TECHNICAL EQUIVALENCY ASSESSMENT OF GCLs TO CCLs

This paper was presented at the 7th Geosynthetic Research Institute Seminar in 1993. It contains a comprehensive comparison of geosynthetic clay liners (GCLs) to compacted clay liners (CCLs). The authors begin with an overview of the various types of GCLs available on the market at that time. They make a detailed comparison of GCLs to CCLs in the following three areas:

- hydraulic properties
- physical/mechanical properties
- construction issues

The more important points or comparisons are highlighted below.

Hydraulic Properties
The authors conclude that a GCL is at least equivalent to a CCL with respect to the steady state flow of water, even though a GCL is much thinner. The GCL's effectiveness is due to its extremely low permeability.

In the short term, a CCL probably has better Cation Exchange Capacity (CEC) than a GCL. However, this advantage makes no difference over the life of the landfill because the full adsorptive capacity of the CCL will be exhausted relatively quickly. Consequently, CEC will make no difference in the performance of the liners in the long run.

The authors draw a similar conclusion about break-out time. Break-out time is not an important factor because all liners leak to some extent. What is more important is the total volume of leakage through a given liner over a given period of time.

Physical/Mechanical Properties
The authors looked at several properties in this section and determined that GCLs are equivalent or superior to CCLs with respect to freeze/thaw, wet/dry cycles and total and differential settlement. GCLs are not permanently damaged by either freezing or desiccation due to the bentonite's self-healing nature. Also, GCLs perform better under differential settlement than CCLs because their geotextiles allow the GCLs to withstand larger stains. CCLs will crack severely after only 0.85% strain.

Slope stability is a very site specific issue because of the many different factors involved. However, the authors' point out that slope stability is also very product dependent. Different GCLs have by nature of their reinforcing mechanisms, different stability characteristics.

The authors do note that GCLs are not equivalent to CCLs with regard to bearing capacity. Heavy equipment, such as that used at most landfills, cannot drive directly on top of a GCL. A soil cover of 1 to 3 feet is required to protect a GCL from heavy equipment. This type of protection is not required for a CCL.

Construction Issues
The authors point out that GCLs are more susceptible to puncture than CCLs. However, they also mention, "Although the GCLs can be punctured during construction, careful CQC/CQA should be capable of addressing this potential problem. Further, for final covers, an occasional small puncture may be of little consequence."

GCLs do have several advantages over CCLs when it comes to construction. GCLs can be deployed much more quickly and do not require any water. This last point is important because a large CCL can require several hundred thousand gallons of water just to raise the water content a few percent.

The Quality Assurance of a manufactured GCL is relatively simple and straightforward. In contrast, "The proper construction of a low-permeability CCL is a relatively challenging task." Extensive testing of the finished liner must accompany careful selection and placement of the soils. All of these factors substantially increase the time and cost of constructing a CCL without any increase in the performance of the liner.

Conclusions
The conclusions reached by the authors state, "While no general conclusion can be reached about GCL equivalency to a CCL at all sites (either for liner or cover applications), it is expected that GCLs can be shown to provide better or equivalent performance at many sites."

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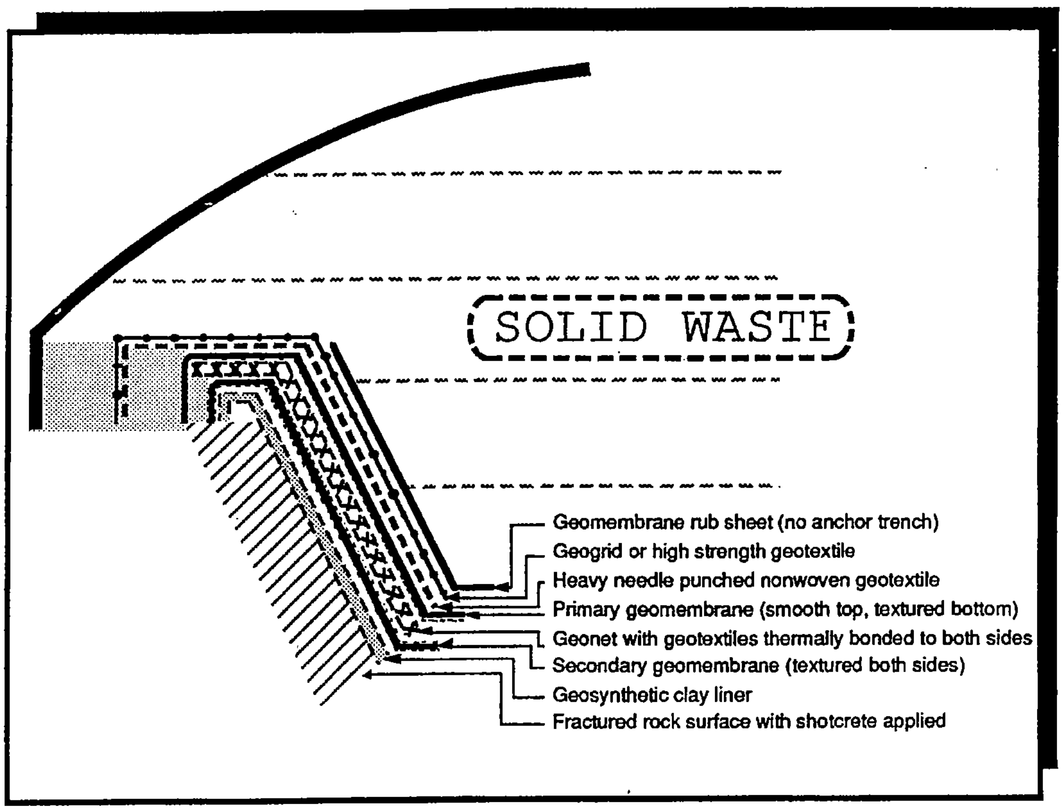

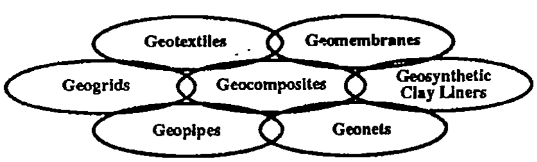

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TECHNICAL EQUIVALENCY ASSESSMENT OF GCLs TO CCLs

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ABSTRACT

Since their introduction as barrier materials in waste containment systems in 1986, geosynthetic clay liners (GCLs) have been installed in a variety of applications. Perhaps the major applications have been as leachate containment barriers beneath landfills and surface impoundments, and as infiltration water barriers in landfill covers. When one considers that the traditional barrier material in these applications is a compacted clay liner (CCL), it is only logical that the two materials should be compared and contrasted to one another in such a way so as to assess technical equivalency. This paper provides the salient features for providing such an assessment. It is primarily based on technical issues and results in a framework that can possibly be used for assessment of both liner and cover barrier materials.

In this assessment it is seen that other than issues of puncture resistance and product thinning due to abutting objects and uneven subgrades (both of which can be avoided by proper CQC/CQA procedures), GCLs can generally be used on an equivalent basis as CCLs. However, site specific conditions like long term slope stability may provide unique situations calling for specific products or alternate designs.

Needed to further this assessment of GCLs to CCLs is a continued dialogue with respect to technical issues, close monitoring of GCL installations, and involvement of regulatory agencies in the decision making process.

INTRODUCTION AND SCOPE

The traditional hydraulic barrier material used to contain solids and liquids in a variety of applications is clearly one made from natural soils, typically clays. Such clay barriers can occur via a natural clay stratum, a compacted soil liner or an amended clay liner. These natural soil materials will be called by the collective term of "compacted clay liners", or "CCLs", in this paper.

Clearly, CCLs are the basic material required by regulatory agencies in the containment of solid waste. A recent study for municipal solid waste liner systems has shown the following, Fahim and Koerner (1993):

- CCLs are used as a single liner beneath waste in 19 states
- CCLs are used as a composite liner beneath a geomembrane in 20 states
- CCLs are used as a single cover in 36 states
- CCLs are used as a composite cover beneath a geomembrane in 6 states

The minimum U. S. EPA requirements are generally for the CCL to be from 300 to 900 mm thick with a maximum hydraulic conductivity of 1×10^{-7} cm/sec in the liner and 1×10^{-5} cm/sec in the cover. Note, however, that current municipal solid waste regulations (Subtitle "D") call for a geomembrane to be placed above the CCL in both situations of a liner beneath the waste and a cover above the waste.

A tremendous data base is available on CCLs for waste containment applications. This is evidenced by major research efforts, U.S. EPA SW-869 (1983), Goldman, et. al. (1988) and Daniel, (1987), development of specialized laboratory test equipment, U.S. EPA (1986), development of unique construction procedures and equipment, Rogowski, (1990) and an entire CQC/CQA monitoring protocol, Daniel and Koerner (1993). Thus any new liner material intended to challenge the status of CCLs must necessarily be compared and contrasted to the existing situation.

One such competing material that might be considered for a single liner (not a composite) replacement of a CCL is a geomembrane (GM). Indeed, 8 states have selected this option for liners beneath the waste and 17 have for covers above the waste. Both strategies, however, do not meet the minimum technology guidance of U.S. EPA regulations which, as mentioned previously, require composite GM/CCL systems. For this paper it will be assumed that the GM (if used at all) will be used in a complimentary manner to the underlying clay liner as a composite liner.

A second, and more recent, competing material to a CCL is a geosynthetic clay liner, or GCL. Geosynthetic clay liners are defined in ASTM D4439 as follows:

"Geosynthetic clay liners are factory manufactured hydraulic barriers typically consisting of bentonite clay or other very lower permeability material, supported by geotextiles and/or geomembranes, which are held together by needling, stitching, or chemical adhesives."

Bentonite panels (the forerunner to GCLs) were first manufactured in the early 1980's and were initially used for foundation waterproofing and for sealing water retention structures. The panels were subsequently modified to be flexible rolls incorporating either geotextiles or geomembranes, i.e., GCLs, and were first used for landfill liners in 1986. Since then, GCLs have been used for a variety of lining applications and final cover systems for municipal and hazardous solid wastes.

The realization that GCLs are new, however, is evidenced by the survey mentioned earlier, Fahim and Koerner (1993), where no Federal regulations and only two State regulations even mention GCLs as a possible replacement of, or augmentation to, CCLs. In Colorado, GCLs are possible to use in the liner system and in Michigan in the cover system.

Interestingly, replacement of any natural material with a synthetic alternative (via technical equivalency) is usually a possibility. If one wishes to substitute a GCL for a CCL, one must demonstrate that the GCL will be equivalent in terms of meeting performance objectives. However, neither Federal nor State regulations mention the criteria by which equivalency should be evaluated. At the present time equivalency must be evaluated on a case-by-case basis using criteria that have not yet been defined. The lack of equivalency accepted criteria is perhaps the single greatest problem that the designer and/or owner of a waste facility face in seeking regulatory approval for substitution of a CCL by a GCL.

Importantly, one should not think of a GCL as being totally equivalent to a CCL. Indeed, there is no possibility that a 10 mm thick layer of bentonite could possibly be equivalent to a 300 to 900 mm thick layer of compacted clay in all respects. The critical issue is whether substituting an alternative material such as a GCL for the more traditional CCL will meet or exceed the performance objectives of the site specific situation. If the GCL will meet or exceed the performance objectives, then it should be considered that equivalency has been established.

This paper is intended to establish a framework for assessing such equivalency for waste containment liners and covers. In so doing, many generalities must be taken since no two site performance objectives, or set of demands, are identical. Even further (and with respect to solid waste landfills), liner systems beneath the waste will have very different objectives than covers above the waste. With these concepts in mind, and for the purposes of this paper, GCLs will be contrasted to CCLs in both liners and covers from a generic and widely encompassing perspective.

OVERVIEW OF GCLs

Since compacted clay liners (CCLs) are historically known, clearly established and well documented, e.g., U.S. EPA SW-869 (1983), Goldman, et. al. (1988), and Daniel, (1987), we will only focus on a description of geosynthetic clay liners (GCLs). The description will be brief, however, since more complete descriptions are available in the open literature, Daniel and Boardman (1993) and Estornell and Daniel (1992), and can be regularly updated from manufacturers of the various GCL products.

The essence of a GCL, of course, is the layer of bentonite which is held between or on carrier layers of geotextiles or a geomembrane. Bentonite is a unique clay mineral with very high swelling potential and water absorption capacity. When wetted, bentonite is the least permeable of all naturally occurring, soil-like minerals. Bentonite is a chemically stable mineral that has undergone complete weathering and will last, in effect, forever.

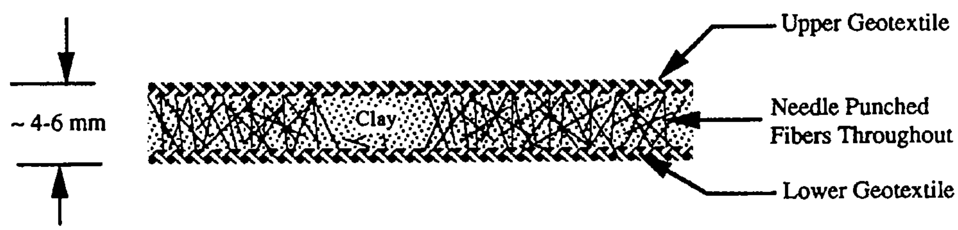
GCLs are manufactured by placing powdered or granulated bentonite (with or without an adhesive mixed into the bentonite) on a geotextile or geomembrane substrate. The bentonite layer is typically 7 to 10 mm thick and is placed at a unit weight of approximately 5.0 kg/m^2. Those GCLs with a geotextile substrate (4 of the 5 available types) have covering geotextiles as well, see Figure 1(a). The product (with or without adhesives) is often stitch bonded as in Figure 1(b), or needle punched as in Figure 1(c), thereby gaining considerable structural integrity. For one GCL, the substrate is a geomembrane where an adhesive mixed with the bentonite results in the final product, see Figure 1(d).

One particular style of each of the commercially available GCL products is shown in the upper photograph of Figure 2. This photograph shows the products stacked upon each other in dry (lower) and hydrated (upper) pairs. The lower photograph shows greater detail of one of the products in the hydrated (left) and dry (right) states.

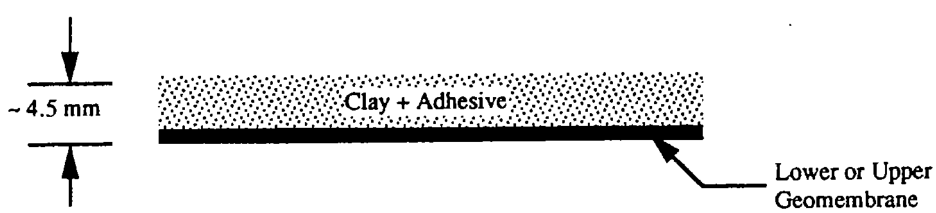
As one can surmise from these photographs, there exists very real differences between GCLs and a 300 to 900 mm thick layer of clay-soil. In addition to the obvious thickness issue, Table 1 counterpoints many of the relevant features. Daniel (1993) further elaborates on these differing features.

(a) Adhesive Bound Clay to Upper and Lower Geotextiles

(b) Stitch Bonded Clay Between Upper and Lower Geotextiles

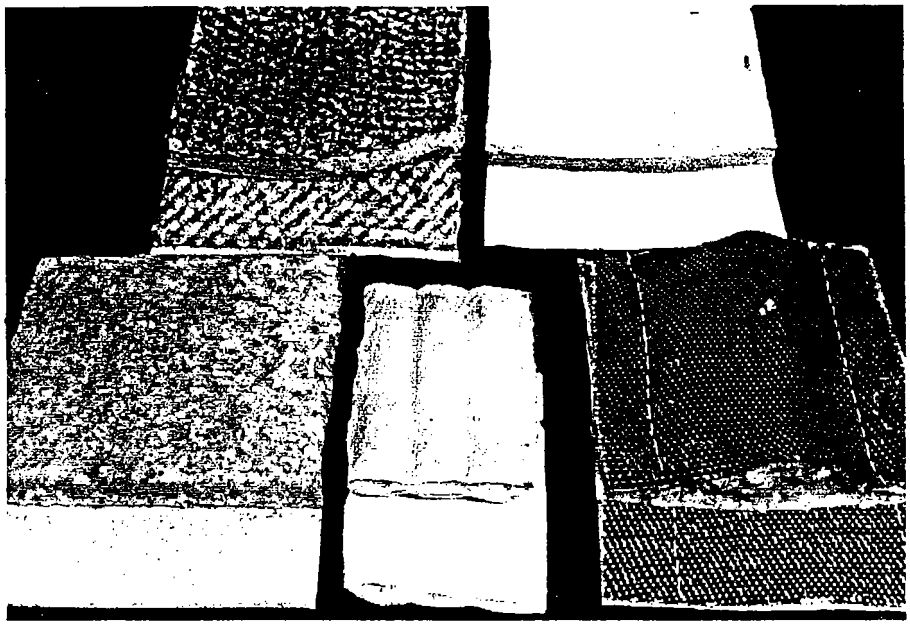


(c) Needle Punched Clay Through Upper and Lower Geotextiles

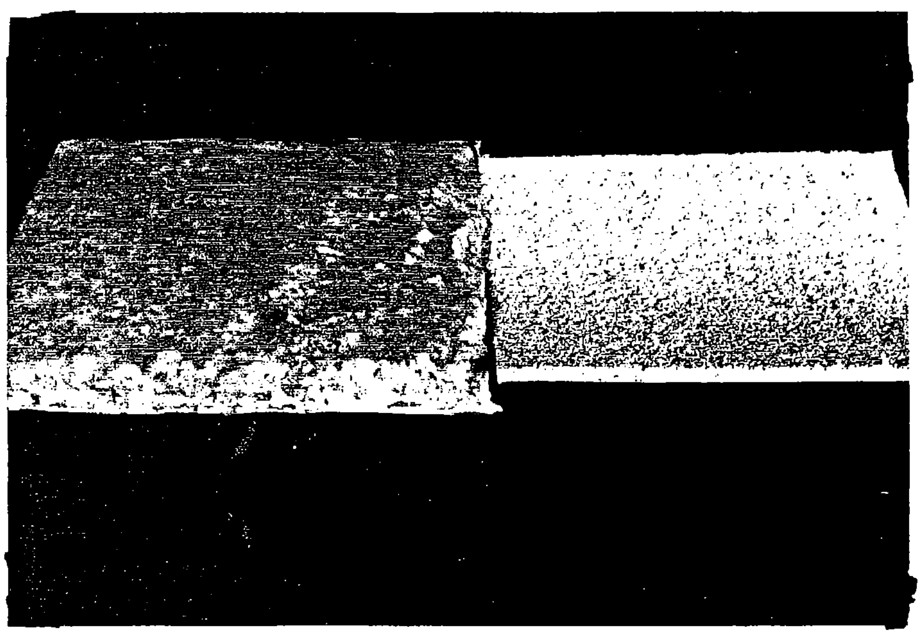


(d) Adhesive Bound Clay to a Geomembrane

Figure 1 - Cross section sketches of currently available geosynthetic clay liners (GCLs).



(a) Different Products in Dry versus Hydrated Conditions



(b) A GCL Hydrated (Left) vs. Dry (Right)

Figure 2. Commercially Available Geosynthetic Clay Liners (GCLs)

Table 1. Some selected differences between GCLs and CCLs.

Characteristic	Geosynthetic clay liner	Compacted clay liner
Materials	Bentonite, adhesives, geotextiles, and geomembranes	Native soils or blends of native soils and bentonite
Thickness	Typically 7 to 10 mm (when hydrated)	Typically 300 to 900 mm
Hydraulic conductivity	$\leq (1 \text{ to } 5) \times 10^{-9}$ cm/s	$\leq 1 \times 10^{-7}$ cm/s
Speed of construction	Rapid, simple installation	Slow, complicated construction
Need for MQC and MQA	Factory manufacturing requires constant monitoring	Naturally found materials or mineral layers requiring no monitoring
Status of CQC and CQA	Relatively simple, straight-forward, common-sense procedures	Complex procedures requiring highly skilled and knowledgeable people
Field desiccation sensitivity	GCLs cannot desiccate during construction unless prematurely hydrated	CCLs are nearly saturated; can desiccate during construction
Available of materials	Materials readily shipped to any site	Varies widely from readily available to not available at all
Installed Cost	Typically \$6.00 to \$8.00 per square meter for a large site	Highly variable -- estimated range: \$6.00 to \$30.00 per square meter
Experience	Limited due to newness and nonfamiliarity	Has been used for many decades with great confidence as a liner material

Note:
MQC = manufacturing quality control
MQA = manufacturing quality assurance
CQC = construction quality control
CQA = construction quality assurance

TECHNICAL EQUIVALENCY ISSUES

In this section as many issues as felt to be typically encountered in comparing GCLs to CCLs are presented. They are arranged in three somewhat arbitrary categories (hydraulic, physical/mechanical and construction) and are listed for liners as well as covers. Each of the issues in Table 2 will be discussed individually in the text to follow.

Table 2. Technical equivalency categories and specific issues to be addressed.

Category	Criterion for evaluation	Possibly relevant for: Liners	Covers
Hydraulic Issues	Steady flux of water	X	X
	Steady solute flux	X	
	Chemical adsorption capacity	X	
	Breakout time:		
	- Water	X	X
	- Solute	X	
	Horiz. flow in seams or lifts	X	X
	Horiz. flow beneath geomembranes	X	X
	Generation of consolidation water	X	X
	Permeability to gases		X
Physical/ Mechanical Issues	Freeze-thaw behavior	X[1]	X
	Wet-dry behavior		X
	Total settlement response	X[2]	X
	Differential settlement response	X[2]	X
	Slope stability considerations	X	X
	Vulnerability to erosion		X
	Bearing capacity (squeezing)	X	X
Construction Issues	Puncture resistance and resealing	X	X
	Subgrade condition considerations	X	X
	Ease of placement or construction	X	X
	Speed of construction	X	X
	Availability of materials	X	X
	Requirements for water	X	X
	Air pollution concerns	X	X
	Weather constraints	X	X
	Quality assurance considerations	X	X

notes:

[1]Relevant only until liner is covered sufficiently to prevent freezing

[2]Settlement of liners usually of concern only in certain circumstances, e.g., vertical or lateral expansions

HYDRAULIC ISSUES

The essence of any barrier material is its ability to contain the targeted liquids. The usual liquids are leachate, i.e., the solute, for liner systems beneath the waste and water for the cover system above the waste.

Steady Flux of Water. Water flux is defined as the volume of water flowing across a unit area in a unit time. The steady downward flux of water (v) through an individual layer of porous material with zero water pressure at the base of the layer is defined from Darcy's law as:

$$v = k \frac{H + T}{T} \qquad (1)$$

where k is the hydraulic conductivity, H is the depth of liquid ponded on the layer, and T is the thickness of the layer.

Equation 1 is applicable only for flow through the bentonite component of a GCL; if the GCL contains a geomembrane, water flux will be controlled by water vapor diffusion through the geomembrane component. The geomembrane component, if present, should be included in the equivalency analysis, e.g., by using appropriate water vapor transmission rates. Also, Eq. 1 applies to a CCL or GCL liner alone and not to composite liners. Composite action with a geomembrane is considered later.

In order to estimate the required hydraulic conductivity of the GCL for equivalency assessment, assume that the water flux through the GCL is equal to the water flux through the CCL:

$$v_{GCL} = v_{CCL} \qquad (2)$$

or:

$$k_{GCL} \frac{H + T_{GCL}}{T_{GCL}} = k_{CCL} \frac{H + T_{CCL}}{T_{CCL}} \qquad (3)$$

If the hydraulic conductivity and thickness of the compacted clay liner are known, and the thickness of the GCL is known, the required hydraulic conductivity of the GCL to ensure equivalent performance in terms of steady flux of water is:

$$(k_{GCL})_{Required} = k_{CCL} \frac{T_{GCL}}{T_{CCL}} \frac{H + T_{CCL}}{H + T_{GCL}} \qquad (4)$$

The required hydraulic conductivity of the compacted clay liner (k_{CCL}) is usually 1×10^{-7} cm/s. The thickness of GCLs (T_{GCL}) varies from product to product, but is typically about 7 mm after hydration at low overburden stress. The head of water (H) on the CCL or GCL is assumed to be 300 mm for purposes of illustration. The required hydraulic conductivity of the GCL, based on Eq. 4 and these conditions, is therefore:

- For equivalence to a 300-mm-thick compacted clay liner:
  $$(k_{GCL})_{Required} = 4.6 \times 10^{-9} \text{ cm/sec}$$
- For equivalence to a 600-mm-thick compacted clay liner:
  $$(k_{GCL})_{Required} = 3.4 \times 10^{-9} \text{ cm/sec}$$

As see in Table 1, the hydraulic conductivity of the bentonite component of commercially-produced GCLs is typically ≤ 1 to 5×10^{-9} cm/s. Thus, it is seen that equivalency of a GCL to a CCL, in terms of the steady water flux, can be established for most, if not all, GCLs in their manufactured condition.

Steady Solute Flux. Long-term, steady flux of solute in leachate may be analyzed on the basis of advection alone, diffusion alone, or advection plus diffusion. It is assumed that the concentration of a solute of concern in the leachate remains constant. Regarding advection, the advective mass flux, $v_{m,A}$, is:

$$v_{m,A} = c_{leachate}\, k \frac{H + T}{T} = c_{leachate}\, v \qquad (5)$$

where $c_{leachate}$ is the concentration of the solute of interest in the leachate and, as before, v is the water flux. The advective mass flux ratio, $F_{m,A}$, is defined as the mass flux of solute through a GCL divided by the mass flux of solute through a CCL:

$$F_{m,A} = \frac{v_{m,A(GCL)}}{v_{m,A(CCL)}} \tag{6}$$

or:

$$F_{m,A} = \frac{c_{leachate}\, k_{GCL} \dfrac{H + T_{GCL}}{T_{GCL}}}{c_{leachate}\, k_{CCL} \dfrac{H + T_{CCL}}{T_{CCL}}} = \frac{c_{leachate}\, v_{GCL}}{c_{leachate}\, v_{CCL}} = \frac{v_{GCL}}{v_{CCL}} \tag{7}$$

Thus, the ratio of solute flux is the same as the ratio of water flux. Therefore, if one has demonstrated equivalency in terms of steady water flux, one has necessarily also demonstrated equivalency in terms of steady mass flux of solute.

Chemicals can also migrate through liners via diffusion. Two cases are considered:

1. Single Liner or Bottom Liner in Double Liner System. Theoretically, steady-state diffusion is never reached with a clay liner resting on native soil, unless there is a boundary condition, e.g., water table with uncontaminated water at a shallow depth below the liner. Conditions at a particular site must be considered in order to determine the pattern of diffusion through a liner resting on native soil. However, in nearly all cases essentially equivalent performance is anticipated from a GCL if the native soils are included in the assessment, as they should be.

2. Upper Liner in Double Liner System. Over time, the solute of interest in the leachate will diffuse to the base of the upper liner and into the underlying leak detection layer. The concentration at the base of the liner will eventually equal the concentration on top of the liner. Thus, the diffusion-driving concentration gradient will become zero and diffusive transport will cease. The issue of steady diffusion through an upper liner in a double liner system is moot.

Solutes can also migrate through soil liners by advection plus diffusion. However, since advective and diffusive mass fluxes are additive, and since the advective mass flux dominates, demonstration of equivalency in terms of water flux will generally ensure equivalency in terms of total mass flux.

Chemical Adsorption Capacity. Regulations generally have no specific adsorption requirements. Adsorption of organics tends to be different from adsorption of inorganics. Adsorption of inorganics is controlled by cation exchange reactions and geochemical processes such as precipitation. Adsorption of organic solutes is generally assumed to be controlled by the amount of organic carbon in the soil and a partition coefficient for the solute (which is characterized by the octanol-water partition coefficient or water solubility of the organic species).

For inorganics, the maximum adsorbed mass per unit cross-sectional area of liner (M) resulting from cation exchange processes may be defined as follows:

$$M = C \rho_d T \tag{8}$$

where C is the cation adsorption capacity (maximum mass of solute sorbed per unit mass of dry soil), ρ_d is the dry mass density of the soil, and T is the thickness of the liner. The ratio of thickness of a typical GCL to a CCL is small (on the order of 0.01). Thus, in order for a GCL to have equivalent cation adsorption capacity, the adsorption coefficient of the GCL would have to be at least 100 times that of the CCL.

The cation exchange capacity of bentonite clay is typically on the order of 100 to 150 meq/100g. Natural soil materials used to construct CCLs have typical CECs in the range of 3 to 30 meq/100g. The ratio of cation adsorption capacities, denoted F_{CEC}, is:

$$F_{CEC} = \frac{C_{GCL}}{C_{CCL}} = \frac{C_{GCL}}{C_{CCL}\,\frac{\rho_{dGCL}}{\rho_{dCCL}}}\;\frac{T_{GCL}}{T_{CCL}} \qquad (9)$$

For the typical range of values, F_{CEC} would be expected to be in the range of 0.03 to 0.75. It appears unlikely that equivalency can be demonstrated for cation adsorption capacity using the expressions just presented. However, cation exchange is just one of several processes that can affect adsorption. Precipitation of inorganic solutes can be a far more important mechanism than cation exchange, and pH is often a dominant variable controlling precipitation processes in many geochemical environments. Thus, site-specific factors, and not just simple comparisons of CECs and relative soil masses, will often need to be considered when relative adsorption capacities are compared.

Non-polar organic solutes are sorbed by carbon present in the soil. The carbon content of bentonite in GCLs is capable of estimation, but CCLs will be highly variable in their organic carbon content. Although site-specific assessments would be required (due to variability of CCLs), equivalency of a GCL to a CCL probably cannot be demonstrated in terms of capacity to adsorb non-polar constituents in leachate because the mass of bentonite present in a GCL is far less than the mass of soil present in a CCL.

Adsorption, however, is only relevant in the short term. When steady state mass transport is reached, adsorption capacity is exhausted. Equivalency in terms of adsorption, if evaluated at all, should be evaluated in terms of a specified performance period.

Breakout Time of Water or Solute. Neither GCLs, nor CCLs, are initially saturated with water. GCLs contain essentially dry bentonite, but CCLs are often close to being saturated at the time of construction. When liquid first enters the upper surface of an unsaturated liner, no liquid discharges from the base of the liner until the liner absorbs enough water to reach field capacity at the base of the liner.

The time to discharge water from the base of the liner is difficult to analyze in a simple way. For CCLs, the time depends greatly upon the hydraulic conductivity, initial water content, tendency to swell, and rate of water infiltration into the top of the liner. For GCLs, the time to initiate discharge of water from the base is usually fairly short (a few weeks) if the liner is continuously flooded with solute or may be extremely long if solute is slowly absorbed by the bentonite. For GCLs that contain a geomembrane, the time may be much greater. A comparison of time to initiate discharge of solute from the base of the liner would have to be performed on a site and product specific basis.

Regarding a landfill cover, a GCL might be compared to a CCL in terms of the time to discharge water from its base on the assumption that leachate production within the underlying waste would not begin until water is discharged from the base of the barrier layer. However, many would consider the "breakout time" of water from the barrier layer to be essentially irrelevant because over the long term, the time to initiate discharge water from the barrier layer is not important. Over the long term, the flux of water through the barrier layer is the important issue. A liner with a hydraulic conductivity of 1×10^{-9} cm/s allows only about 0.25 mm (0.01 inch) of water to flow through it per year under continuous exposure to a water source and unit hydraulic gradient. For those GCLs that contain a geomembrane, the presence of the geomembrane should be taken into account in the evaluation of breakout time.

In general, it is not believed that breakout time should be an important issue in an equivalency assessment. Other factors seem far more important.

Horizontal Flow in Seams or Lifts. The liquid flow just described is considered to be, and is laboratory measured as, the vertical flow through the clay matrix. Concerns are raised as to horizontal flow which might be more rapid and tend to increase the water or solute flux over a large area. For GCLs, the concern is clearly in the overlap seam area. Yet, large scale experiments tend to substantiate manufacturers recommendations that the overlap areas either self-seal or, by adding bentonite, co-mingle with the abutting geotextiles to form an adequate seal, LaGatta, (1992). For CCLs, the concern is between individual lifts with inadequate bonding from one surface to the next, Rogowski (1990). This issue, as with the GCLs, is clearly related to CQC/CQA monitoring which will be discussed later. If properly constructed, neither material should be a major concern with respect to horizontal liquid flow.

Horizontal Flow Beneath Geomembranes. When used as the lower component of a composite liner, both GCLs and CCLs must achieve "intimate contact" with the overlying geomembrane. The reason being that liquid (water or solute) passing through a hole in the geomembrane should not be able to spread horizontally attacking the underlying clay over an enlarged area.

Using a radial transmissivity device, laboratory test results on five different GCLs placed beneath a geomembrane with a small centrally located hole has been reported by Harpur, et al. (1993). Transmissivity test results at two different normal stresses were evaluated, see Table 3.

Table 3. Apparent transmissivities of various GM/GCL combinations compared to theoretical GM/CCLs.

Clay Beneath Geomembrane	Type of Bentonite	Type of Upper Geotextile Against Geomembrane	Apparent Transmissivity in Units of m^2/sec	
			7 kPa	70 kPa
GCL-A	adhesive/granules	none	3×10^{-12}	3×10^{-12}
GCL-B	power	woven-slit film	3×10^{-11}	9×10^{-12}
GCL-C	adhesive/granules	woven-spunlaced	8×10^{-11}	6×10^{-12}
GCL-D	granules	woven-slit film	2×10^{-10}	1×10^{-10}
GCL-E	powder	nonwoven-needled	1×10^{-10}	8×10^{-11}
theoretical best CCL lab conditions		none	6.4×10^{-10}	
theoretical best CCL field conditions		none	6.4×10^{-9}	

Comparing the GCL group with CCLs is difficult due to lack of data with GM/CCLs. However, theoretical data also shown in Table 3 indicates that all GM/GCL combinations evaluated are significantly lower in transmissivity than the anticipated GM/CCL transmissivity. Bentonite extruding through covering geotextiles, or intruding into them gives rise to these lower GM/GCL transmissivity values. While actual GM/CCL data needs to be developed it appears as though GCLs are superior to CCLs with respect to transmissivity.

For both GCLs and CCLs, the intimate contact issue can be challenged when the covering geomembrane has waves in it due to high temperature expansion. This is an equal concern for both GCLs and CCLs with no preference for one material over the other.

Generation of Consolidation Water. Application of normal stress to a CCL tends to squeeze water out of the clay matrix. If this were to occur in a landfill cover, the water migrating into the underlying waste would eventually become leachate. Dry GCLs have no capability to produce consolidation water upon loading. In general, the GCL should be viewed as superior to a CCL in terms of minimizing production of consolidation water. However, because the applied loads in final covers are so small, the entire issue of production of consolidation water is usually moot for covers. This issue is far more important for clay liners located above leak detection layers in double liner systems beneath landfills.

In double lined waste containment facilities at least six states require a composite primary liner located above a leak detection system for MSW, Fahim and Koerner (1993). For hazardous waste, the number is considerably higher. When the clay liner component is a CCL placed at, or near, saturation, each lift of solid waste placed in the facility causes consolidation to occur. The expelled water enters the leak detection system and invariably causes confusion. Is the liquid consolidation water or leachate passing through the entire primary composite liner? Only through chemical analysis (MS/GC testing) and comparison with the primary leachate can a definitive answer be given. Additionally, this generation of expelled pore water occurs with each lift of additional waste that is placed in the facility. It has been very troublesome (and difficult to interpret) at a number of facilities. Dry GCLs do not have this problem and can be considered superior in this regard.

Permeability to Gases. The permeability of a barrier layer to various gases may be very important if the barrier layer is expected to restrict the movement of gas through the cover of a MSW landfill. Decomposing MSW landfills produce methane, carbon dioxide and trace amounts of numerous other gases. For clay soils, the gas permeability is extremely sensitive to the water content of the soil. Dry clay materials are highly permeable to gases, but water-saturated clay materials are practically impermeable to gases.

Compacted clay liners are compacted at a water content that is wet of optimum. The volume of air present in the CCL tends to be very low. Conversely, the gas permeability of GCLs depends greatly on how much moisture has been absorbed by the bentonite. The gas permeability is high for dry bentonite sandwiched between two geotextiles. For GCLs that contain a geomembrane, the geomembrane dominates the material's gas permeability and gives it a very low permeability. Equivalency in terms of gas permeability probably can be demonstrated for GCLs that contain a geomembrane or for GCLs that are sufficiently hydrated to attain a low permeability to gages. The bentonite in the GCL can be forced to hydrate quickly either by placing the GCL in contact with a moist soil or by applying water to the overlying soil after the GCL is placed and covered. Laboratory tests indicate that absorption of water by the bentonite occurs within a few weeks, Daniel, et al. (1993). The hydration of the bentonite can be forced to occur if gas permeability is a critical issue.

While this discussion tends to favor CCLs, it must be mentioned that if the CCL cracks due to desiccation or differential settlement the preferred pathways will bypass the intact soil mass causing the CCL to become high in its gas permeability.

PHYSICAL/MECHANICAL ISSUES

A number of physical/mechanical issues must be addressed since an inadequate structural performance of either a CCL or a GCL could result in an inadequate hydraulic performance, or even result in a failed system.

Freeze/Thaw Behavior. CCLs are known to be vulnerable to large increases in hydraulic conductivity from freeze/thaw cycling, e.g., Kim and Daniel (1992), although compacted soil-bentonite mixtures may not be as vulnerable to damage. Limited laboratory data indicate that GCLs do not undergo increases in hydraulic conductivity as a result of freeze/thaw. Thus, from the available data, GCLs appear to be superior to CCLs in terms of freeze/thaw resistance.

Wet-Dry Behavior. Wetting and drying of CCLs and GCLs can cause the respective materials to swell or shrink. The main concern with CCLs is that desiccation can lead to cracking and to an increase in hydraulic conductivity.

Available laboratory data indicate that desiccation of wet GCLs does cause cracking, but rehydration of the GCL causes the bentonite to swell and the material to self heal, Kim and Daniel (1992). Thus, GCLs appear to be superior to CCLs in terms of ability to self-heal if the material is wetted, dried, and then rewetted.

Total Settlement Response. Total settlement refers to large scale settlement without significant bending or distortion of the liner system. Clearly, such settlement can be anticipated with MSW landfill covers. Hazardous solid waste (HSW) should be considerably more stable in this regard. Large scale (mass) settlement might also occur in liner systems placed as lateral or vertical expansions. It is believed that GCLs and CCLs would both respond similarly to total settlement and that neither would be damaged if there is no significant bending or distortion.

Differential Settlement Response. LaGatta (1992) studied the effects of differential settlement on the hydraulic conductivity of GCLs. He placed a water-filled bladder in a "false bottom" located beneath the GCL. The GCL was placed over the bladder and was then covered with 600 mm of gravel to simulate cover material. The GCL was flooded with 300 mm of water, and water draining out the bottom of the experimental apparatus was collected for 2 to 4 months, until the flow rate became steady. Then the bladder was incrementally deflated to produce a differential settlement. Boardman (1993) performed similar tests but subjected dry (rather than hydrated) GCLs to differential settlement; the GCLs were hydrated and permeated after the distortion took place in the dry material. The extreme differential settlement caused by the deflated bladders did not produce large increases in hydraulic conductivity for most of the GCLs tested.

Distortion is defined as the differential settlement, Δ, divided by the horizontal distance over which that settlement occurs, L, as shown in Figure 3. Distortion produces tension, which can lead to cracking. It appears from LaGatta's and Boardman's tests that many GCLs can withstand large distortion (Δ/L up to 0.5) and tensile strain (up to 10 to 15%) without undergoing significant increases in hydraulic conductivity. This finding is in sharp contrast to the results for compacted clay, which are summarized in Table 4 as compiled by LaGatta (1992). Normal compacted clay materials cannot withstand tensile strains greater than approximately 0.85% without failing by cracking. Pure bentonite, on the other hand, is reported to have a tensile strain at failure of 3.4%, but LaGatta measured much greater tensile strains without cracking in many GCLs, probably due to the beneficial reinforcing and/or confining effects from the geotextiles or geomembrane of the GCLs. In any case, the available data indicate that GCLs can withstand much greater tensile deformation than CCLs without cracking, which is a favorable characteristic for final covers. GCLs are considered to be superior to CCLs in terms of resistance to damage from differential settlement.

While this same discussion can be applied to the liner system beneath the solid or liquid waste the general situation is not as compelling since soil subgrades should be far more competent than with a body of solid waste. The notable exception, of course, is for vertical and lateral expansions of landfills over existing facilities. Here the situation described above for covers is even further exacerbated due to the high magnitudes of the applied normal stresses.

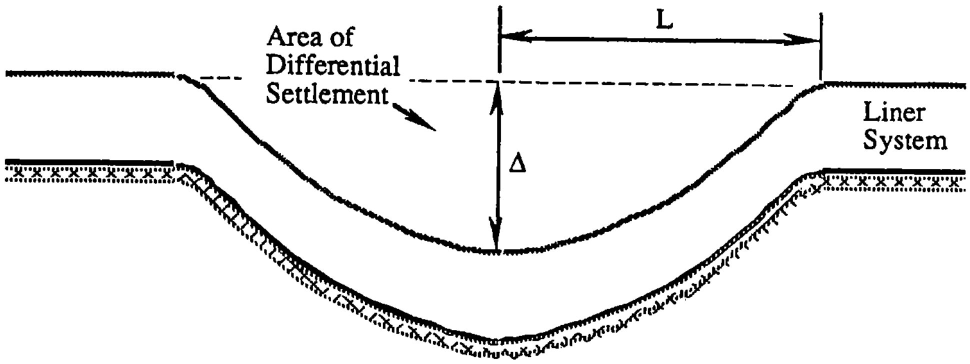


Figure 3. Definition of Liner Distortion "ΔL"

Table 4. Data on tensile strain at failure for compacted clay, LaGatta (1992).

Type or Source of Soil	Water Content (%)	Plasticity Index* (%)	Failure Tensile Strain (%)
Natural Clayey Soil	19.9	7	0.80
Bentonite	101	487	3.4
Illite	31.5	34	0.84
Kaolinite	37.6	38	0.16
Portland Dam	16.3	8	0.14
Rector Creek Dam	19.8	16	0.1
Woodcrest Dam	10.2	Non-plastic	0.18
Shell Oil Dam	11.2	Non-plastic	0.07
Willard Test Embankment	16.4	11	0.20

*Defined as the liquid limit minus the plastic limit per ASTM D4318

Slope Stability Considerations. The mid-plane shear strength of GCLs is obviously sensitive to the water content and type of GCL. Water-saturated GCLs that contain unreinforced, adhesive-bonded bentonite have angles of internal friction for consolidated-drained conditions of approximately 10 degrees. Dry or damp materials are 2 to 3 times higher than water-saturated GCLs. Also, needle-punched and stitch-bonded GCLs have higher strengths, at least in the short term. On-going creep studies of some types of hydrated needle punched GCLs, however, show that linear creep may occur at shear stresses of less than 50% of the short term strength. Whether these trends continue for all needle punched products at all normal stresses is not known. Note that it is possible to lock the needled fibers in place by adhesives or thermal fusion, and thus long term stability is possible. This same study shows that stitch bonded GCLs are very stable under similar conditions. Furthermore, the interface shear strength at the upper and/or lower surfaces of a GCL may be an issue depending on the type of surfaces of the GCL and the nature of the abutting material.

The shear strength of CCLs varies widely. Major factors include type of clay, percentage of clay, water content, density, etc. Thus no comparative conclusions with GCLs can be made.

For stability analyses involving composite liners, one often must consider interfacial shear with an adjacent layer, e.g., a geomembrane. No general statement can be made about equivalency of a GCL to a CCL in terms of interface shear strength because the assessment depends on the specific materials involved, degree to which the bentonite or clay can wet, slope angle, and other site-specific conditions. Even further, slope stability must sometimes be assured against seismic conditions. Again site specific or product specific conditions will be required to make an equivalency assessment.

Vulnerability to Erosion. Erosion resistance may be of concern in final covers if adequate cover soil is not present. With a well-designed and properly maintained cover system, the barrier layer should never be subjected to forces of erosion after the construction phase is over and equivalency should not be an issue. In some cases, however, there may be insufficient cover soil to guarantee that the barrier layer will not be exposed. Because of the presence of erosion-resistant geosynthetic materials in GCLs, most GCLs can potentially be more resistant to erosion than CCLs. However, if a GCL is exposed to erosive forces, the bentonite may be washed out of some products. Thus, equivalency depends upon the specific materials being considered. For many sites, erosion will not be of any concern, e.g., situations with adequate cover soil or for a GCL or CCL underlying a geomembrane.

In general, erosion is not a consideration for either GCLs or CCLs placed as a liner system beneath the waste.

Bearing Capacity (Squeezing). Both CCLs and GCLs must have adequate bearing capacity to support the applied normal stresses. The clay must not squeeze laterally becoming thinner in localized areas under concentrated loads, e.g., wheel loads from construction equipment or maintenance vehicles. Both static and dynamic loads must be resisted depending on the local situation. Even further, if a leak detection system is located beneath the CCL or GCL, fugative particles could clog the drainage layer rendering it ineffective.

Hydrated bentonite in GCLs is not as strong as the typical soils used in constructing CCLs hence GCLs are probably not equivalent to CCLs. However, under most circumstances, a GCL will provide adequate bearing capacity if the material is buried under sufficient soil overburden. Equivalency is heavily dependent upon site-specific conditions and the situation is essentially a design and CQC/CQA consideration and must be viewed as such.

CONSTRUCTION ISSUES

There are a host of construction issues which must be addressed in assessing equivalency of GCLs to CCLs. The best of designs can be defeated if installation is not possible, or is made so difficult so as to engender long term problems.

Puncture Resistance and Resealing. Geosynthetic clay liners are thin and, like all thin geosynthetic materials, are vulnerable to damage from accidental puncture during or after construction. In contrast, thick CCLs cannot be accidentally punctured. Some GCLs have the capability to self-seal around certain punctures, e.g., penetration of the GCL with a sharp object such as a nail. The swelling capacity of bentonite gives GCLs this self-healing capability. Of perhaps greater concern than penetration of the GCL by an object after construction is accidental puncture during construction. For example, if the blade of a bulldozer accidentally punctures the GCL during spreading of cover material, the GCL would probably not self seal in the vicinity of the puncture.

Geosynthetic clay liners will generally not have equivalent puncture resistance to CCLs. However, this does not mean that a GCL cannot meet or exceed the performance objectives of a compacted clay liner. Proper CQC/CQA procedures can be established and implemented to make the probability of puncture during construction extremely low. In final covers, one or two accidental punctures would probably not have a major impact on the overall performance of the barrier layer. In a bottom liner system subjected to a continuous head of leachate, a different conclusion would be drawn about the significance of undetected and unrepaired damage to a GCL from puncture. Ultimately, site-specific conditions and quality assurance procedures will be critical in dealing with the puncture issue and in establishing equivalency of a GCL to CCL for a particular project.

Subgrade Condition Considerations. Compacted clay liners are constructed with heavy equipment. If the subgrade is uneven a CCL can be placed and compacted in a straightforward manner. On the other hand, stones and rocks can cause localized thinning or even puncture of a GCL. If the subgrade contains stones or rocks, the integrity of the GCL will be compromised. Also, in order for the overlapped seams in a GCL to self seal properly, the overlapped panels must be placed on a very smooth and even subgrade. Subgrades with frozen ruts can be particularly troublesome for GCLs and their potential to thin out over the raised ridges is very high. Thus, equivalency of a GCL to a CCL in terms of the effect of subgrade clearly depends on the conditions of the subgrade. This, in turn, depends upon subgrade restrictions placed in the plans and specifications and on the level of CQC/CQA monitoring.

Subgrades must be very carefully prepared for the successful placement o a GCL. It is of significantly less concern when placing a CCL.

Ease of Placement or Construction. A GCL will always be easier to place than a CCL, unless weather conditions are adverse (e.g., constant rain), in which case even a GCL will also be difficult to construct. In general, GCLs are superior to CCLs in terms of ease of placement or construction.

Speed of Construction. GCLs can be placed much more quickly than CCLs. GCLs are superior to CCLs in terms of speed of construction.

Availability of Materials. Suitable clays for construction of a CCL may or may not be available locally, depending on the location of the site. Because GCLs are manufactured materials, they are readily available and can be shipped to a site quickly. The cost of shipment is usually not a large percentage of the total cost of a GCL. Thus, GCLs will always be at least equivalent to CCLs in terms of availability of materials and will be superior to CCLs at sites lacking local sources of suitable clay.

Requirements for Water. Construction water is necessary for many compacted clay soils in order to make a CCL. They are usually placed at a moisture content wet of optimum to achieve the desired low hydraulic conductivity. The total amount of water required to moisten a clay liner can be very large. For example, if a 600 mm thick compacted clay liner were to be constructed over a 5 ha site, and the natural water content of the soil had to be increased 5% to achieve the required moisture conditions, the total amount of water necessary would be approximately 1,500,000 liter. In arid regions, this water may represent a valuable resource, and in some remote locations, it may be very expensive to provide the water. Furthermore, if the only water available is from a local stream which is polluted, the expelled water during consolidation could be a concern in generating leachate or in masking leak detection liquids in double lined systems.

Geosynthetic clay liners do not require construction water and are superior to CCLs in this regard.

Air Pollution Concerns. Air pollution is a subject of great concern in some areas. Construction of CCLs liners tend to be an energy intensive activity with heavy equipment excavating, hauling, processing, spreading, and compacting the soil with repeated passes of heavy compactors. All of this activity adds to air pollution in terms of hydrocarbon emissions from the equipment and air-borne particulate matter (dust). GCLs are factory fabricated, shipped to the site, moved into position by machinery, and then unrolled (sometimes by hand). Air pollution at the factory during GCL manufacturing is generally carefully controlled and monitored. Relatively speaking, the impacts to air quality are less with a GCL than a CCL.

Weather Constraints. Compacted clay liners are difficult to construct when soils are wet, heavy precipitation is occurring, the weather is extremely dry (clay desiccates), the soil is frozen, or the temperature is below freezing. GCLs are difficult to construct during precipitation. Weather constraints during placement generally favor GCLs.

Some, if not all, GCLs must be covered before they hydrate. If a geomembrane will be placed over a GCL, the GCL must be covered almost immediately with the geomembrane. Construction should proceed downgradient with the geomembrane shingled over the edge of the GCL upon the completion of each day's work. If soil is placed over the GCL, backfilling must be kept as close as possible to the exposed edge. Furthermore, the exposed edge should be protected by a temporary membrane at the end of each day's work. The fact that many GCLs must be covered before they are hydrated can be a significant weather constraint for GCLs. CCLs also have weather constraints after placement. CCLs must not be allowed to freeze or desiccate, and wet weather often creates rutting and damage to the surface.

Equivalency in terms of weather constraints must be considered on a site-specific basis, but weather constraints generally favor GCLs over CCLs.

Quality Assurance Considerations. The proper construction of a low-permeability, CCL is a very challenging task. Careful control must exist over materials, moisture conditions, clod size, maximum particle size, surface preparation for a lift of soil, lift thickness, compaction coverage and energy, and protection of each completed lift. Comparatively, CQC/CQA requirements are much less rigorous for GCLs compared to CCLs, but no less critical. In general, while CQC/CQA for a CCL requires a number of relatively sophisticated tests and points of control by very experienced and capable personnel, CQC/CQA for GCLs is more nearly the application of common sense. Far fewer things can go wrong with the installation of a GCL compared to placement and compaction of a CCL. However, testing procedures and observational techniques are well established for CCLs but are not for GCLs. There are major ongoing efforts to establish testing methods for GCLs. ASTM Committee D-35 has recently dedicated an entire subcommittee to this particular material. While it would appear that GCLs are superior to CCLs in terms of ease of quality control, more work needs to be done to establish standard test methods and procedures for GCLs.

SUMMARY OF EQUIVALENCY ASSESSMENT

Clearly an equivalency analysis of GCLs to CCLs will be needed on a site-specific basis. Any broad conclusions that can be drawn will tend to be fairly general. However, a generalized summary of the technical equivalency issues just discussed will be attempted. Tables 5(a) and 5(b) are arranged to parallel the issues in Table 2 and just discussed. Table 5(a) is for liner systems beneath waste materials and Table 5(b) is for cover systems above the waste. Each table is arranged so as to counterpoint GCLs to CCLs in the following manner:

- the GCL is probably superior
- the GCL is probably equivalent
- the GCL is probably not equivalent
- equivalency depends on site specific or product specific conditions

Clearly, the "not equivalent" category of GCLs to CCLs in each table is most important. These issues will be discussed separately. Unfortunately, many issues fall into the "equivalency depends on site specific or product specific conditions" category. They, of course, remain unanswered at least in the generalized sense of this paper.

Table 5(a). Generalized technical equivalency assessment for liners beneath landfills and surface impoundments.

Category	Criterion for evaluation	GCL is probably superior	GCL is probably equivalent	GCL is probably not equivalent	Equivalency depends on site or product
Hydraulic Issues	Steady flux of water		X		
	Steady solute flux		X		
	Chemical adsorption capacity			X	
	Breakout time				
	Water				X
	Solute				X
	Horiz. flow in seams or lifts		X		
	Horiz. flow beneath geomembrane	X			
	Generation of consolidation water	X			
Physical/ Mechanical Issues	Freeze-thaw behavior	X			
	Total settlement		X		
	Differential settlement	X			
	Slope stability				X
	Bearing capacity			X	
Construction Issues	Puncture resistance			X	
	Subgrade condition			X	
	Ease of placement	X			
	Speed of construction	X			
	Availability of materials	X			
	Requirements for water	X			
	Air pollution concerns	X			
	Weather constraints				X
	Quality assurance considerations		X		

Regarding "chemical adsorption capacity" of GCLs in liner systems, equivalency cannot be shown. More of concern, however, is what impact does this issue have on the performance of a given facility. For example, if the liner is a GM/GCL composite the issue might be moot for a properly installed geomembrane. In the short term, absorption by the GCL may be adequate due to very low water flux. In the long term, the adsorption capacity of all liners may eventually be exhausted and is therefore not relevant. If the composite is the primary liner of a double liner system, the leak detection system will handle the liquid and adsorption is not relevant. Thus only when the GCL is used by itself can real concern be expressed, and even then, site-specific conditions are very important.

Regarding "bearing capacity", or squeezing, of hydrated GCLs there is concern for both liners and covers. The hydration of GCLs can be quite rapid. Within a few days, Daniel, et al. (1993) show that 40% moisture content can be attained from soil suction considerations. Concentrated loads from construction equipment and/or maintenance equipment can readily

Table 5(b). Generalized technical equivalency assessment for covers above landfills.

Category	Criterion for evaluation	GCL is probably superior	GCL is probably equivalent	GCL is probably not equivalent	Equivalency depends on site or product
Hydraulic Issues	Steady flux of water		X		
	Breakout time of water				X
	Horiz. flow in seams or lifts		X		
	Horiz. flow beneath geomembranes	X			
	Generation of consolidation water	X			
	Permeability to gases				X
Physical/ Mechanical Issues	Freeze-thaw behavior	X			
	Wet-dry behavior	X			
	Total settlement		X		
	Differential settlement	X			
	Slope stability				X
	Vulnerability to erosion				X
	Bearing capacity			X	
Construction Issues	Puncture resistance			X	
	Subgrade condition			X	
	Ease of placement	X			
	Speed of construction	X			
	Availability of materials	X			
	Requirements for water	X			
	Air pollution concerns	X			
	Weather constraints				X
	Quality assurance considerations		X		

cause squeezing and lateral migration of the hydrated bentonite in some GCL products. GCLs, thin to begin with, can further decrease in their thickness, to the point where the geotextiles are possibly touching one another. This issue must be addressed in design (e.g., to provide suitable thickness for haul roads and access roads) and in strict CQC/CQA procedures during construction.

Regarding "puncture resistance", thin GCLs do not have the same resistance as much thicker CCLs. Although the GCLs can be punctured during construction, careful CQC/CQA should be capable of addressing this potential problem. Further, for final covers, an occasional small puncture may be of little consequence. Indeed, puncture is probably of much greater concern for a bottom liner than for a final cover and of much more concern for single liner systems than for the upper liner in a double liner system. Also, if puncture is of concern, a layer of relatively low permeability soil or waste material may be placed below the GCL to provide a back-up should puncture occur at an isolated location. It should be stated, however, that GCLs enjoy several important advantages over a compacted clay liner which may more than offset its greater vulnerability to puncture.

Regarding "subgrade conditions", the thinness of GCLs is again at issue. With only 7 to 10 mm of thickness of a GCL to begin with, no amount of thinning is tolerable without negatively affecting the water or solute flux calculations provided earlier. Subgrade conditions must be specified as being free from stones, gravel, ruts (particularly when frozen) and all other perturbations in the subgrade material. When placed over the geonet of a leak detection system, rib indentation can cause GCL thinning. This is readily prevented by using the proper separation geotextile between the GCL and geonet, but must be designed accordingly. Thus adverse subgrade conditions can be eliminated as a issue of non-equivalency, but only with proper design and rigorous CQC/CQA procedures.

CONCLUSIONS AND RECOMMENDATIONS

Presented in this paper was an overview of geosynthetic clay liners (GCLs), with the intention of comparing and contrasting them to traditional soil liners. When used for waste containment, such soil liners are usually compacted clay liners (CCLs). However, instead of basing potential equivalency on non-quantifiable issues (like a lack of endorsement by regulatory agencies), three categories of technical issues were evaluated. They were hydraulic, physical/mechanical, and construction categories, each of which had numerous specific issues.

It was seen that there are numerous advantages of GCLs over CCLs. These include better resistance to freeze-thaw, better self healing characteristics in wet-dry conditions, less vulnerability to damage from differential settlement, less consumption of landfill space, easier placement, faster placement, lack of need for local clay materials, less need for construction water (relevant for arid areas), and greater ease of good quality assurance. Geosynthetic clay liners will probably cost less than compacted clay liners for many, and perhaps most, sites. The major disadvantages of GCLs are greater vulnerability to damage from puncture, poor subgrade conditions, lateral squeezing and subsequent thinning of the product. All are potentially controllable by proper design procedures and by rigorous CQC/CQA procedures. While not generally a critical issue, the chemical adsorption capacity of a GCL is lower than a CCL.

As suggested by Tables 5(a) and 5(b), many equivalency issues depend on the particular GCL product selected and the unique site specific conditions. In general, equivalency will have to be evaluated on a case-by-case basis. An important site-specific issue is likely to be slope stability. It may be difficult to provide adequate factors of safety against slope failure on relatively steep slopes that contain certain GCLs. However, designers have a choice of products and, as an option, a variety of reinforcement materials (such as geogrids and geotextiles) available for use, if necessary.

While no general conclusion can be reached about GCL equivalency to a CCL at all sites (either for liner or cover applications) it is expected that GCLs can be shown to provide better or equivalent performance at many sites.

Although GCLs are not without limitations, their favorable properties are sufficiently advantageous that owners, designers, and regulatory officials could give serious consideration to expanded use of GCLs as containment barrier materials. There is a need to reach agreement about the criteria upon which GCLs will be evaluated, and it is hoped that this paper will help to continue the dialogue that will ultimately lead to establishment of agreed upon and appropriate criteria to assess technical equivalency.

REFERENCES

Boardman, B. T., (1993) "The Potential Use of Geosynthetic Clay Liners as Final Covers in Arid Regions," M.S. Thesis, University of Texas, Austin, Texas.

Daniel, D. E., (1987) "Earthen Liners for Land Disposal Facilities," Proceedings, Geotechnical Practice for Waste Disposal, Univ. of Michigan, ASCE, June, pp. 21-39.

Daniel, D. E., (1993) "Geosynthetic Clay Liners (GCLs) in Landfill Covers," Proceedings SWANA Conference, San Jose, CA.

Daniel, D. E. and Boardman, B. T. (1993) "Report on Workshop on Geosynthetic Clay Liners," U.S. Environmental Protection Agency, Cincinnati, Ohio, in press.

Daniel, D. E. and Koerner, R. M., (1993) "Quality Control and Quality Assurance for Waste Containment Facilities," EPA/_____, August.

Daniel, D. E., Shan, H.-Y. and Anderson, J. D., (1993) "Effects of Partial Wetting on the Performance of the Bentonite Component of a Geosynthetic Clay Liner," Proceedings, Geosynthetics '93, Vancouver, B.C., IFAI Publ., pp. 1483-1496.

Estornell, P. and D. E. Daniel (1992) "Hydraulic Conductivity of Three Geosynthetic Clay Liners," Journal of Geotechnical Engineering, Vol. 118, No. 10, pp. 1592-1606.

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

Goldman, L. J., Greenfield, L. I., Damle, A. S., Kingsburg, G. L., Northein, C.M. and Truesdale, R. S. (1988) "Design, Construction and Evaluation of Clay Liners for Waste Management Facilities," EPA/530-SW-86-007-F, Cincinnati, OH, November.

Harpur, A., Wilson-Fahmy, R. and Koerner, R. M. (1993) "Transmissivity Measurement at the Geomembrane-to-Geosynthetic Clay Liner Interface," Proceedings 7th GRI Conference on Liners Systems: Innovations, Concerns and Design, IFAI, (in these Proceedings).

Kim, W. H. and D. E. Daniel (1992) "Effects of Freezing on the Hydraulic Conductivity of a Compacted Clay," Journal of Geotechnical Engineering, Vol. 118, No. 7, pp. 1083-1097.

LaGatta, M. D. (1983) "Hydraulic Conductivity Tests on Geosynthetic Clay Liners Subjected to Differential Settlement," M.S. Thesis, University of Texas, Austin, Texas, 1992, [also see Landfill and Surface Impoundment Performance Evaluation Manual, U.S. EPA SW-869, Technical Resource Document, Cincinnati, OH, April].

Rogowski, A. S. (1990) "Relationship of Laboratory and Field Determined Hydraulic Conductivity in Compacted Clay liners," EPA/600/2-90/025, Cincinnati, OH, June.

U.S. EPA (1986) "Saturated Hydraulic Conductivity, Saturated Leachate Conductivity and Intrinsic Permeability," EPA Method 9100, Cincinnati, OH.