GEOSYNTHETIC CLAY LINER - FIELD PERFORMANCE

Thomas G. Stam
Bentofix Technologies, Inc.
Serrot International, Inc., Henderson, NV, USA

ABSTRACT

The "field performance" of Geosynthetic Clay Liner (GCL) products is a topic that is general in scope yet one that deserves discussion in consideration of the scrutiny these materials have undergone over the last decade. When exploring GCL "performance", one must first determine what issues are most relevant to the measurement of long term success, being aware that this may differ between applications. As GCLs are a combination of geosynthetics and natural materials, chemical as well as physical issues will be focused upon, hydraulic properties being a function of both.

In very general terms, the overall performance of the GCL products themselves has been good. That is not to say there have not been application problems involving GCLs either directly or indirectly. However, the track record has been quite successful, resulting in few if any unresolved long-term problems – none to the author's knowledge. This paper reviews four of the primary applications for GCLs. It discusses a number of problems encountered, and relates the information that is available from these past complications to the overall successful field performance found with GCLs.

Background - With the first application of a GCL (bentonite matting) in a waste containment application at the CID facility in Illinois (GCL sandwiched between two layers of HDPE), Schubert (1987), the GCL market began to steadily grow. As neither field experience nor monitored facilities existed, their acceptance was based purely upon laboratory generated data modeled to best replicate what was thought to be field conditions.

Whereas GCL materials then lacked significant usage upon which we could gauge performance, current estimates suggest we now have several hundred million square meters installed worldwide and abundant projects where performance has been well established. This volume of GCL is also testament to the vision of early GCL "pioneers", as the ability to translate laboratory data into full-scale applications and the willingness to "look outside the box" was the key to the industry growth.

Since that first application of GCLs in the waste containment industry, professionals in the geosynthetics industry have encountered numerous variations of GCL based single and composite liner systems for any number of different applications. This includes the continued use of unreinforced GCL "sandwiched" between layers of HDPE as was used at the CID site. Significant advancements in GCL needlepunch reinforcement technology have allowed more economical design approaches to be used, as it is no longer necessary to attempt to isolate the bentonite in a dry condition. Liner system variations now include the substitution of natural barrier and drainage components with geosynthetics, alternative thickness' and composition of these components, as well as puncture prevention methodologies to protect the entire system. Versions of the composite liner concept also cross international borders with different perspectives, values and regulations on the design approach leading to differing construction and minimum prescriptive requirements.

SUCCESS MECHANISMS - When discussing the field performance of a material, the discussion inevitably encompasses failures as well as successes. Oddly, our measuring stick of success is typically our lack of failures. It is unfortunate but the failures tend to stand out more, as they are more interesting to discuss and as there are so many more success stories. Our task could therefore be described as an effort to design uninteresting products and projects.

The performance of a particular liner system can be examined in terms of the inherent characteristics of each geosynthetic material, the influence on their performance due to installation practices, the appropriateness of material combinations, the nature of the materials to be contained as well as their overall performance from a historical perspective. Application success is the culmination of many variables working together as planned or, if not planned, working in a manner that ultimately achieves the originally desired result. Success can be inadvertent and likely is in many cases where there are variables yet to be discovered!

The success of a geosynthetic material in a particular application can also be indexed against the material it was used to replace. For instance, a GCL would be considered to be performing successfully or at least to the best extent possible if it were outperforming what was capable with a compacted clay layer. In the end "finding the reasons for success is more difficult than finding the reasons for failure", Bass et al. (1985). By learning from our failures and identifying the specific aspects of performance that are important to the effectiveness of an application, we can continue to successfully apply geosynthetic technology in a broad range of projects.

ASPECTS OF SUCCESSFUL GCL PERFORMANCE - An evaluation of GCL successes can be based upon index values or site specific performance criteria. The approach will be dictated by the application itself. A double lined facility with a leak detection system can be directly monitored for its hydraulic performance whereas a secondary containment application may require more subjective measures. It could be argued in some instances that index properties are irrelevant as they only indicate the condition of the material when produced, yet these index tests are helpful for benchmarking purposes in non-monitored applications.

Independent of design issues, GCL chemical, hydraulic and structural characteristics are relevant to establishing performance criteria. These categories can be broken down further depending upon the specific requirements of an application.

Chemical performance can encompass permeant compatibility as well as adjacent material compatibility with the bentonite component (as would be appropriate for secondary containment). Relevant to the geotextile or geomembrane components, it could also relate to polymer stability. This category could also be linked to other influencing factors such as the application normal load, effectiveness of polymer or other chemical additives as well as the bentonite's first fluid of hydration.

Hydraulic properties can be evaluated in terms of desiccation/rehydration effects, the specific hydraulic conductivity as well as the overall GCL flux efficiency. Hydraulic properties are related to the application normal load, the effectiveness of polymer or other chemical additives, influences of adhesives, needlepunched fiber density as well as the first fluid of hydration.

Structural categories include GCL internal or interface characteristics, the overall dimensional stability of the product, geotextile or geomembrane characteristics, needlepunching or reinforcing structure effectiveness as well as general product durability. The confining pressures of the application as well as the uniformity of those pressures would be considered as associated influencing factors on performance.

An additional area that will also be touched upon is application design. That is, regardless of a GCL product's quality, misapplication of the technology can result in less than satisfactory results. Many GCL problems are not necessarily the result of using a GCL. They are the result of using the incorrect GCL, or of using the GCL incorrectly. These issues and categories are broken down further by their study in the following four major types of applications where GCLs have been used.

SECONDARY CONTAINMENT FOR BULK STORAGE OF FLUIDS. GCLs were first used in secondary containment projects in the mid 1980's when impending US EPA regulations required stricter secondary containment measures be followed for bulk storage of petroleum products, Bruton (1991). At that time, the concerns we now recognize were not always considered, as many performance characteristics and requirements of GCL products remained ill defined. With the knowledge we possess today, the appropriateness and performance of GCLs for secondary containment purposes could be "measured" by a number of key parameters, including but not limited to:

- Compatibility with fuel or other stored fluid
- Hydraulic performance with stored fluid
- Compatibility with and sufficient thickness of cover material
- Control over GCL hydration/desiccation

- Construction/installation practices and detail construction
- Physical damage during or subsequent to installation
- Cathodic protection measures
- Design / product selection

Interestingly, with all of these application “yardsticks”, it has been and remains difficult to quantitatively measure the performance of GCLs or other lining products in these applications without intrusive sampling or large scale flood testing. In light of this “limitation” inherent to this type of application, the use of GCLs must be carefully considered to ensure the various concerns have been fully addressed, such that a quasi-quantitative or qualitative approach may be used to measure success.

Probably the first significant instance where the performance of a GCL came under scrutiny and where a qualitative analysis was used was on a secondary containment project for a New York utility company. In late 1990 to early 1991, this GCL secondary containment application was observed to have excessive leakage after only a few years in use. Whereas rainwater ponded over the surface of the impoundment in the first few years after the installation, this was not witnessed in subsequent years.

In this case, it appeared to be a combination of the GCLs compatibility with dolomitic cover material (James Clem Corporation, 1992), acidic rain, improper drainage for these conditions and, although not indicated in the remediation report, possibly insufficient cover material thickness. In general, acidic rainwater draining through the dolomitic cover leached calcium and magnesium ions which exchanged with the sodium ions in the bentonite of the GCL. This appears to be the first known and studied instance of ion exchange in a GCL material.

While all other aspects of the installation had been properly addressed either consciously or unconsciously, the unknown at the time (cover soil compatibility – ion exchange) caused an increase in permeability. The project was remediated with another layer of GCL, using an alternate source of cover material. Associated impoundments for this utility company which were exhibiting the same phenomenon, were remediated by the surface application of soda ash, which had the effect of replenishing the sodium ions and lowering the permeability without removal of the GCL, Dobras et al (1993).

While other options to GCLs exist for secondary containment applications, it was this project that brought to light an aspect of these products that had previously been unappreciated, leading to more successful GCL installations in subsequent secondary containment projects as well as other GCL applications.

Ion exchange is not a new phenomenon, and in consideration of the overwhelming number of successfully performing projects since this was first studied in the early

1990's, it would appear to be important but not a major impediment to efficient GCL performance.

PRIMARY LINER FOR FLUID CONTAINMENT STRUCTURES – The primary containment of fluids is quite different than a layer of GCL acting as a "safety net". When a GCL must contain fluids continuously, a minor construction flaw, product deficiency or design shortcoming will reveal itself quite quickly. GCLs gained rapid acceptance in lakes, ponds and sewage lagoon projects, as the previous experience of the first GCL manufacturer was bentonite amended soil applications for the municipal market. GCLs were a natural replacement for amending poor quality soils with bentonite, as the same clay product was being used and in a manner that allowed for greater assurances of an entire area being thoroughly covered in a shorter period of time.

While there are many similar performance aspects to be considered, as in other applications, there are a few that are specific to high gradient conditions of primary fluid containment structures. Key considerations include but are not limited to:

- Compatibility / hydraulic performance with fluid to be contained
- Compatibility with cover materials / gradation of cover materials
- Gradient Impacts on performance
- Proper cover material thickness / confining pressure
- Subgrade preparation / gradation
- Construction/installation practices and detail construction
- Physical damage during or subsequent to installation
- Stability (while full / during draw-down)
- Control over GCL hydration/desiccation
- Hydraulic performance under site specific conditions
- Design / product selection

A number of methods have been used over the years to quantitatively measure the performance of liquid impoundments including barrel tests and direct measurement of fluid levels. In a number of instances, the impoundment recharge makes performance measurement difficult.

Sometimes the performance is much easier to gauge, as decreased water levels of several feet over a few days would suggest something wasn't quite right! In 1994, a GCL lake project at a residential development on the central coast of New Jersey was observed to drop in excess of 5 feet over a two-week period during its initial filling. It was originally thought the problem was due to a GCL production/product quality control problem or an installation mistake. In most cases, significantly abnormal leakage is due to placement (installation) mistakes, Gartung (1998).

Upon further investigation, it was found there were several contributing factors, and that the installation itself was in accordance with the recommended procedures at that time. The GGL product had been installed with a relatively porous (i.e. lightweight) nonwoven placed against a course sand subgrade. As the gradient increased during the filling process, the geotextile's ability to contain the swelling bentonite was overcome by the increasing hydrostatic pressures. Subsequent excavation of the installation revealed areas of "patchy" bentonite piping through the relatively open nonwoven geotextile into the coarse sand subgrade to a depth of 15-20 cm (Figure 1). The capabilities of the geotextile had been overcome and there was no soil back-up mechanism to resist the hydrostatic pressures or any structure for the bentonite particles to bridge upon.

The phenomenon was clearly the result of the unusually high gradient as well as a very porous subgrade and lightweight geotextile layer. This and an isolated number of similar events with thin porous geotextile based GCLs suggested a greater need for fine-grained subgrades when GCLs are used in high gradient conditions. Specific to high gradient conditions, other lessons learned included the need for high quality, robust, relatively low AOS geotextiles to contain the bentonite. It also suggested that a woven slit film geotextile might be the preferred component to place against the subgrade, if the alternative is an inadequately engineered nonwoven.

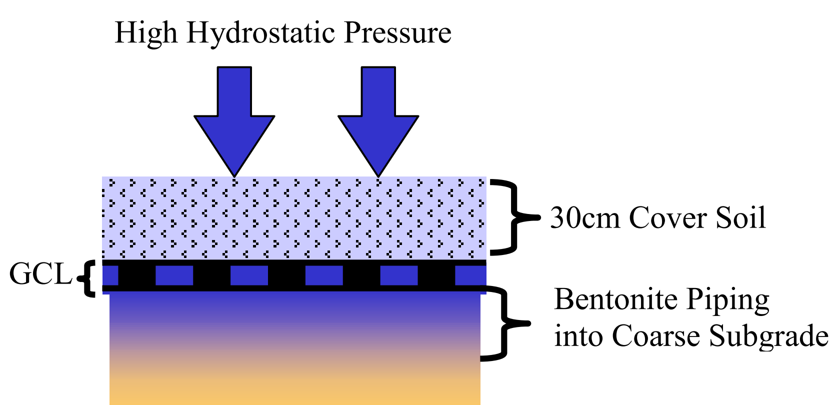

Figure 1 - Hydrostatic Pressure Induced Bentonite Piping Through "Open" Geotextile

Many success stories precede and follow this project where, through luck or calculation, the site conditions and GCL materials selected and installation procedures followed were appropriate for effective performance of the installation. Since this phenomenon was first identified, new GCL products, proper GCL selection, suitable subgrade materials, proper orientation of the GCL geotextiles, diligent installation techniques as well as reliance upon manufacturer experience all have resulted in an essentially 100% rate of product success.

Although there were lessons learned from this experience, instances do occur where history is repeated. These instances would be categorized as design issues rather than product deficiencies. As reported by Peggs and Olsta (1998), lagoons do still get constructed with improper subgrade conditions and with GCLs containing areas of inadequate geotextile mass. Excessive leakage was observed upon the initial filling of three western WWT lagoons where the manufacturer reportedly informed concerned parties that problems were likely to occur. In this case, a combination of factors lead to the problems witnessed. These included the possible use of the wrong product, improper installation of that product, inadequate subgrade preparation/conditions, lack of adherence to manufacturer minimum recommendations, improper product orientation as well as the application of index data for performance calculations.

This occurrence also suggests that success is not guaranteed by previous experience and while it was the product that exhibited "problems" it was likely the design that failed. Success is not just a result of lessons learned, it is also a result of lessons heeded.

SINGLE AND COMPOSITE LINER LANDFILL CAPS/CLOSURES - GCLs have been widely accepted for use in landfill closures as they offer a clay barrier option without the technical and construction problems associated with compaction of clay over surfaces with variable structural characteristics. Interestingly enough, while compacted clay liners (CCLs) are repeatedly determined to be inadequate for landfill closures for any number of reasons, GCLs are in many cases not considered as a suitable replacement for CCL, even when data which suggests their performance superiority.

Landfill caps and closures bring yet another set of parameters to the table. High gradient conditions are of no concern as the GCL in this instance is acting as a shield – to prevent the intrusion of moisture rather than to contain. While hydraulic issues are still a concern, the stability issue plays a more important role in a successful GCL installation. The efficiency or success of a GCL closure may simply be the lack of "hits" at a monitoring location. Index tests can be used to determine if the GCL has altered from it's original state but recent studies suggest that index properties may not be a good indicator of in-situ performance.

A number of primary performance characteristics that could be considered when discussing GCL success for landfill closures includes:

- Compatibility with cover materials
- Proper cover material thickness / confining pressure
- Proper drainage / gas ventilation systems
- Subgrade preparation / gradation
- Root penetration prevention

- Construction/installation practices and detail construction
- Physical damage during or subsequent to installation
- Control over GCL hydration/desiccation
- Slope Stability (static / seismic conditions)
- Gas permeability
- Hydraulic efficiency
- Design / product selection

A great deal of information has begun to surface regarding the efficiency of landfill closures, the result of both stability as well as hydraulic studies. Probably the most recognized stability study is the EPA Test Plots in Cincinnati. While this was a large-scale study, not an actual application, its mere scale and the results obtained would suggest that it is in fact representative of results obtained elsewhere. Unlike the typical installation, these large field tests provided valuable quantitative and qualitative information.

Significant information regarding interfaces has been garnered from this study although outside the original focus, Koerner et al. (2000). The only slides that occurred were internally in an unreinforced GCL and interfacially where a reinforced GCL's woven geotextile was installed to interface with the overlying HDPE geomembrane (the latter occurring twice). Until these test plots were constructed it was in some cases thought better to place a woven geotextile against the geomembrane in composite applications, to promote greater intimate contact between GCL and geomembrane, minimizing the potential for planar flow of fluids at the interface. This large-scale field study clearly indicated that orienting the nonwoven component of the GCL against the textured geomembrane could in most cases optimize interface strengths. This is likely the reason that in all known GCL installations for closure applications where the nonwoven has been installed against the overlying geomembrane, that no stability issues have surfaced. Research by Wilson-Fahmy and Koerner (1995), suggests that this orientation, with a thicker nonwoven against an overlying geomembrane, will also provide sufficient potential for intimate contact that is equivalent or superior to that achievable with a CCL. These test plots corroborate why GCLs have been so successful in closure applications.

This study also indicated another important facet of most reinforced GCL products, that for low normal load applications, a stable design may be obtained by obtaining satisfactory interface strengths. As the critical shear plane was internal only on unreinforced GCLs, slope stability for unreinforced GCLs should focus on fully hydrated internal shear strengths. As the slide on test plot "F" would suggest, one must plan for possible hydration when working with bentonite materials as minor wrinkles in a membrane could lead to widespread hydration. Under such aggressive assumptions, the structure's quality control and quality assurance are both of particular importance.

The hydraulic success of GCLs in closure applications has until recently been more of an enigma. Whereas the GCLs in these systems are easily accessible, Gartung et al (1998), there have been no direct means to measure their performance. Results on specimens excavated do indicate that index properties can change, but when the moisture content of the bentonite remains unaffected, even ion exchange can leave the product's hydraulic performance within expected ranges. This was the case for GCL excavated from the Cincinnati test plots. Analysis on hydrated specimens taken from plot "I" indicated ion exchange had occurred yet index permeability tests on those specimens yielded hydraulic values within certifiable ranges. The uniformity of the GCL moisture content is likely attributable to a combination of the overlying geomembrane, the depth of cover soil as well as the relatively moist subgrade.

The efficiency of GCLs in landfill closures has also be investigated in large-scale lysimeters. Maubeuge et al (2000), also indicates the long-term performance of several large, highly instrumented lysimeters is in an acceptable range and likely to outperform compacted clay liner systems. While this statement may depend on the poor performance of the CCL, the fact remains that the GCL is a replacement for the CCL. When all indications are that the hydraulic efficiency of GCLs is superior to CCLs, it is a wonder that CCLs are still considered viable alternatives to GCLs. Yet this is precisely the case with many federal and state regulations, Fahim et al (1993), Koerner et al, (1998).

SINGLE AND COMPOSITE LANDFILL BASE LINERS - Coming full circle, the application that put GCLs on the map is also one that could be considered the most critical. Whereas the three primary applications for GCLs previously discussed have been very successful, the remedy of problems for them has also been very simple. Whether due to easy access for research or the lower sensitivity of those applications, they have been rather straightforward to address. A failure of a landfill base liner application would have much more severe repercussions.

Because of the sensitivity of these applications, the preliminary work that is typically performed to use a GCL in these systems has likely been the cause of their overwhelming success. Landfill base liners also require many of the aforementioned issues to be scrutinized:

- Compatibility with waste contained
- Subgrade preparation / gradation
- Construction/installation practices and detail construction
- Physical damage during or subsequent to installation
- Stability (static / seismic conditions)
- Hydraulic efficiency
- Design / product selection

For many years, GCLs have been required to be approved via "alternative material" clauses in many state regulations. This has been arduous task in many instances as even in light of data that suggests the CCL materials being replaced are inferior, the GCLs were deemed unacceptable until there were "similar applications in my state". It was difficult obtaining approval for these materials in a given state when the criterion for use in the state included demonstrating prior use – in that state. We have progressed dramatically in terms of GCL acceptance as well as performance documentation.

One instance of a GCL base liner slope failure described by Stark (1998), included the use of an unreinforced GCL where the bentonite had been adhered to a membrane. With the bentonite surface installed against the soil subgrade, the overlying stresses of relocated waste, caused a translatory failure between the geomembrane and the bentonite component. This appears to be an isolated case as unreinforced GCLs are rarely used in slope applications. Needlepunch reinforced GCLs are by far the predominant material used to replace clay layers on slopes or in demanding base liner situations.

The hydraulic success or efficiency of GCLs in these applications has recently been researched in a study completed for the US EPA, Koerner (2000). In this study, three types of liner systems were investigated; a geomembrane alone, a geomembrane overlying a GCL and a geomembrane overlying a CCL. Leak detection systems included both sand as well as geonets. This resulted in six different liner system combinations, (Table 1). Data was also broken down to reflect the initial, active and post closure life stages of the individual cells.

Table 1 – Leakage Rates from Leak Detection Systems of Double-Lined Landfills from EPA Study CR-821448, after Koerner, (2000) [All Flow Rates are in Gal/Acre-day (gpad)]

Liner/LDS Type	I - (GM-Sand)			II - (GM-GN)			III - (GM/CCL-Sand)		
Life of Cycle Stage	1	2	3	1	2	3	1	2	3
Average Flow	41	18	6.8	10	11	ND	12	15	6.8
Minimum Flow	0.81	0.0	0.02	0.51	0.15	ND	0.13	2.4	0.0
Maximum Flow	229	158	26	40	38	ND	126	71	29
No. of "points"	30	32	8	7	11	ND	31	41	15
No. of landfills	11	11	4	4	6	ND	11	11	4
Liner/LDS Type	**IV - (GM/CCL-GN)**			**V- (GM/GCL-Sand)**			**VI - (GM/GCL-GN)**		
Life of Cycle Stage	1	2	3	1	2	3	1	2	3
Average Flow	18	8.9	7.0	14	2.38	0.03	0.70	0.28	ND
Minimum Flow	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	ND
Maximum Flow	74	54	14	104	30	0.10	3.6	1.0	ND
No. of "points"	21	27	12	19	19	4	6	4	ND
No. of landfills	6	9	3	3	3	1	2	2	ND

Life Cycles: Stage 1 – Initial Life Stage 2 – Active Life, Stage 3 – Post Closure, ND = No Detection (of leakage)
"points" = Number of measuring points (i.e., outlets of single or multiple cells)

As landfill base liners are rarely excavated to retrieve index test specimens, the most definitive measure of success is logically the efficiency of the lining system as a whole. The data presented in Table 1 represents the average flow rates of 287 single or multiple cells monitored for up to 10-years. Of significance is the fact that the GM/GCL systems outperform the standard GM/CCL in all cases and at every life cycle stage.

While index properties may or may not have been altered since installation, the primary focus should be on whether the GCL is performing the intended task for which it was designed. This data clearly shows that GCLs are performing their intended purpose. It is data of this nature that begs the question, when will CCL materials be required to demonstrate their equivalence to GCLs before they can be used?

MANUFACTURING SUCCESSFUL FIELD PERFORMANCE - The success that has yet to be discussed is that of the manufacturing process itself. The production capabilities and product diversification has been quite an achievement in consideration of the raw materials. Many ASTM standards have been developed for most of the key testing and protocol issues we face. Manufacturing processes are continually improved ensuring higher product uniformity and quality.

For reinforced GCLs, it is often stated that needlepunched GCLs suffer from broken needles, which might not be surprising considering the fact that needles are being pushed through a layer of abrasive granular clay. In practice, this has not proven to be a problem when high-power magnets are employed in conjunction with needle/metal detectors. When needle breakage occurs, the magnets can remove needle fragments while the needle/metal detectors identify any fragments that may escape removal. The area is hand inspected and the needles discarded. GCLs can be certified to be needle-free!

GCL successes in the field would not have occurred had the manufacturing processes not succeeded first.

SUMMARY CONCLUSIONS - In considering the field performance of GCLs, or any other geosynthetic material for that matter, little attention is given to the system if failure does not occur. To the contrary, this is where we should be focusing our attention, to determine what we are doing right. A number of problem projects have been presented here as the lessons learned from these experiences have contributed to the larger continued success of GCL products and applications.

It is difficult to analyze success, as it is likely that in many cases we do not know whether a system is on the brink of failure or is working with a large safety factor. There are many “yardsticks” by which failure can be measured yet very few for successes. We have witnessed in excess of a decade of many successes but don’t know why in all instances. A simple and reasonable statistical analysis, as a function of the several hundred million square meters installed worldwide, would suggest the percentage of GCL successes is 99.9%. Research by Othman et al. (1996) also suggests a similar hydraulic efficiency for composite landfill liners utilizing an underlying GCL component.

Problems are generally a misunderstanding of the performance characteristics of GCLs or a misunderstanding of the differences between the various GCL options. These performance characteristics should be understood by designers in order to specify the GCL that will optimize performance. Installers and CQA personnel should also understand the performance characteristics to ensure that applications are properly constructed.

GCLs are not panaceas for all lining applications but they have been proven to be very successful when properly employed. While some of the problems encountered could be attributed to the GCL products themselves, there are also instances where the designs are failing the GCLs. The base of knowledge we have accumulated must be understood and used to ensure future applications will perform as well as those to date.

As the complexity of GCL products increases, it will become even more important to be capable of matching the appropriate product with each specific application. The future success of GCLs will demand this ability. You can use some GCLs all of the time but you can't use all GCLs all of the time. All GCLs are not created equal.

REFERENCES

Bass, J.M., Lyman, W.J., Tratnyek, J.P. (1985) EPA/600/S2-85/100 Project Summary "Assessment of Synthetic Membrane Successes and Failures at Waste Storage and Disposal Sites"

Bruton, D. (1991), "Bentonite Mats Meet Secondary Containment Standards," Geotechnical Fabrics Report, May/June, 26-27

Dobras, T. N., Elzea, J. M. (1993), "In-Situ Soda Ash Treatment for Contaminated Geosynthetic Clay Liners," Geosynthetics '93 Proceedings, pp 1145 – 1159

Fahim, A., Koerner, R.M. (1993), "A Survey Of State Municipal Solid Waste (MSW) Liner And Cover Systems," GRI Report #11, August 10, 1993

Gartung, E., Zanzinger, H. (1998), "Engineering Properties and Use of Geosynthetic Clay Liners," Proceedings Geotechnical Engineering of Landfills, N. Dixon et al. Ed., Nottingham; Thomas Telford Pub, 1998, pp. 131 – 148

James Clem Corporation (1992), “Final Report, Shoreham Site Investigation and Remediation Recommendations” pp 1-16

Koerner, J.R., Soong, T.Y., Koerner, R.M. (1998), “A Survey Of Solid Waste Landfill Liner And Cover Regulations: Part I – USA Status,” GRI Report #21, December 7, 1998

Koerner, R.M., Daniel, D.E., Bonaparte, R. (2000), “The Cincinnati GCL Test Plots – Status as of January 2000,” Proceedings ESD Great Lakes Solid Waste Conference, March 15, 2000

Koerner, R.M. (2000), “GRI Fact Sheet – Leachate Recirculation in Municipal Solid Waste Landfills With Alternative Liners Incorporating GCLs”

Maubeuge, K.V., Ehrenberg, H., Blumel, Walter, M. (2000), “Assessment of Different Geosynthetic Clay Liners in Lysimeters Under Various Cover Soil Thicknesses,” Proceedings EuroGeo-2, Bologna, Italy, October 2000, pp.

Oathman, M.A., Bonaparte, R., Gross, B.A. (1996), “Preliminary Results of Study of Composite Liner Field Performance,” Proceedings of the 10th GRI Conference, Philadelphia, Pa. USA, pp. 110 - 137

Peggs, I. D., Olsta, J. T. (1998), “A GCL and Incompatible Soil Case History: A Design Problem,” Proceedings of the 12th GRI Conference, Philadelphia, Pa. USA, pp. 117 - 138

Schubert, W. R. (1987), “Bentonite Matting in Composite Lining System,” Geotechnical Practice for Waste Disposal ’87,” ASCE Geotechnical Special Publication No. 13, pp.784-796

Wilson-Fahmy, R.F., Koerner, R.M. (1995), “Leakage Rates Through Holes In Geomembranes Overlying Geosynthetic Clay Liners,” Proceedings Geosynthetics ’95, Nashville, TN, pp 655 - 668