Field identification and mitigation of geosynthetic clay liner seam separation in a tailings impoundment composite liner system

P.E. Kowalewski, PE, K.S. Sessions, PE, J.W. Knudsen, PE, A.K. Butler, PE
Tierra Group International, Ltd., Elko, Nevada, USA

A. Jung
CETCO, Evergreen, Colorado, USA

ABSTRACT: The use of geosynthetic clay liners (GCLs) as a component of composite liner systems in landfills, ponds, heap leach facilities, and tailings impoundments has increased significantly over the past 5 to 10 years. Field observations (Thiel and Richardson, 2005 and Koerner and Koerner, 2005) and laboratory testing (Thiel et al., 2006) have indicated that under specific unconfined and exposed conditions, seam separation may potentially occur due to several different mechanisms, including tension necking or shrinkage due to repeated wetting and drying cycles. During the construction of a raise to an existing tailings storage facility in the western United States, it was suspected that the GCL secondary liner, installed during construction of the previous stage, experienced seam separation in a limited area. A field investigation was conducted to identify affected areas, a root cause analysis was completed, and measures were developed and implemented to repair the identified affected seams. New installation procedures and both destructive and non-destructive testing protocols were developed to prevent future occurrences.

1 PROJECT INTRODUCTION

During the construction of a raise to an existing tailings storage facility (TSF) (lined with a composite geosynthetic liner system consisting of a geosynthetic clay liner (GCL) secondary liner overlain by a textured 1.5-mm (60-mil) linear low density polyethylene (LLDPE) primary liner, gaps were identified between adjacent panels of GCL deployed during the previous construction stage. The previous construction stage was completed in 2007; the composite liner system was left in an unconfined (unloaded) exposed condition for approximately 6 years. The GCL was "heat tacked" and the standard overlaps increased over the manufacturer's minimum recommended overlap to mitigate potential GCL movement from tension necking or shrinkage due to repeated wetting and drying cycles.

2 PROJECT BACKGROUND

2.1 *Project Location and Description*

The project site is located in the Great Basin Region of the western United States at an elevation of approximately 1765 meters (5800 ft). The TSF is a fully lined (with geosynthetics) facility, consisting of lined rockfill embankments on three sides of the facility and contained by natural topography that slopes into the impoundment area on the remaining side. The TSF has been raised multiple times using a modified downstream construction method on the embankments and industry-standard slope lining methods for the impoundment area. The facility has been in continuous operation for over 20 years and has not experienced any significant operational or environmental issues during its operation.

2.2 *Site Climate*

The site's climate is characterized as semi-arid, with approximately 276 mm (11 in) of average annual precipitation compared to approximately 1400 mm (55.1 in) of average annual evaporation. Approximately half of the site's precipitation occurs as snowfall during winter months and rainfall events during warmer months are often in the form of short duration, high intensity thunderstorms. Temperature at the site ranges from lows of approximately -29°C (-20°F) in winter to highs of approximately 32°C (90°F) during the summer. The site experiences significant surface water flows during the annual freshet event each spring, which often occurs over a very short duration (several weeks).

3 FIELD IDENTIFICATION OF GCL SEAM SEPARATION

During construction of the TSF raise, the leading edge of the composite liner system from the previous stage of construction was exposed and removed from the anchor trench to allow for the composite liner system of the new construction stage to be "tied in" to the existing system. When the leading edge of the composite liner system was exposed and removed from the anchor trench, the Liner Installer and Resident Engineer observed that there were "gaps" between the adjacent panels of the GCL (secondary liner) and the prepared low permeability soil foundation was exposed. The Resident Engineer and Liner Installer walked the seam down the slope and, using both tactile (applying pressure with toe or heel of boot to primary liner) and auditory (tapping the primary liner with the handle of a shovel or rake) methods, they were able to identify several areas along the seam where they suspected the GCL panels may have separated. In all of these locations, the primary LLDPE liner was intact and showed no signs of distress or damage. The primary liner was then cut to expose the underlying secondary liner. As can be seen in Photo 1, a section of the GCL liner had separated, resulting in a loss of continuity of the secondary liner system.

Following the identification of the initial GCL panel separation, the Liner Installer, Resident Engineer, and Design Engineer consulted with the Owner to identify a plan for identifying the potential extent of the seam separation in the field and develop a mitigation plan. The initial investigation plan consisted of the following:

- Review the GCL and Liner Panel Deployment Plans from the previous stage of construction;
- Review the Liner Installer's Quality Control (QC) data from the previous stage of construction;
- Review the Resident Engineer's Daily Reports from the previous stage of construction;
- Extend the field investigation area of the GCL seams in both directions away from the initially identified seam. Use both the tactile and auditory methods on the primary liner to try and identify potential areas where the GCL may have separated. Mark the primary liner using spray paint for follow-up investigation (cutting of the primary liner to expose the underlying GCL);
- Develop a field repair procedure to repair the seam separation in the GCL and repair the overlying LLDPE primary liner;
- Review the Design Report for the facility to determine if any unique features exist in the area of concern;
- Conduct a literature review on seam separation to aid in the root cause determination; and
- Consult with the GCL manufacturer's technical staff to discuss the observed conditions in the field. Have the manufacturer's technical staff visit the site and observe the conditions firsthand to aid in the identification of the root cause and aid in the formulation of a mitigation plan.

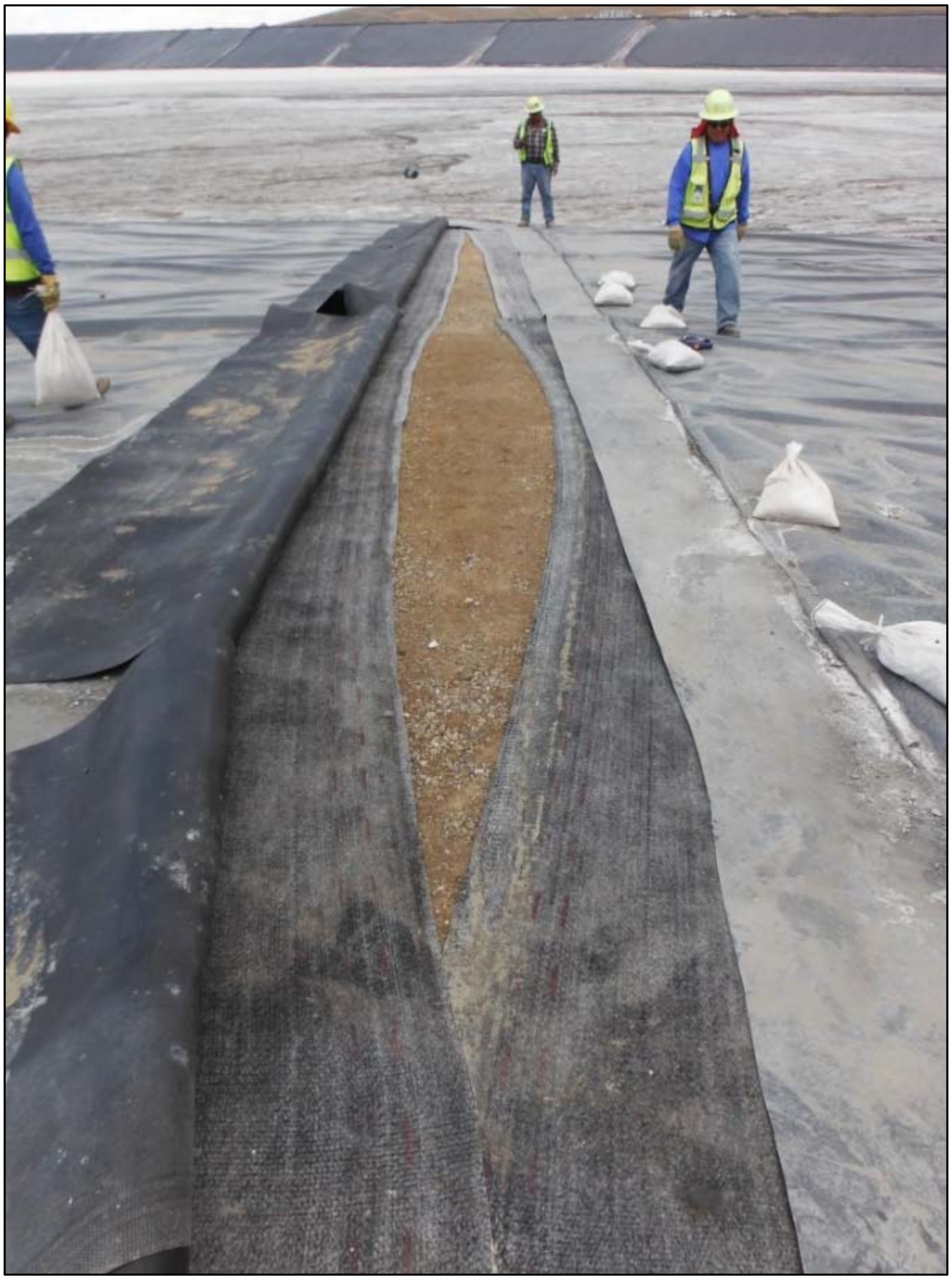

Photo 1. Example of Observed GCL Panel Separation

3.1 *Field investigation*

The Resident Engineer and Liner Installer walked the primary LLDPE liner along the approximate alignments and locations of the underlying GCL panel seams, as determined from the Panel Deployment Plans, to identify additional areas where seam separation may have occurred. Over 50 areas of potential seam separation were identified using the tactile and auditory identification methods. A total of 49 seam separation areas were positively identified after cutting open the primary liner and exposing the underlying GCL. Each separation was numbered, measured, and photographed prior to repairs. Panel separation was surveyed either prior to patching the primary LLDPE liner or after LLDPE patching by surveying marls on the liner showing the extents of the GCL separation (made by Resident Engineer at the time of patching). The seam separation widths (measured at their maximum aperture) ranged from approximately 9 cm (3.6 in) to 101 cm (3.3 ft) and ranged in length from 0.3 m (1 ft) to 22.9 m (75 ft).

The following observations were noted during the initial inspection of the separated GCL panels, which occurred in July 2013:

- The majority of the GCL panels inspected (43 of the 49) showed no wrinkles or folds near the separation or in the middle of the panels; however, six of the identified 49 separations did have some folds at the edge where the GCL had appeared to be folded back on itself (later concluded to be a result of installation or removal of the primary textured LLDPE liner over the GCL and not related to the dimensional change of the GCL);
- There was no tearing or other damage to the GCL;
- GCL was moist but not near saturation. Individual bentonite grains were evident at some of the edges of the GCL but was sufficiently dry that loose bentonite crystals could be shaken out of the GCL at the edges;
- There was no evidence of heat bonding (tacking) in the middle of the separations;
- Original installed width of the panels was approximately 4.4 m (14.5 ft). Some of the installed panels were as narrow as 3.2 m (10.5 ft);
- One of the observed separations was held together by a short stretch of heat-bonded seam with separation occurring on either side of the heat bond; and
- Subgrade below the GCL was moist but not saturated.

The observation that the seams did not appear to be separated where an adequate heat-bonded seam (tack) was present (Photo 2) and incorporated into the field repair method used on the identified separations.

3.2 *Field repair method*

The Owner, Liner Installer, Resident Engineer, and Design Engineer collaborated to develop a field repair method to use on the separated GCL panels. The TSF was actively receiving tailings at the time of the investigation; as a result, the liner system could not be fully removed and reinstalled, instead, an in-situ repair (patching) needed to be used. The following method was used to repair each of the identified separations:

- Expose the entire GCL panel separation (seam) area;
- Measure the length and maximum width of panel separation;
- Survey the GCL panel separation extents (if surveyor was available); if surveyor was not available at the time of the repair, survey the extent of the LLDPE patch on the primary liner to identify approximate extents of the GCL repair;
- Install seaming bentonite at the edges of the GCL panel separation;
- Place a GCL patch over the panel separation area, with at least 15 cm (6 in) of overlap onto the existing GCL in every direction;
- Continuously heat-bond seam (tack) all edges of the GCL patch to the existing GCL; and
- Repair the primary LLDPE liner and perform installation QC measures according to the Project Construction Documents.

The field repair method was implemented to minimize the amount of time the primary LLDPE liner was open, exposing the secondary GCL liner. Minimizing GCL exposure was a significant concern during the repair process due to the frequency of thunderstorms occurring at the site during the time of the repairs.

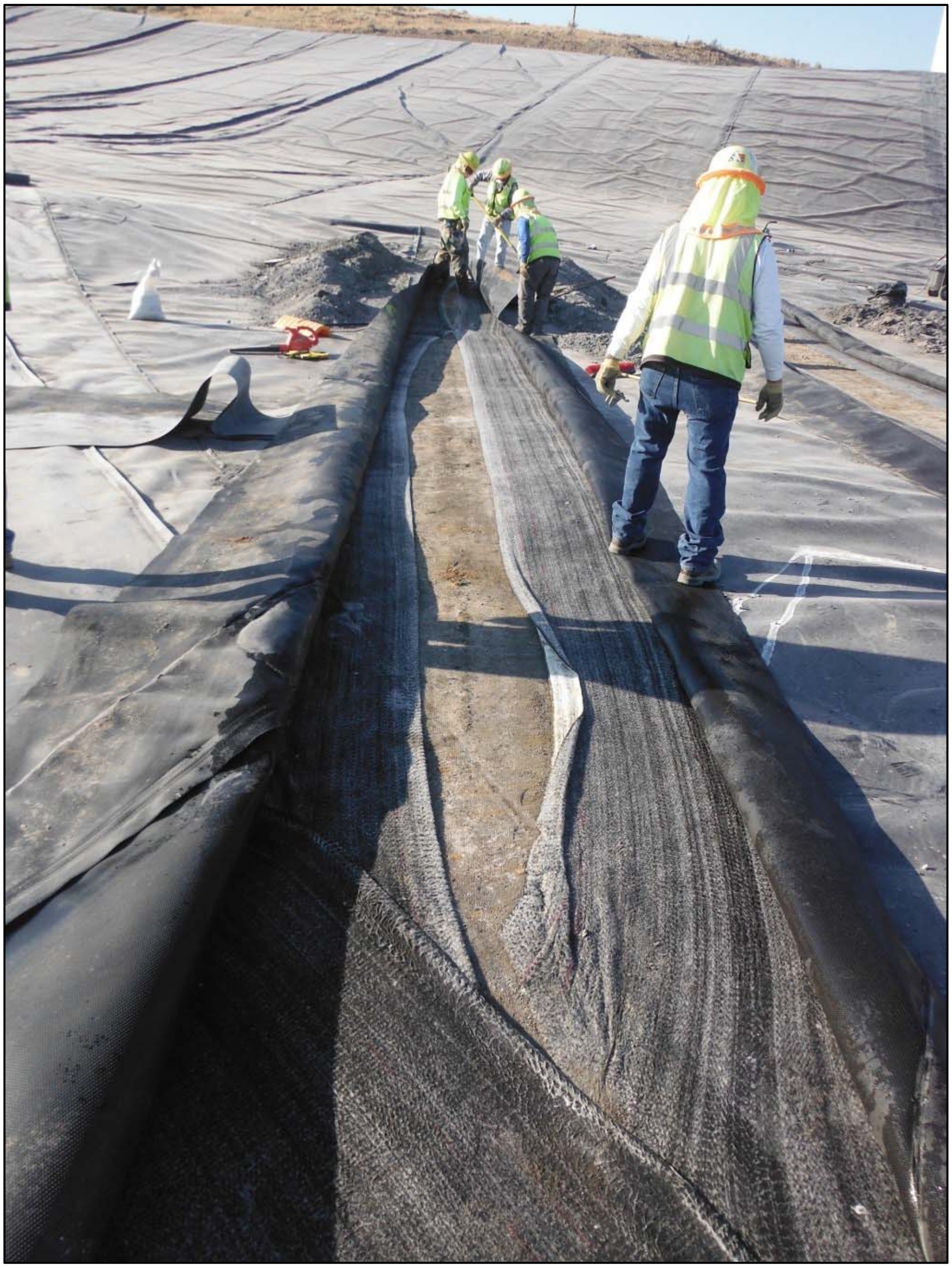

Photo 2. GCL Panel Separation (Note Lack of Separation at Heat Bond)

4 ROOT CAUSE ANALYSIS

Once the panel separations were identified, the primary concerns were to identify the extent of the panel separations, repair the separations to ensure continuity of the secondary GCL liner, and determine why the panel separations occurred to aid future geocomposite liner system design. The results of the field investigation, literature review, review of construction documents, review of design documents, and consultation with the GCL manufacturer were used to formulate a root cause, which in turn led to the development and adoption of mitigation measures to prevent future GCL seam separations.

4.1 *Literature review*

At the time the GCL seam separation was identified in the TSF, the GCL panel separation issue was not undocumented; the first reported cases of GCL separation were reported in 2005 (Koerner and Koerner, 2005). In all reported cases, the geomembrane was left exposed (no cover soil placed over the liner) and no steps were taken to mechanically seam adjacent GCL panels. Subsequent laboratory and field investigations have been undertaken to better understand the issue. Research points to two main causes of GCL seam separation: repeated cycles of wetting and drying and tension "necking" leading to the narrowing of the GCL panel.

In response to these findings, laboratory testing (Thiel et al, 2006) was performed to further evaluate the effects of cyclic wetting and drying on the dimensional stability of GCLs. Five different geotextile-encased GCL products were tested, each made with different types of cap and carrier geotextiles, various water contents (of the bentonite encased in the GCL), and various needlepunch densities. Laboratory testing procedures consisted of placing 36 cm x 61 cm [14 in x 24 in] GCL samples in aluminum pans; clamping the ends (to simulate field conditions on a slope where there is anchorage or ballast at both ends); and subjecting the samples to 40 cycles of hydration and oven-drying at 60°C [140°F] (to simulate cooling and heating extremes expected under an unconfined, exposed geomembrane in the field). After each cycle, the sample width was measured and divided by the initial width to calculate shrinkage. The data show that all the geotextile-encased GCLs tested, regardless of geotextile type or manufacturer, exhibited significant shrinkage in unconfined conditions with repeated wetting and drying cycles. The final shrinkage after 40 cycles ranged from 12.8% to 23.0% (Athanassopoulos, 2013b). Applying these results to the 4.4-m (14.5-ft) wide GCL panels would equate to shrinkage on the order of 0.56 m (1.85 ft) to 1.01 m (3.32 ft), which is consistent with the observed magnitude of shrinkage observed at the TSF.

Based on the results of the laboratory testing, it was recognized that the potential for GCL shrinkage exists under unconfined conditions. A novel approach to address this issue was implemented at the Carlota Mine in Arizona (Thiel and Thiel, 2009). At Carlota, GCL seams were overlapped and heat-bonded with the application of a flame from a torch followed by the application of light pressure either by foot pressure or by dragging a sandbag over the heat-seamed area. The GCLs were then covered with the primary geomembrane for up to 60 days. In subsequent months, holes were cut into the primary liner to check on the GCL seams. There was no evidence of GCL shrinkage in any of the locations.

Rowe et al (2010) obtained samples of the GCL seams that had been heat bonded at Carlota and subjected them to 40 wetting and drying cycles in laboratory pan tests similar to those performed by Thiel et al (2006). Following the repeated wetting and drying cycles, the shrinkage was measured at the seams as well as in areas outside of the seams. The areas outside the seams showed shrinkage of a similar magnitude as that previously identified (Thiel et al, 2006) but noted that the seams all remained intact. The seam strength was then tested and determined to be as strong, or stronger, than the GCL material itself.

Based on the results of these findings, in cases where it is not possible to place cover soil over the liner system in a timely manner and the cover system will remain exposed for prolonged periods, heat bonding the seams of geotextile-encased GCLs was recommended (Thiel and Rowe, 2010).

Joshi et al (2011) prepared heat bonded seams with four different GCL products and measured the tensile strength of the seams. The seam strength varied depending upon the geotextile types (woven versus non-woven) used in the GCL but overall ranged from approximately 4.38 to 7.88 N/mm (25 to 45 lb/in) for non-woven/woven GCLs and 9.11 to 13.48 N/mm (52 to 77 lb/in). Similar testing was completed by TRI in 2013 to determine the tensile strength of heat-bonded seams on a non-woven/non-woven GCL made with either a torch or a hot air gun. The results showed high seam strengths ranging from 7.01 to 8.76 N/mm (40 to 50 lb/in].

Bostwick (2009) devised a test to measure the tensile forces generated as a fully hydrated GCL shrinks due to drying. In the study, a non-woven/non-woven GCL sample was placed in an aluminum plan, similar to the previous studies (starting with Thiel et al, 2006). Rigid aluminum side pieces were attached to the edges of the GCL and an aluminum bar was connected to the side pieces. The plate and bar configuration allowed the full shrinkage force to be transferred to the aluminum bar. Strain gages were placed on the aluminum bar and measured to determine the forces as the GCL shrunk. The maximum shrinkage force measured using this approach was 1.66 N/mm [9.5 lb/in], which is significantly less than the measured strength of the heat bonded seams (as per Joshi et al, 2011 and TRI, 2013).

4.2 *Review of liner installation records*

The Resident Engineer and Design Engineer reviewed all of the liner installation records for the area in question to determine if there were any issues encountered with regard to the material quality (for either the GCL or LLDPE), reviewed the Liner Installer's start-up records from each day (documentation of trial welds, etc.) to determine if any significant changes had occurred while deploying the liner in this area. The Liner Deployment Plans were reviewed to understand the orientation of the GCL panels with respect to the slope of the underlying foundation. No points of concern were identified that could be attributed to contributing to the observed seam separation issues with the GCL.

4.3 *Review of facility design reports*

The design report prepared for the previous stage of construction was reviewed to identify any issues that could contribute to the observed seam separation. Upon reviewing the design report, one item stood out: the area where the seam separation had been identified was roughly bounded on the north and south by two spring drains that had been installed to convey observed surface expressions of groundwater (springs) below the liner system. As mentioned above, the site experiences a significant amount of surface runoff each spring in response to the annual freshet. Around the site (particularly on the hillside to the east of the mine), numerous springs and seeps flow for short durations as shallow groundwater flows exit the hillside and report to surface drainages. The spring drains constructed beneath the facility capture these flows and convey them beneath the TSF in a pipe constructed in a gravel-filled/geotextile-wrapped trench. The fact that the seam separation was observed in the vicinity of the spring drains guided the Team to the observation that it was very likely the GCL had experienced multiple cycles of wetting and drying. At this site, each spring, there is a significant amount of water available in the subsurface (east side of the TSF only, the other three sides are rockfill embankments), then during the summer months it can get extremely hot (especially on the black primary liner). These conditions would appear to be very similar to those envisioned and tested by Thiel et al (2006).

4.4 *Consultation with GCL manufacturer*

The consultation with the GCL manufacturer proved to be very informative. The manufacturer was engaged to perform an independent literature review, conduct a site visit, and collaborate with the Design Engineer to develop a mitigation plan for the current and future stage construction activities. The following is a summary of the observations made by the GCL manufacturer's technical representative following the site visit:

- No evidence of heat bonding (heat tacking) was observed on the upper or lower panels of GCL in the areas where the GCL panels had separated;
- Exposed subgrade was moist approximately 1 cm (0.4 in) below the surface; and
- Bentonite, in some areas, was in crystal form but was coarse-grained, cracked, and dissimilar to the condition of the bentonite crystals during GCL production/manufacturing.

The GCL manufacturer initiated an independent research program in conjunction with the Geosynthetic Research Institute (GRI) to evaluate options for heat bonding the seams to achieve adequate strength and develop both destructive and non-destructive test methods for implementation during construction. This research has led to the development of three draft GRI Test Methods (GCL6 through 8, respectively), which are summarized below:

GRI Test Method GCL6: Field Seaming

Six methods are described for field seaming, including thermal fusion, adhesives, tape, and sewing. The standard recommends thermal fusion seaming (heat bonding), using either a hand-held hot air or propane torch device. For heat bonding methods, the specification recommends the following:

- Seaming should be performed on clean, dry GCL that has not been hydrated and is free of fugitive bentonite or other debris;
- Heat should be applied to melt but not burn the geotextiles of the GCL; and
- Normal pressure should be applied to the seam immediately after heat is applied (simple foot pressure is acceptable).

The specification concludes with recommendations regarding QC/QA procedures, such as documenting the ambient conditions during seaming, field seaming identification, trial seams, and destructive/non-destructive test documentation.

GRI Test Method GCL7: Destructive Testing

This specification addresses destructive testing of field seams, performed either in the laboratory or at the work site. Highlights of the destructive test recommendations include:

- Destructive testing to be performed on field seams or on trial (startup) seams and destructive test frequency should be determined on a case-by-case basis;
- If destructive tests are taken from field seams, the destructive test location should be patched with heat-bonded GCL with a minimum overlap of 0.3 m (1 ft) past all cut edges;
- Five specimens (cut perpendicular to the seam) should be tested in tensile shear to the point of failure and the average value should be reported;
- Failure modes can be seam failure or geotextile failure;
- Loss of bentonite/clay during the destructive test will not affect the test results as the geotextile seam strength is irrespective of bentonite; and
- Destructive test can be performed using a laboratory constant rate of extension (CRE) machine or a typical field tensiometer fitted with 2.5×10 cm (1×4 in) clamps.

The method also lists typical expected test values and required reporting such as precision, identification, and recordkeeping. The standard does not specify a destructive test frequency or minimum required seam strength. The Design Engineer recommended performing destructive tests only on trial welds, which should be performed at the beginning of each shift, after breaks, and per machine, per user. This will eliminate the need for repairs over destructive test locations and will provide a more consistent final product. Additional destructive tests will be required at the discretion of the Owner, Engineer, or Quality Assurance (QA) Provider during construction. The Design Engineer also recommended establishing a minimum required seam strength value equal to the maximum shrinkage force of 3.50 N/mm (20 lb/in), which is greater than the maximum observed shrinkage force of 1.66 N/mm (9.5 lb/in) reported by Bostwick (2009).

GRI Test Method GCL8: Non-Destructive Testing

GRI Test Method GCL8 asserts that non-destructive testing can be compared to destructive test results at a magnitude less than the ultimate strength. In this standard, the in-situ test is performed using a spiked plate, a 4.54-kg (10-lb) weight, and typical luggage scale to apply a horizontal force to the GCL seam. CETCO recommends a target horizontal load of 1.75 N/mm (10 lb/in) for a duration of 5 seconds and a test frequency of 1 per 45.7 m (150 ft). The test should be performed under dry conditions and with a target ambient temperature range of 4.4 to 37.8°C (40 to 100°F). Any separation, geotextile delamination, or rotation under loading should be observed and noted. In the event any of these occur, the test should be viewed as "failing" and the seam should be repaired and re-tested or a patch should be installed over the tested area.

The standard also lists recommended reporting requirements, such as load applied, length of load application, and photographs documenting equipment and field technique.

4.5 *Root Cause Determination*

Following the completion of the field investigation to determine the extents of the seam separation, literature review, construction document review, design report review, and consultation with the GCL manufacturer and leading researchers at GRI and TRI, the Team concluded that the separations in the field were likely caused by GCL shrinkage in response to repeated wetting and drying cycles induced by subsurface drainage in that specific area of the TSF and inadequate heat bonding of the seams. The Design Team had identified the possibility of seam separation during the design and had incorporated heat tacking of the seams into the deployment plan for the GCL. However, the specification did not require continuous heat seaming. The review of the GCL seam performance strongly indicated (and was reinforced by laboratory observations) that continuous heat bonding of the seams was required to prevent separation. Field evidence (condition of the bentonite) indicated that the bentonite had been hydrated and dried. The presence of moisture below the GCL (observed in July) also reinforced the hypothesis that moisture was being introduced to the GCL through the foundation. The temperature of the primary LLDPE liner elevates every summer during daylight hours, which provides a mechanism similar to the oven drying of the GCLs used in the laboratory experiments (Thiel et al, 2006).

5 MITIGATION MEASURES

The Team implemented the following mitigation measures to ensure that GCL seam separation does not occur:

- Adoption of the recommendations contained in GRI Draft Test Methods GCL6, GCL7, and GCL8. GCL will be overlapped and continuously heat-bonded using either a torch, hot air device, or similar apparatus. A Liner Installer worked in conjunction with GRI to evaluate the modification of a hot wedge welder to perform the continuous heat seaming of the GCL. The modifications allowed continuous welding of the GCL seam and provided seams with tensile strengths that consistently exceeded minimum required values; and
- Covering of the liner system (LLDPE and GCL) as soon as practicable. Scheduling of TSF staged construction should seek to minimize the window of unconfined exposure of the liner system, especially in areas where subsurface moisture (seeps, springs, etc.) may hydrate (and subsequently dry out) the underlying GCL.

6 CLOSING REMARKS

Heat bonding of GCL seams provides a bond that is significantly stronger than the shrinkage forces developed within the GCL material and mitigates the potential for shrinkage of the GCL during repeated cycles of wetting and drying in an unconfined (unloaded) condition. While heat bonding the GCL seams does require some additional effort, the authors' experience has shown that it does not significantly increase the overall time required for installation of the composite liner system.

During the preparation of this paper, as well as during the design of other facilities and subsequent raises to the TSF discussed in this paper, GCL manufacturers have asserted that their materials of construction or manufacturing methods minimize (or in some cases eliminate) the potential for GCL shrinkage. While not doubting their assertions, the authors strongly advise product-specific laboratory testing before determining the seaming method to be used. The authors are also aware of several field studies of GCLs (in progress) that are aiming to provide additional information regarding the shrinkage of GCLs and how to mitigate the seam separation issue. Based on the observed field performance and studies reviewed during this project, the authors strongly recommend heat seaming of all GCL seams when there is a potential for repeated wetting and drying of the GCL in an unconfined condition. In the event a Design Engineer is considering waiving this requirement (heat bonding of seams), the authors strongly recommend product-specific laboratory testing using a procedure similar to that originally presented in Thiel et al (2006) prior to approving this type of variance. The magnitude of shrinkage observed as a result of the repeated cycles of wetting and drying in the laboratory did line up well with those observed in the field and are believed to be representative of the potential shrinkage that can occur.

7 REFERENCES

Athanassopoulos, C., 2013a. *Technical Memorandum – Notes from July 29, 2013 Site Visit.* Internal Memorandum issued to Client. July 30, 2013.

Athanassopoulos, C., 2013b. *Technical Memorandum – Literature Review on GCL Panel Separation.* Internal Memorandum issued to Client. November 15, 2013.

Bostwick, L., 2009. *Laboratory Study of Geosynthetic Clay Liner Shrinkage When Subjected to Wet/Dry Cycles.* Master's Thesis. Queen's University, Kingston, Ontario, Canada. May 2009.

Joshi, P., Brachman, R.W.I., and R.K. Rowe, 2011. *Heat-tacked overlap strength of four GCLs.* 2011 Pan-Am CGS Geotechnical Conference. Toronto, Ontario, Canada. October 2011.

Koerner, R.M. and G.R. Koerner, 2005. *GRI White Paper #5 – In-Situ Separation of GCL Panels Beneath Exposed Geomembranes*. Geosynthetics Institute, Folson, PA. 15 April 2005.

Rowe, R.K., L. Bostwick, and R. Thiel, 2010. *Shrinkage Characteristics of Heat-Tacked GCL Seams.* Geotextiles and Geomembranes 28 (2010).

Thiel, R., Giroud, J.P., Erickson, R., Criley, K. and Bryk, J., 2006. *Laboratory measurements of GCL shrinkage under cyclic changes in temperature and hydration conditions,* 8th International Conference on Geosynthetics, Yokohama, Japan 1: 21-44.

Thiel, R. and G.N. Richardson, 2005. *Concern for GCL Shrinkage When Installed on Slopes";* GRI-18 – Geosynthetics Research and Development in Progress.

Thiel, R. and C. Thiel, 2009. *GCL Shrinkage – A Possible Solution*. GFR, V27N1. February – March 2009, pp 10-21.

Thiel, R. and R.K. Rowe, 2010. *Technical Developments Related to the Problems of GCL Panel Separation When Placed Below an Exposed Geomembrane*. Proc. 3rd Int. Symposium on GCLs, Wurzburg, Germany, pp. 93-102.

TRI, 2013. Test results from unpublished test work for Confidential Client.