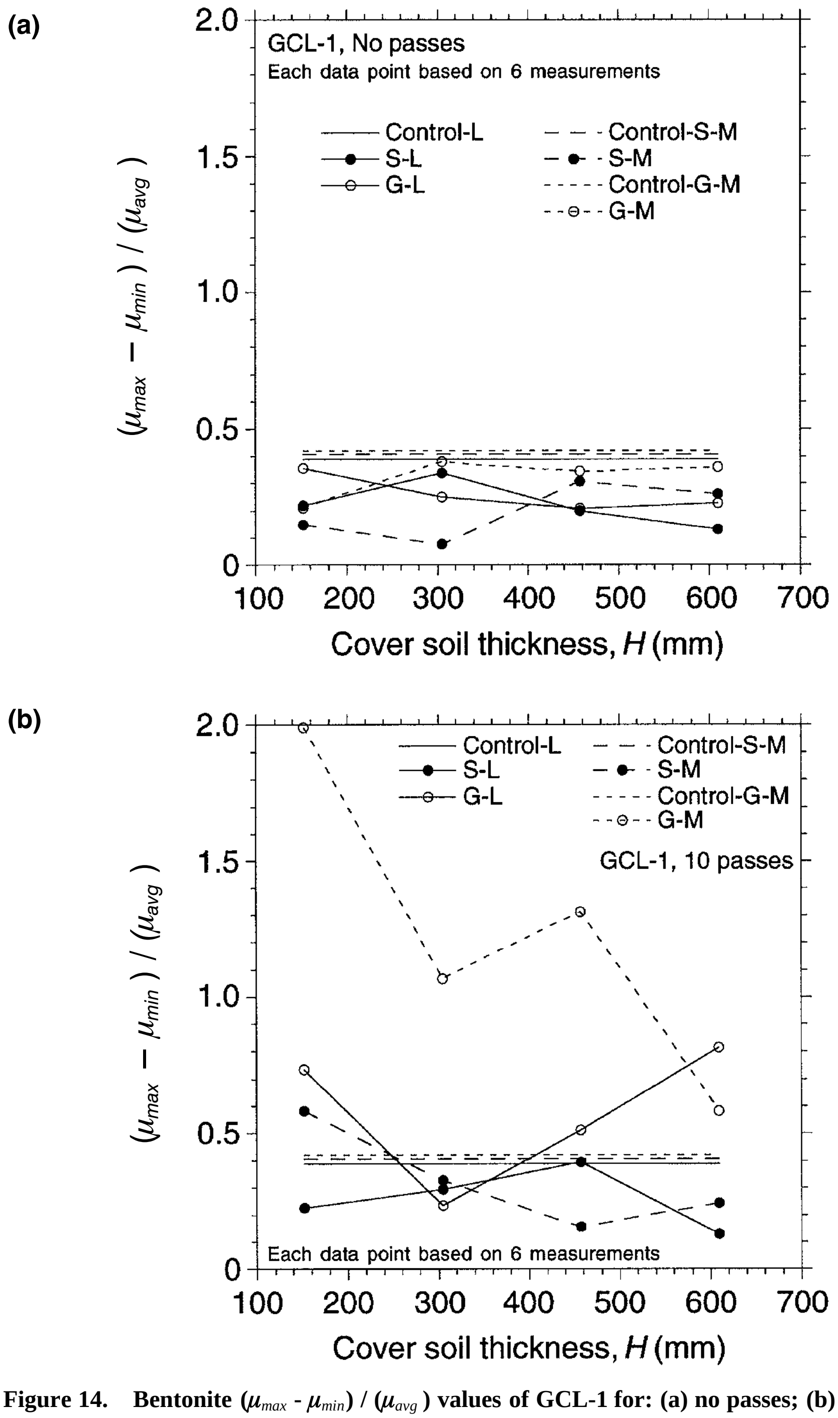


Figure 14. Bentonite (μ_{max} - μ_{min}) / (μ_{avg}) values of GCL-1 for: (a) no passes; (b) 10 passes after hydration.

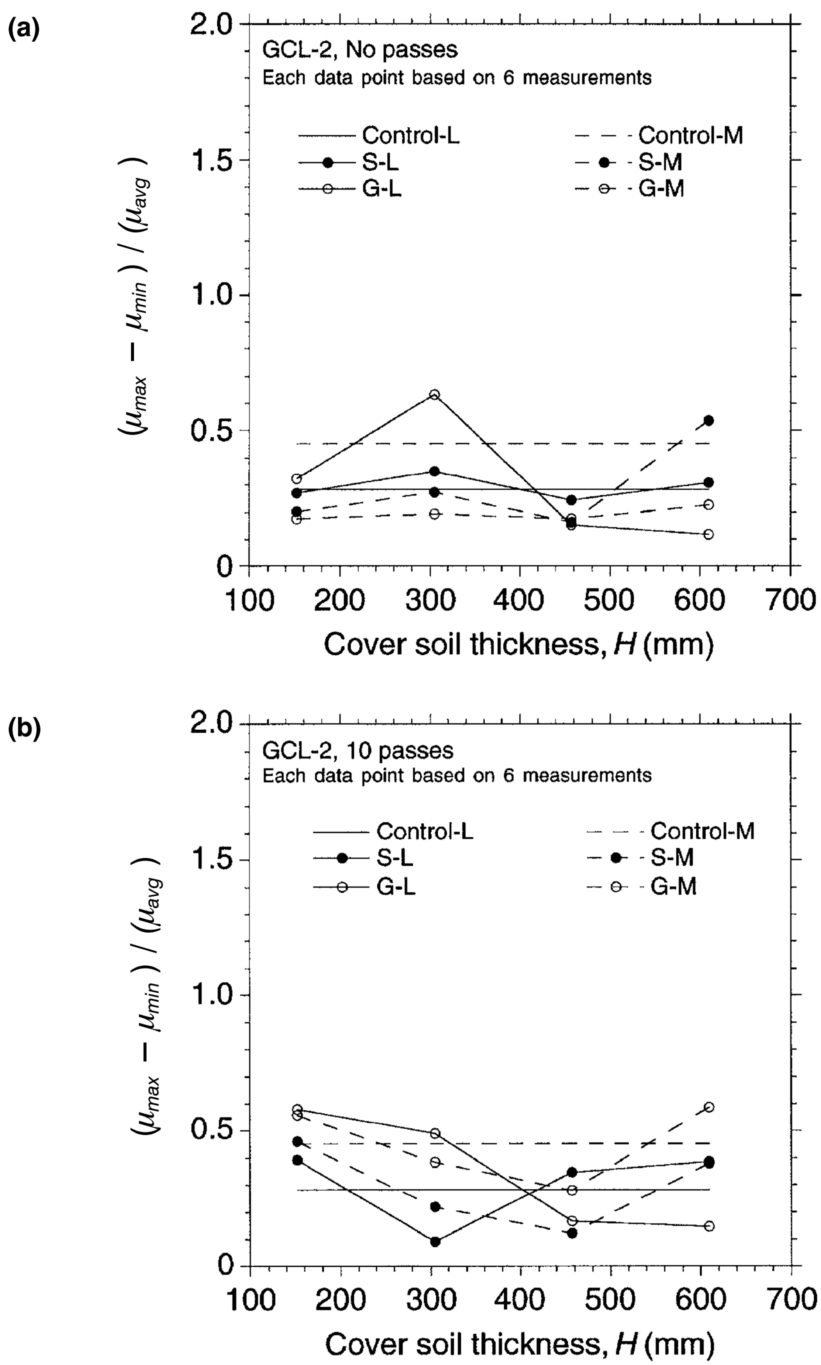


Figure 15. Bentonite (μ_{max} - μ_{min}) / (μ_{avg}) values of GCL-2 for: (a) no passes; (b) 10 passes after hydration.

4.2.5 *Thickness*

The average of six thickness measurements, t_{avg} , for each GCL-1 field specimen is shown in Figure 16a. Values of t_{avg} for no passes after hydration range from 4.4 to 9.5 mm and, similar to the trend of w in Figure 11a, generally increase with decreasing H. Values of t_{avg} for 10 passes after hydration are typically smaller, ranging from 2.6 to 8.5 mm. Consistent with the reduction of μ shown in Figure 12b, t_{avg} for the G-M specimens decreases significantly with decreasing H, reaching a value of 2.6 mm at H = 152 mm. Values of t_{avg} for GCL-2 (Figure 16b) are more consistent than those for GCL-1, ranging from 5.5 to 8.2 mm. In addition, t_{avg} is essentially independent of H and the number of passes after hydration. Values of t_{avg} for S-M and G-M are generally higher due to the higher water contents of these specimens (Figure 11b).

Figure 17 presents $(t_{max} - t_{min}) / t_{avg}$ for GCL-1 and GCL-2, where t_{max} and t_{min} are the maximum and minimum values of six thickness measurements for each field specimen. The GCL-1 thickness shows more variability for 10 passes after hydration, especially for the gravel-covered specimens. Values of $(t_{max} - t_{min}) / t_{avg}$ for the G-M specimen increase sharply with decreasing H, reaching nearly 2.3 for H = 152 mm. This suggests that, for H = 152 mm, the G-M specimen was locally very thin, which is consistent with field observations. Variability of individual thickness measurements is less for GCL-2. Values of $(t_{max} - t_{min}) / t_{avg}$ for 10 passes after hydration are generally larger, with a maximum of 0.8 for G-M at H = 152 mm.

4.2.6 *Hydraulic Conductivity and Index Fluid Flux*

Table 1 presents values of initial thickness, final thickness, hydraulic conductivity, k, and index fluid flux, v, for four GCL specimens that received 10 passes of the medium-weight bulldozer after hydration (H = 330 mm). Each value is less than the corresponding manufacturer's certified properties for k (5×10^{-11} m/s) and v (1×10^{-8} $m^3/m^2/s$). The G-M GCL-1 specimen, which experienced the most damage, yields the highest values of k and v. Entrainment of gravel fragments in the bentonite and spatial variability of bentonite mass per unit area may have produced higher flow rates locally within this specimen.

5 DISCUSSION

The primary objective for installation of GCLs is to place them without compromising their design properties (physical, mechanical, and hydraulic) or their ability to maintain design function as a barrier layer. The information presented in the current paper is relevant to GCLs placed against natural soils during construction and is, thus, complementary to the recommendations of ASTM D 6102. The current study may also serve as a guide for future related investigations, providing information on procedures specific to GCLs that are not addressed in ASTM D 5818.

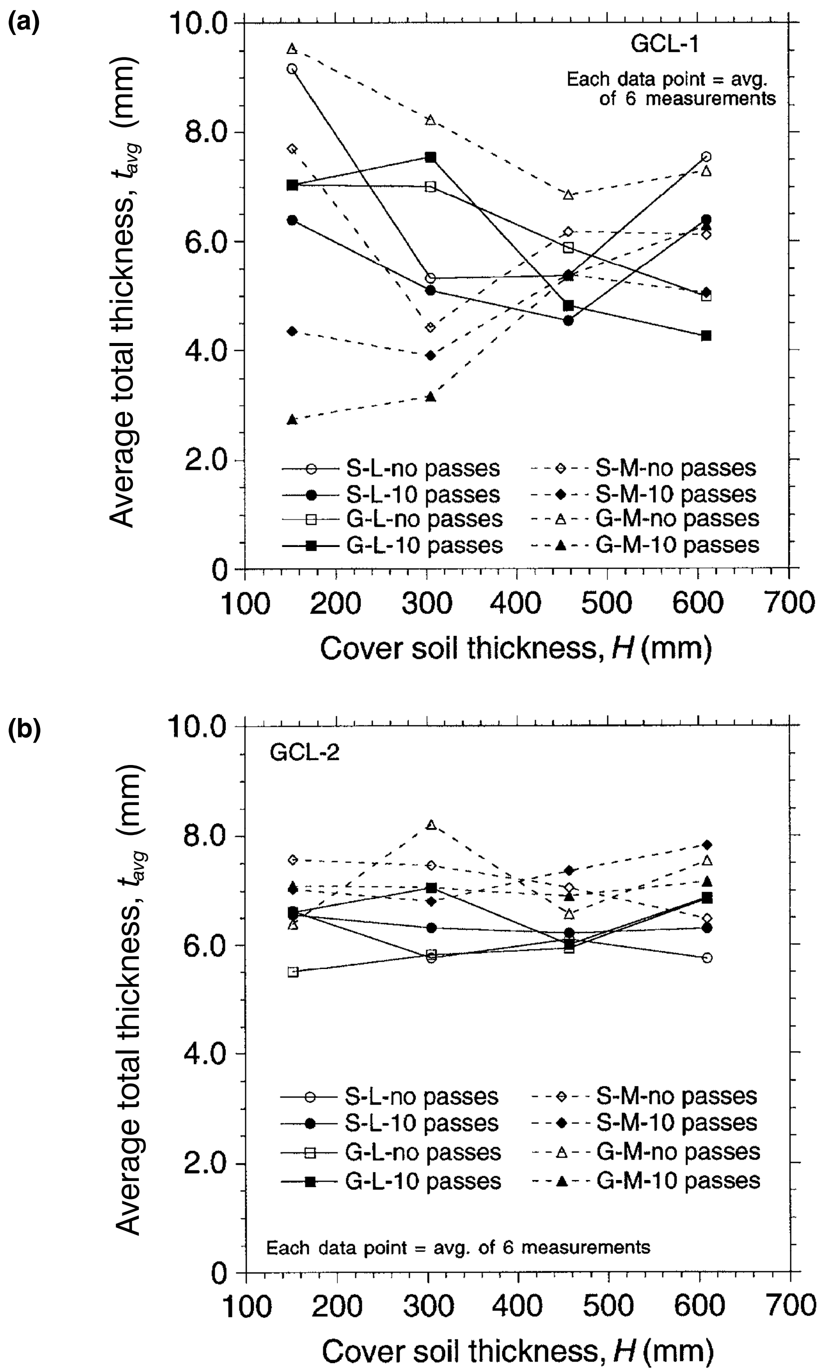


Figure 16. Average total thickness values for: (a) GCL-1; (b) GCL-2.

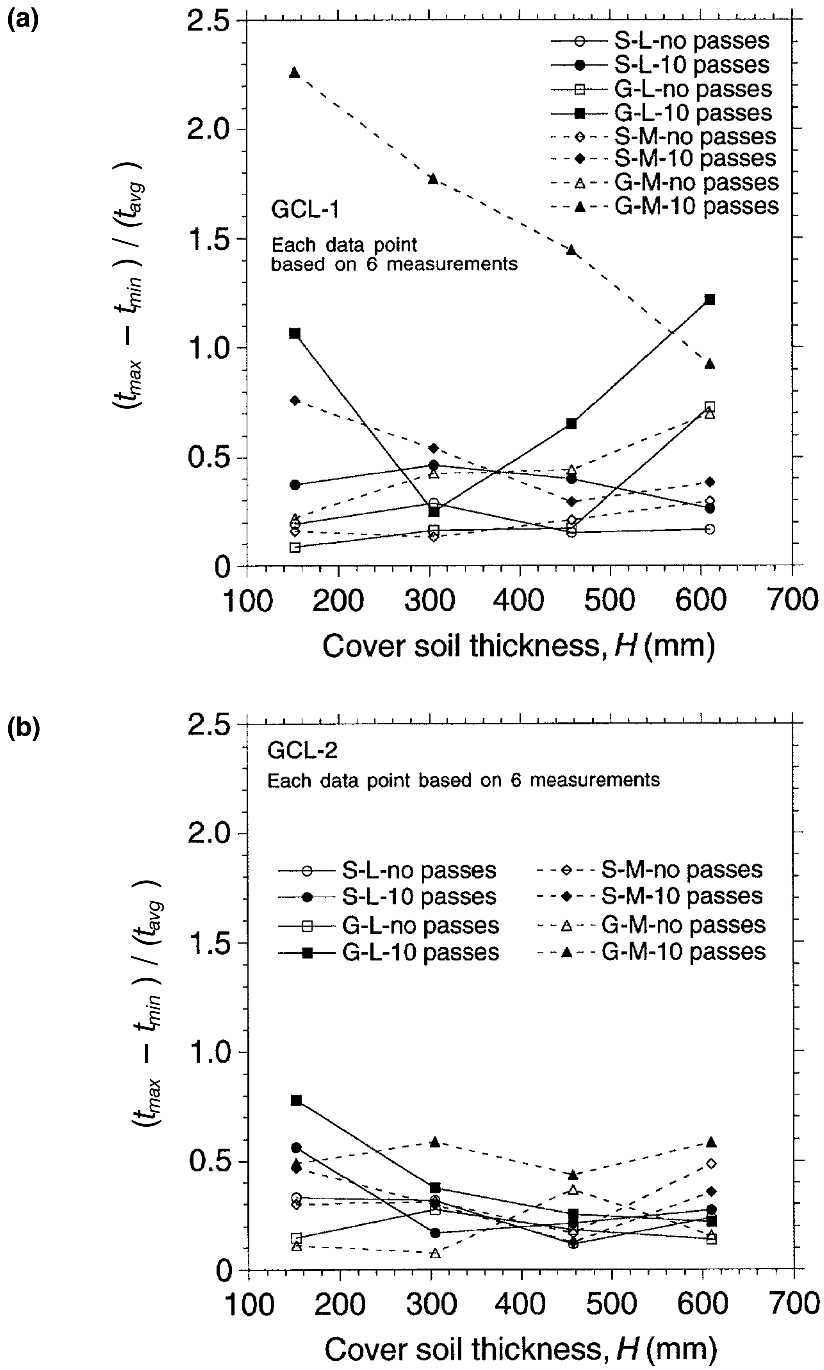


Figure 17. $(t_{max} - t_{min}) / t_{avg}$ **values for: (a) GCL-1; (b) GCL-2.**

Table 1. Hydraulic conductivity test results for four GCL specimens.

Specimen	Initial thickness (mm)	Final thickness (mm)	Hydraulic conductivity, *k* (m/s)	Fluid flux, *v* ($m^3/m^2/s$)
GCL-1 S-M, 10 passes	6.2	5.8	1.9×10^{-11}	5.4×10^{-9}
GCL-1 G-M, 10 passes	10.4	8.9	3.6×10^{-11}	6.7×10^{-9}
GCL-2 S-M, 10 passes	9.0	8.4	2.3×10^{-11}	4.7×10^{-9}
GCL-2 G-M, 10 passes	11.0	9.9	1.8×10^{-11}	3.2×10^{-9}

The gravel cover soil in the current study represented a more severe installation condition, with respect to particle size gradation and angularity, than that recommended by ASTM D 6102 and the manufacturer. Preconstruction test pads would normally be recommended for this soil to determine the necessary cover thickness. Considering that, for $H = 305$ mm, only one failure (bentonite migration) occurred for the gravel cover soil (GCL-1, G-M, $H = 305$ mm, and 10 passes after hydration) and that no failures were observed for the sand cover soil, the recommendations of ASTM D 6102 appear reasonable. Additional field studies using well-graded cover soils and cover soils with rounded particles would be helpful for further refining the ASTM D 6102 guidelines.

The hydraulic conductivity tests may not have characterized the true hydraulic performance of the GCL field specimens because of differences in specimen boundary conditions in the field and laboratory (i.e. soil versus rigid porous disks). Re-migration of bentonite from thick to thin locations may have occurred in the laboratory permeameters and consequently changed the measured hydraulic conductivity and index fluid flux values. Due to the soft consistency of hydrated bentonite, laboratory hydraulic conductivity tests are probably incapable of truly characterizing field hydraulic performance for GCL installation damage studies involving coarse soils. Even if cover soil particles are left undisturbed on top of a GCL specimen, different stress concentrations will result and the bentonite may undergo additional migration when the effective confining stress is applied in the laboratory. An in situ hydraulic conductivity test (e.g. sealed double-ring infiltration test) conducted on an undisturbed portion of the installed GCL would probably provide a better indication of hydraulic performance.

Bentonite mass per unit area values proved to be the most sensitive indicator of installation damage for the current study in which the GCLs were well hydrated. This may not be the case, however, for installations in which the bentonite remains relatively dry. Bentonite migration occurs in response to normal stress concentrations and is fundamentally related to the initial water content and thickness of the bentonite, presence and type of reinforcement, type of carrier geosynthetics, rate of loading, and the magnitude and gradient of normal stress on the surface of the GCL. Consistent with the results of bearing capacity index tests (Fox et al. 1996), the needle-punched GCL showed less bentonite migration in the field than the adhesive-bonded GCL. The needle-punched reinforcement prevented bentonite migration through the top geotextile because it provided additional confinement that reduced the water content and increased the strength of the bentonite. Under the same hydration conditions, bentonite in the adhesive-bonded GCL was sufficiently soft to squeeze through the upper geotextile for the most severe case (G-M, H = 305 mm, 10 passes after hydration). Bentonite loss for GCL-1 was insignificant for thicker layers of gravel cover (H = 457 and 610 mm) due to the higher overburden stress and the reduction in applied stress due to load distribution through the cover soil. Interestingly, the S-M plot for GCL-1 showed no significant bentonite loss for all H values, indicating that cover soil particle size (and probably particle size distribution) has an important effect on the potential for bentonite migration under equipment loading conditions. Sand caused less bentonite migration for GCL-1 than gravel because the finer particles reduced local stress concentrations.

Compared to similar investigations for other geosynthetic materials (e.g. geotextiles, geogrids, and geomembranes), GCL installation damage studies are unique because of the sensitivity of these products to hydration and overburden stress conditions and the need to quantify bentonite migration in the exhumed specimens. Cover soils must be carefully removed, preferably by hand, so as to minimize disturbance to the soft bentonite in the underlying GCL. Methods used to remove cover soils for other geosynthetic products, such as water jetting (ASTM D 5818) and mechanized equipment, may not be appropriate for GCLs. Although local water contents could not be measured using the miniature sampling tubes (due to the heating involved), this procedure proved highly effective for the measurement of mass per unit area distribution. As illustrated by the current study, grab tensile and grab peel strengths of hydrated GCL specimens may not be comparable to those of control specimens tested in the as-manufactured condition. Although control values were corrected for hydration, these correction factors must be viewed as approximate because field water contents were not replicated in the subsequent grab tests. One possible method to avoid this problem for adhesive-bonded GCLs would be to peel apart both the field and control specimens and then test the geotextiles individually. Wide-width testing (as per ASTM D 4595) has been used for many studies of geosynthetic installation damage and, had it been available, would have been preferred for the current study.

A number of additional variables not investigated in the current study may affect potential installation damage for GCLs, including type and preparation of subgrade, other GCL product types (e.g. geomembrane-supported products and double, nonwoven products), GCL hydration condition, cover soil gradation and particle angularity, type of construction vehicle (e.g. rubber tire versus tracked vehicles and heavy vehicles), and trafficking procedure (e.g. turning, braking, and number of passes after hydration). Braking and turning of vehicles and construction loading from trucks have been identified as critical installation conditions for damage studies of geomembranes (Wong and Wijewickreme 1993; Richardson 1996; Guglielmetti et al. 1997). The effects of long-term loading, such as that due to waste placement, may need to be addressed in future studies to better understand related damage effects. However, installation stress may be of greater significance than long-term stress due to bentonite consolidation and associated strength gain. The current study provided no information regarding possible installation damage for GCLs placed adjacent to other geosynthetic materials, such as geomembranes with wrinkles (Stark 1998) and drainage geocomposites. Nor has it addressed the possible benefits (or disadvantages, see Heyer 1995) from placing an additional protection geotextile between a GCL and a coarse cover soil. Thus, depending on conditions, the potential clearly exists for more or less GCL damage during installation. The information presented in the current paper should not be used in place of product-specific and site-specific installation damage studies performed, when necessary, according to ASTM D 5818 and ASTM D 6102.

Finally, the significant scatter of results in the current study points toward a need for additional field tests in which statistically significant numbers of data points can be collected. This could ultimately lead to the development of guidelines that can be used at the design stage to account for GCL damage during installation, as is now routinely done for reinforcement geosynthetics. A useful near-term goal would be the development of GCL required survivability tables, similar to those proposed by Christopher and Holtz (1984) and Allen (1991), for geosynthetics in separation and reinforcement applications. Likewise, the difficulty, cost, and time required to perform controlled field studies illustrates the need for a laboratory test that would allow one to estimate GCL installation damage for site-specific and project-specific materials and conditions.

6 CONCLUSIONS

The following conclusions were reached as a result of the current study of installation damage for an adhesive-bonded, and a needle-punched, geotextile-supported geosynthetic clay liner (GCL):

1. Damage to geosynthetic components was measured using grab tension tests, grab peel tests, and direct shear tests. Geosynthetic damage for both GCL products was generally minor for cover soil depths, *H*, equal to 305 mm or greater. Significant levels of geosynthetic damage were measured for lesser cover depths in some cases.
2. Bentonite migration was measured in terms of water content, mass per unit area, and GCL thickness. Reductions in local mass per unit area of bentonite were insignificant for nearly all specimens; the only exception was the adhesive-bonded GCL covered with angular gravel and subjected to 10 passes of the medium-weight bulldozer after hydration. In this case, the GCL failed for $H = 305$ mm. Under the most severe testing conditions, bentonite migration was significantly less for the needle-punched GCL than for the adhesive-bonded GCL because the needling provided additional confinement that reduced the water content and increased the strength of the bentonite.
3. Values of hydraulic conductivity, *k*, and index fluid flux, *v*, measured from four GCL specimens ($H = 305$ mm, medium-weight bulldozer, and 10 passes after hydration) passed the manufacturer's specification for hydraulic performance ($k = 5 \times 10^{-11}$ m/s and $v = 1 \times 10^{-8}$ m^3/m^2/s). This suggests that a GCL may constitute an effective hydraulic barrier after significant bentonite migration has occurred. More research using in situ hydraulic conductivity tests is required to confirm this hypothesis.
4. Installation damage generally increased with increasing cover soil particle size, decreasing cover soil thickness, increasing bulldozer weight, increasing bentonite water content, and trafficking after hydration (10 bulldozer passes). In the current study, measured levels of installation damage were probably relatively high due to the uniformity of particle sizes and the angularity of particles for both cover soils.
5. No failures were observed for installation conditions that met the guidelines of ASTM D 6102 and the manufacturer.

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NOTATIONS

Basic SI units are given in parentheses.

F_p	=	grab peel strength (N)
F_t	=	grab tensile strength (N)
H	=	cover soil thickness (m)
k	=	hydraulic conductivity (m/s)
t_{avg}	=	GCL thickness (average of six local measurements) (m)
t_{max}	=	GCL thickness (maximum of six local measurements) (m)
t_{min}	=	GCL thickness (minimum of six local measurements) (m)
v	=	index fluid flux ($m^3/m^2/s$)
w	=	bentonite water content (dimensionless)
μ	=	bentonite mass per unit area (102 mm × 102 mm specimen) (kg/m^2)
μ_{avg}	=	bentonite mass per unit area (average of six local measurements) (kg/m^2)
μ_{max}	=	bentonite mass per unit area (maximum of six local measurements) (kg/m^2)
μ_{min}	=	bentonite mass per unit area (minimum of six local measurements) (kg/m^2)
σ_n	=	normal stress (N/m^2)
τ_p	=	peak internal shear strength (N/m^2)