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GEOSYNTHETIC CLAY LINERS (GCLs) IN LANDFILL COVERS

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ABSTRACT

Low-permeability, compacted clay liners are commonly required as a barrier to water infiltration in landfill covers. A relatively new material, known as geosynthetic clay liner (GCL), has been proposed as an alternative to a compacted clay liner. A GCL has the practical advantages of relatively low cost (approximately \$0.50 to \$0.60 per square foot for a landfill cover, installed), rapid installation with light-weight equipment, and ease of repair. A GCL also has several technical advantages, including greater tolerance for differential settlement and better self-healing characteristics under wet-dry and freeze-thaw conditions. A potentially important disadvantage of the GCL is that, because it is thin, it is more vulnerable to damage from puncture than a compacted clay liner. However, compacted clay liners are not without their problems, too, and designers, as well as regulators, of final landfill covers are encouraged weigh the advantages and disadvantages of the various materials before reaching a decision about the best material to use for a particular landfill.

Most regulatory agencies require that compacted clay, or the equivalent, be used as a barrier to water infiltration in final covers. Typically, a 1- to 2-ft-thick layer of compacted clay having a hydraulic conductivity (coefficient of permeability) $\leq 1 \times 10^{-7}$ cm/s is required. To achieve regulatory approval, an applicant who proposes to use a GCL rather than a compacted clay liner may be required to demonstrate that the GCL will perform in an equivalent manner to a compacted clay liner. If the GCL can be shown to be equivalent in terms of meeting performance objectives, a basis for regulatory approval is established.

The objectives of this paper are: (1) to provide an introduction to GCLs for those who may be unfamiliar with this lining material; (2) to summarize the potential applications of GCLs to landfill covers; (3) to examine the relative advantages and disadvantages of GCLs compared to compacted clay liners; and (4) to provide a generic assessment of performance equivalency of GCLs compared to low-permeability, compacted clay barriers. The fourth item will comprise the bulk of the paper. The conclusion is drawn that geosynthetic clay liners can be shown to provide equivalent performance to low-permeability, compacted clay liners for many landfill sites. The key issues concerning equivalency are ability to limit percolation of water through the barrier, permeability to gas, slope stability, and puncture resistance

INTRODUCTION TO GEOSYNTHETIC CLAY LINERS

The Material

Geosynthetic clay liners (GCLs) are thin "blankets" of bentonite clay attached to one or more geosynthetic materials (e.g., geotextile or 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 also a chemically stable mineral that has undergone complete weathering and will last, in effect, forever.

Geosynthetic clay liners are manufactured by laying down a layer of dry bentonite, approximately 1/4-inch thick, on a geosynthetic material and attaching the bentonite to the geosynthetic material. Two general configurations are currently employed in commercial processes: bentonite sandwiched between two geotextiles (Fig. 1a) or bentonite glued to a geomembrane (Fig. 1b). The primary purpose of the geosynthetic component or components is to hold the bentonite together in a uniform layer and permit transportation and installation of the material without losing bentonite or altering the thickness of the bentonite. However, the geosynthetic components may serve other important purposes, as well, such as adding tensile or shear strength to the material.

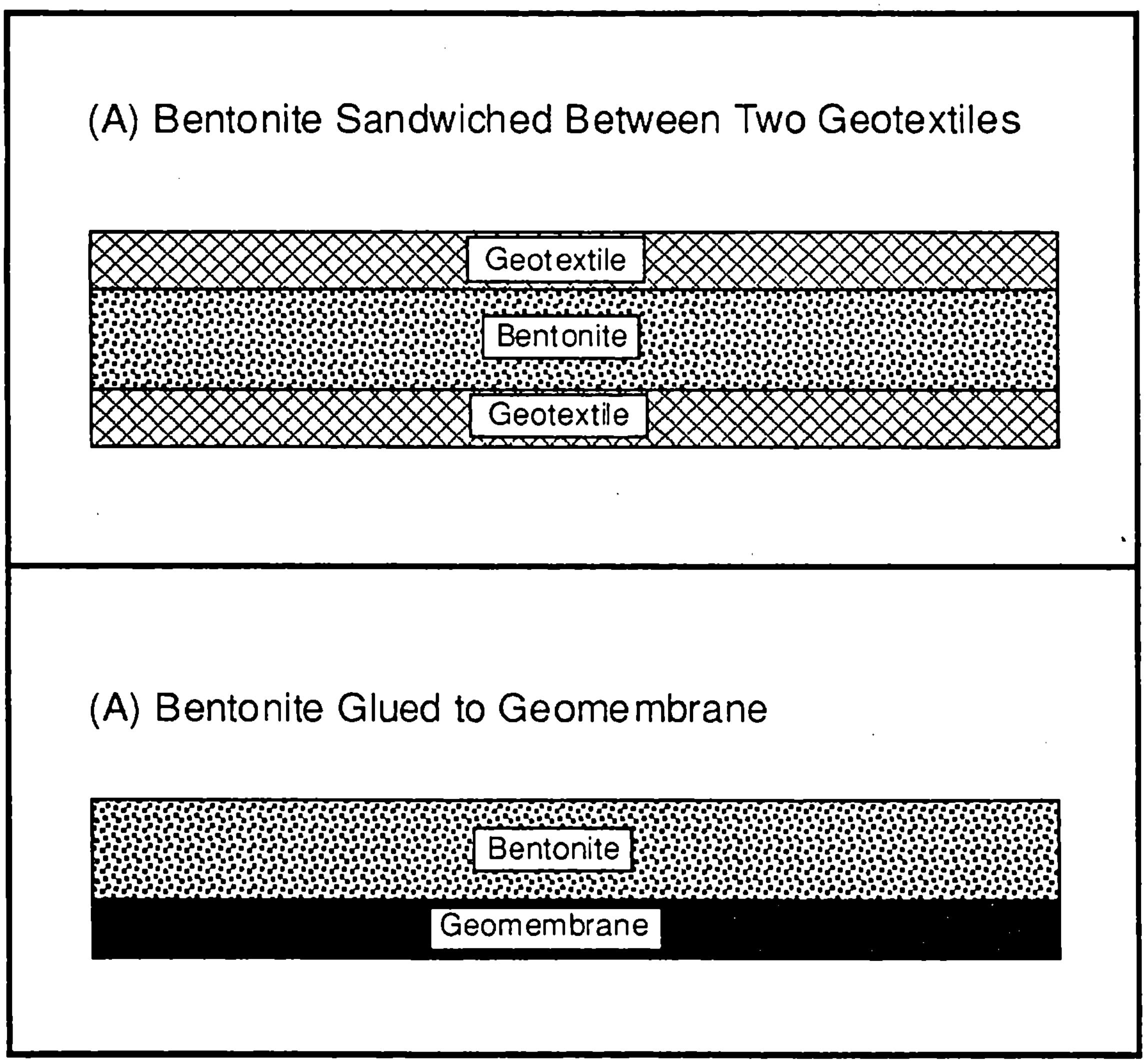

Figure 1. General Configuration of Geosynthetic Clay Liners.

bentonite component of a manufactured GCL is essentially dry, and there are open voids between bentonite granules in the manufactured material. When the bentonite is hydrated with water (for example, by imbibing water from underlying or overlying soils), the bentonite swells and the voids between bentonite granules close. The swelling action of bentonite is crucial to attainment of low permeability.

Geosynthetic clay liners contain approximately 1 pound per square foot of high-quality sodium bentonite that has a hydraulic conductivity (coefficient of permeability) of approximately 1×10^{-9} cm/s or less. Continuous gravity percolation under unit hydraulic gradient through a material with a hydraulic conductivity of 1×10^{-9} cm/s would result in an infiltration rate of 0.01 inches per year, or approximately 1 inch every 100 years. For landfill covers, an intact GCL may be considered essentially impermeable to water.

Geosynthetic clay liners were first manufactured in the early 1980's and were initially used for foundation water proofing and for sealing water retention structures. Geosynthetic clay liners were first used for landfill liners in 1986. Since 1986, geosynthetic clay liners have been used for a variety of lining applications and also in several final cover systems for hazardous wastes, radioactive wastes, and non-hazardous solid wastes.

Commercial Products

Four geosynthetic clay liners are currently manufactured: Bentofix®, Bentomat®, Claymax®, and Gundseal®. The GCLs fall into the broad categories shown in Fig. 1 as follows:

- Bentonite sandwiched between two geotextiles: Bentofix®, Bentomat®, and Claymax®
- Bentonite mixed with an adhesive and glued to a geomembrane: Gundseal®.

The GCLs are sketched in Fig. 2. Bentofix® and Bentomat® consist of bentonite sandwiched between a woven and non-woven geotextile that are needle-punched together. Claymax® 200R consists of bentonite mixed with glue and sandwiched between two woven geotextiles. Claymax® 500SP consists of bentonite mixed with glue and sandwiched between two woven geotextiles that are sewn together. The purpose of stitching the two geotextiles together is to provide additional internal reinforcement and greater shear strength. With all the geotextile-encased GCLs, special geotextiles can be selected to "custom design" the GCL to a particular application. Gundseal® is made by mixing bentonite with an adhesive and attaching the bentonite layer to a polyethylene geomembrane. Gundseal® can be supplied with high density polyethylene (HDPE) or very low density polyethylene (VLDPE), and the geomembrane can be either smooth or textured.

All GCLs are manufactured in panels with widths of approximately 13 to 17 ft and lengths of approximately 75 to 200 ft. The panels are placed on rolls at the factory and are unrolled at the time of installation. The weight of the roll varies, depending on size and materials, from about 1,400 to 4,000 pounds.

The panels are typically overlapped 3 to 12 in. during installation and are said to be "self sealing" at the overlap. A sketch of the overlapped zones is shown in Fig. 3. With geotextile-encased, needle-punched GCLs, sodium bentonite is placed along the overlap (Fig. 3a) at a rate of approximately 0.25 lb/ft. The bentonite penetrates the pores of the geotextiles and is said by the manufacturers to cause the materials to self seam when the bentonite hydrates. With geotextile-encased, adhesive-bonded GCLs, no additional bentonite is needed (Fig. 3b). The material is said to self seal upon hydration at the overlaps through expansion and "oozing" of bentonite out through the openings of the geotextile in the overlap area.

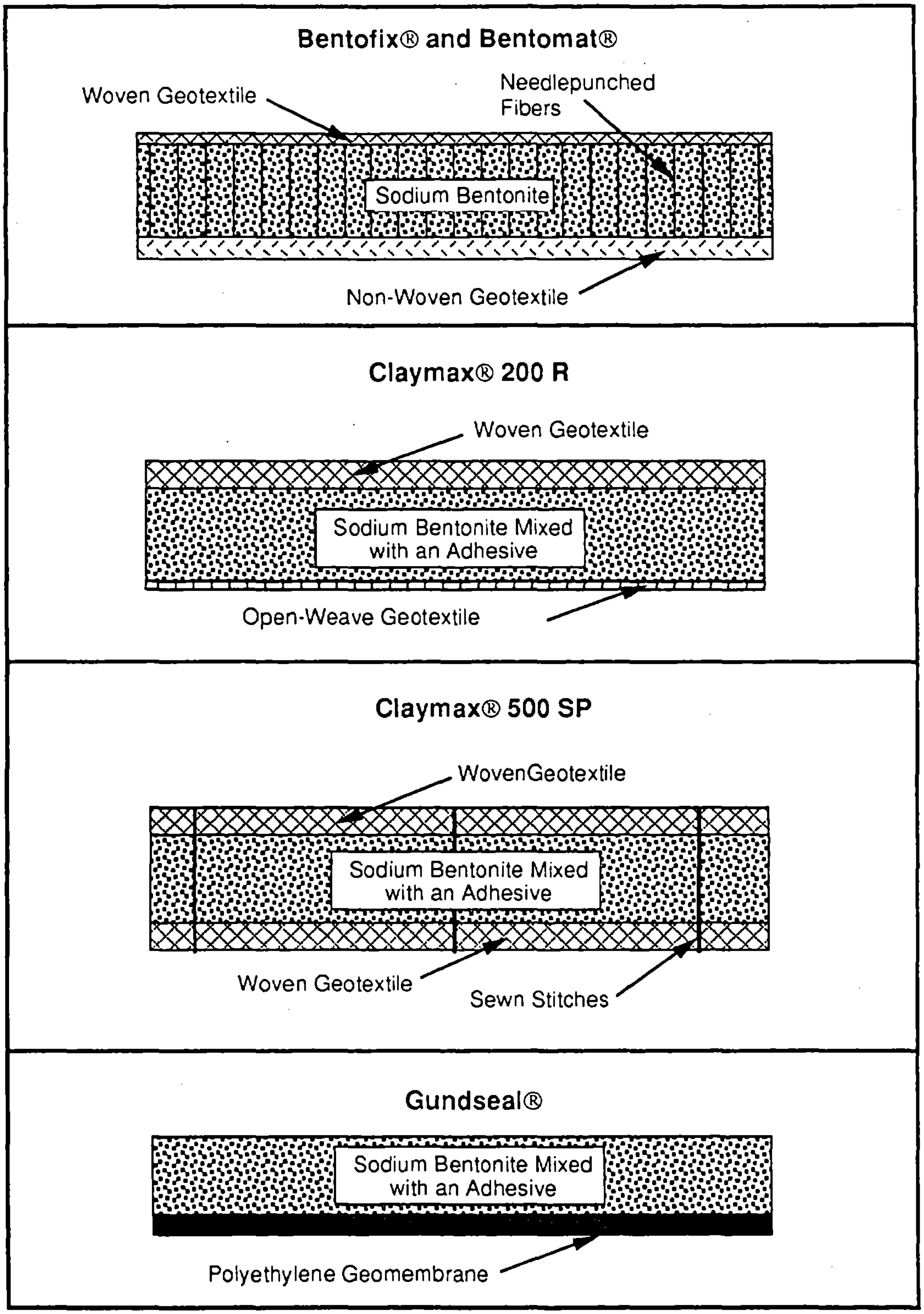

Figure 2. Commercially-Produced Geosynthetic Clay Liners.

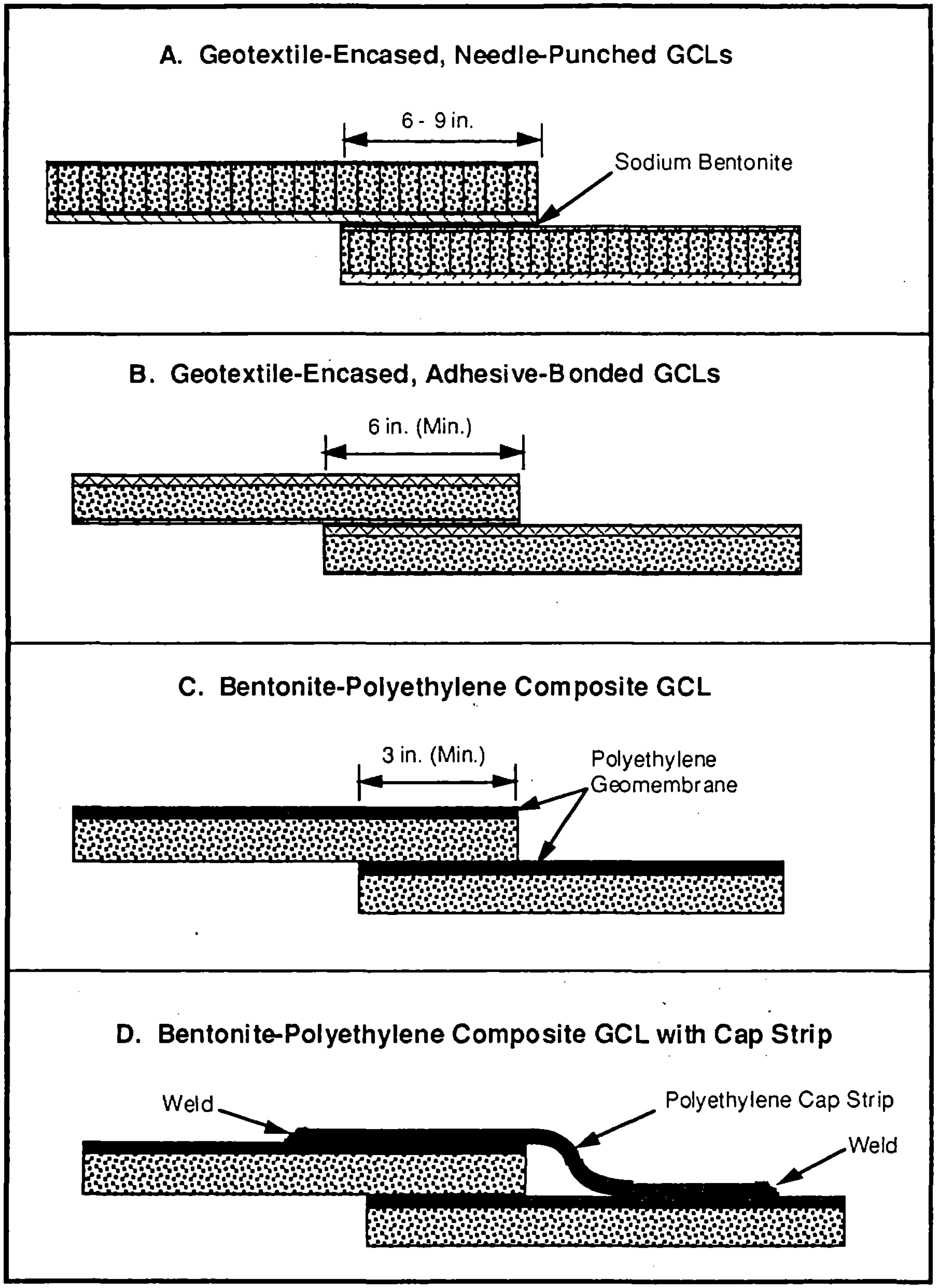

Figure 3. Overlapped Zone of Geosynthetic Clay Liners.

With GCLs containing a geomembrane, the GCL can be placed with the bentonite facing upward (Fig. 2) or, as shown in Fig. 3c and 3d, downward. If the GCL will be used by itself as a composite geomembrane-clay liner, the geomembrane would face upward. If a separate geomembrane is to be placed on the GCL, the bentonite would face upward. The material is said to be self sealing at overlaps with no need for any mechanical seam at the overlap (Fig. 3c). However, if one wants to form a continuous geomembrane out of the geomembrane component of the GCL, a cap strip can be welded over the overlap (Fig. 3d).

Potential Uses of Geosynthetic Clay Liners in Final Cover Systems

Geosynthetic clay liners can be used in final cover systems in several ways, as shown in Fig. 4. One choice (Fig. 4a) is to use the GCL by itself as a barrier to water infiltration. The GCL would be buried below a layer of protective soil. As indicated earlier, the bentonite component is expected to be essentially impermeable to water after it is has been hydrated, assuming that the GCL withstands the potentially damaging effects of wet-dry cycles and differential settlement (discussed later). One possible problem with using a GCL by itself as a barrier layer is that the dry bentonite is initially highly permeable to landfill gas -- the bentonite would have to absorb water, hydrate, and swell before the bentonite becomes an effective barrier to gas migration, and the bentonite could not be allowed to dry out because the bentonite would again become permeable to landfill gas. At extremely arid sites, there may not be adequate water available to hydrate the bentonite to the extent that is necessary in order for the GCL to have a low permeability to gas. However, for those GCLs that contain a geomembrane, the geomembrane itself provides a barrier to gas migration. In addition, a barrier to gas migration within the final cover may or may not be a design consideration, depending on site-specific considerations.

The second potential use of a geosynthetic clay liner in a final cover system is in conjunction with a geomembrane (Fig. 4b) to form a composite geomembrane/GCL liner. The composite could either be formed by using a GCL that contains a geomembrane or by separately constructing a geomembrane on top of a GCL. By placing clay under the geomembrane, the clay serves to seal off any imperfections in the geomembrane, e.g., pinholes or defects in seams, and to help in providing an extremely effective composite barrier to infiltration of water. The geomembrane would protect the underlying GCL from wet-dry cycles and would serve as a gas barrier for those periods when the bentonite component of the GCL is relatively dry. The main advantages of a separately-constructed geomembrane are that a separate polyethylene geomembrane liner could be seamed with the most advanced welding equipment available, which is microprocessor-controlled, dual-track, hot wedge welding equipment, or that some other type of geomembrane besides polyethylene could be used, if desired. If a bentonite-polyethylene composite GCL is used and the polyethylene components are to be seamed at overlaps, a cap strip is typically placed over the overlapped region and the edges of the cap strip are welded with fillet extrusion welding apparatus (Fig. 3d). However, because water flow through non-welded seams is expected to be negligible, the author encourages designers not to use cap strips over overlapped panels unless there is a good reason to do so.

A third option is to sandwich the GCL between two geomembranes (Fig. 4c). One or both geomembranes would be separately installed, depending upon the GCL material employed. The advantage of this design is that even less percolation of water through the barrier would occur. In fact, the bentonite component would become wetted only around minor imperfections in a geomembrane or its seams, where the bentonite would serve to seal off the leakage through the imperfection. This type of design approach, with a triple-composite liner, has rarely (if ever) been used for final covers over solid waste landfills and would be considered an extreme design for those facilities requiring extraordinary protection from water percolation or gas migration through the final cover.

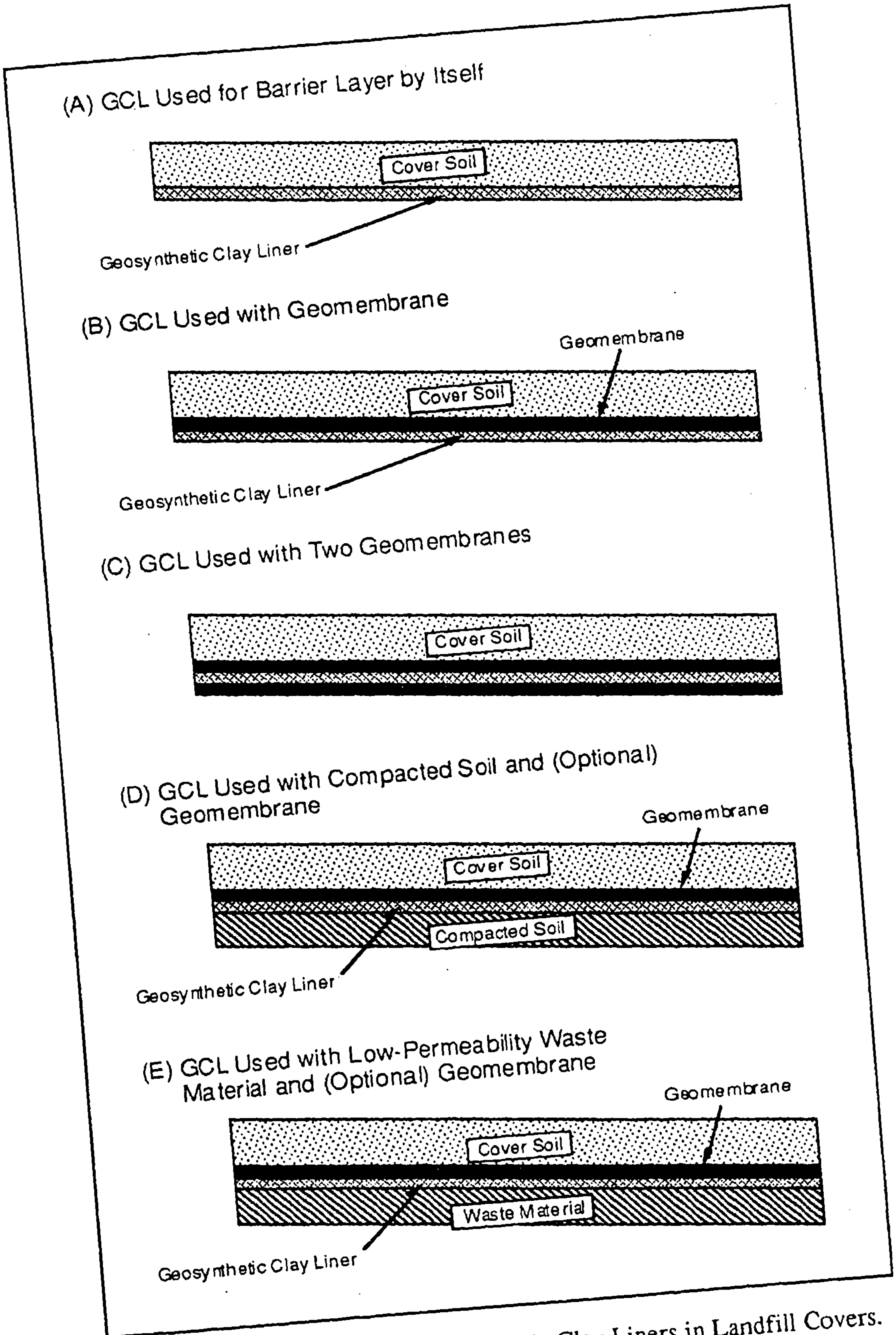

Figure 4. Potential Uses of Geosynthetic Clay Liners in Landfill Covers.

A fourth option is to place the GCL on top of a low-permeability, compacted soil liner (Fig. 4d), possibly with a geomembrane placed on top of the GCL (Fig. 4d). This design adds redundancy of materials and enables one to provide a very high degree of protection in the final cover system. In such cases, the GCL may replace part of a conventional compacted clay liner, or the low-permeability soil component may have a hydraulic conductivity that is greater than the usual 1×10^{-7} cm/s (i.e., use of the GCL lessens the need for extremely low permeability in the underlying soil barrier layer).

A fifth option is to place the GCL on top of a low-permeability, re-used waste material (Fig. 4e), possibly with a geomembrane placed on top of the GCL (Fig. 4e). This design adds redundancy of materials and enables one to make productive use of waste materials. An example of a waste material that might be considered is paper industry sludges (Maltby and Eppstein, 1993).

ENGINEERING PROPERTIES OF GCLs

Hydraulic Conductivity

In general, the hydraulic conductivity of the bentonite component of GCLs varies between about 1×10^{-10} and 1×10^{-8} cm/s, depending on the confining stress. The higher the compressive stress, the lower the hydraulic conductivity. There are some differences between the hydraulic conductivities of the various GCLs, but, except for bentonite-geomembrane composite GCLs (for which the geomembrane will significantly reduce the overall hydraulic conductivity), the differences do not appear to be very large. The available data are summarized by Schubert (1987), Daniel and Estornell (1990), Scheu et al. (1990), Daniel (1991), Eith et al. (1991), Shan and Daniel (1991), Estornell and Daniel (1992), Grube (1992), Daniel et al. (1993), and Daniel and Boardman (1993).

For a final cover system, a confining stress on the order of 200 psf to 600 psf is a reasonable range. Laboratory hydraulic conductivity tests performed on backpressure-saturated test specimens in flexible-wall permeameters indicate that the hydraulic conductivity of the bentonite component of GCLs in this range of compressive stress is approximately 1 to 4×10^{-9} cm/s. Estornell and Daniel (1992) measured the hydraulic conductivity of GCLs in large tanks. The tests were specifically set up to simulate conditions of low overburden stress that are typical of final cover systems and to test very large specimens with overlaps. Of the 10 tests for which hydraulic conductivities were measured, the average value was 4.6×10^{-9} cm/s (normal averaging) or 2.2×10^{-9} (logarithmic averaging). Based on all the data, a reasonable assumption is that a GCL can be supplied with a hydraulic conductivity for a landfill cover application less than 1 to 5×10^{-9} cm/s.

Studies of the hydraulic properties of overlapped seams performed by Estornell and Daniel (1992) indicate that the overlapped seams in GCLs self seam in the manner described by the manufacturers. For geotextile-encased, needle-punched GCLs with additional bentonite along the overlap, the bentonite appears to swell upon hydration and plug voids in the geotextiles present in the overlap. For the geotextile-encased, adhesive-bonded GCLs that have been tested, the bentonite within the GCL appears to ooze out through the openings in the geotextile and to allow the material to self seal. For bentonite-geomembrane composite GCLs, the bentonite swells upon hydration, seals at the bentonite-polyethylene interface, and effects self-seaming at the overlap. Thus, based on the available data, it is reasonable to assume that with proper quality control in the field, seams can be installed that will self-seal.

Strength

Internal Shear Strength. The internal shear strength of GCLs has been determined by the manufacturers and various organizations and testing laboratories. "Internal shear strength" refers to the strength of the material when sheared through the mid-plane of the bentonite. The author and his students at the University of Texas have performed independent tests, which are described below.

Direct shear tests were performed on square specimens that measured approximately 2.5 in. in length and width. Test specimens were cut from parent material, set up in a direct shear apparatus, and subjected to the desired normal load. For tests on water-saturated specimens, the specimens were then soaked with water and allowed to equilibrate; about 3 weeks were required before swelling ceased. Test specimens were sheared very slowly with failure occurring in 3 to 7 days. Results on water-saturated GCLs are summarized in Figure 5.

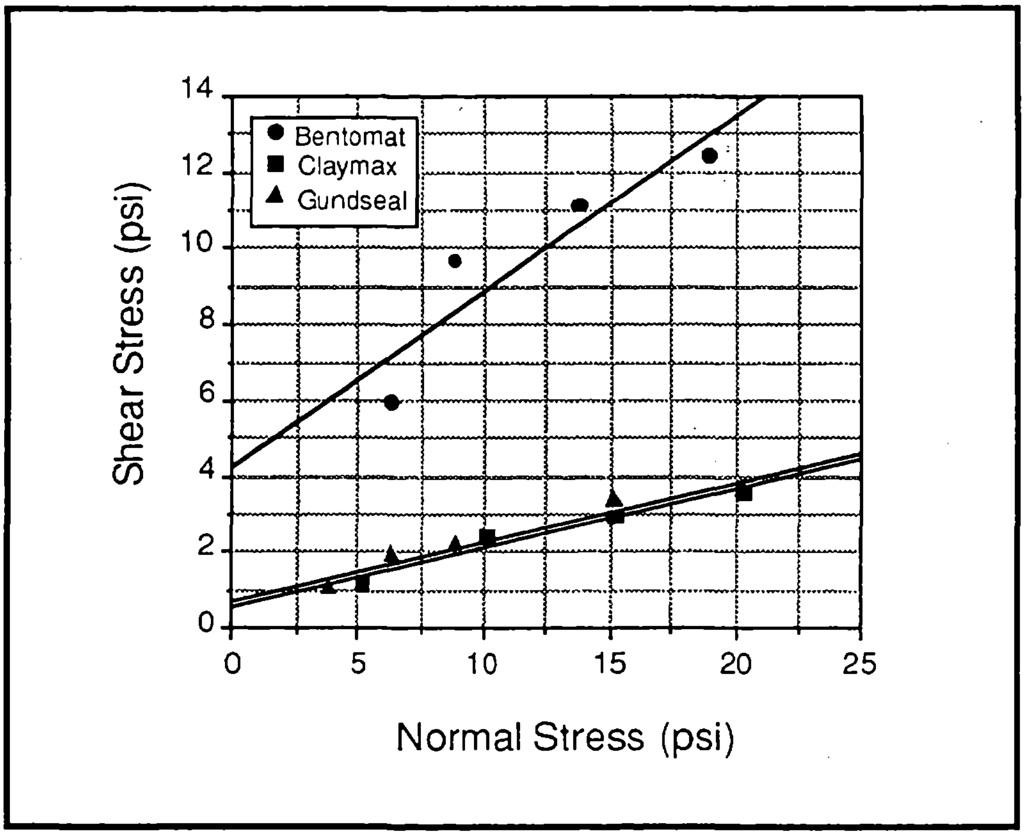

Figure 5. Results of Direct Shear Tests on Fully Hydrated GCLs.

The failure envelopes shown in this figure were determined from linear regression analysis, which yielded the following results:

Geosynthetic Clay Liner	Effective Cohesion (psi)	Angle of Internal Friction (Degrees)
Bentomat®	4.4	29
Claymax®	0.6	9
Gundseal®	1.2	8

The reader is reminded that these results are for completely water-saturated bentonite -- if the bentonite is encased between two geomembranes, it is unlikely that the bentonite will become saturated throughout.

Careful examination of the low-normal-stress region shows that the failure envelope is distinctly curved. This curvature is significant because it means that the materials are stronger at low compressive stresses (such as experienced in final covers) than other situations. In studies recently completed at the University of Texas, tilt-table tests were performed. Samples of GCL materials that measured 12 in. by 12 in. were set up on a tilt table, loaded with a steel plate, placed in a water bath, and allowed to fully hydrate. Then the table was slowly tilted over a period of several weeks until sliding occurred. The tilt table and direct shear data for one GCL (Gundseal®) are shown in Fig. 6. The failure envelope is obviously curved. Figure 7 presents the relationship between angle of internal friction and normal stress. For landfill covers, a typical range of normal stress is approximately 200 to 600 psf. Although the data are presented for only one GCL, similar trends are expected for other GCLs. Designers should exercise care in evaluation of shear strength data to ensure that the proper parameters for the conditions expected in the field are utilized in design.

Dry bentonite is much stronger than water-saturated bentonite. For dry GCLs or slightly damp GCLs, the angle of internal friction (even for the materials that are not internally reinforced) is approximately 35°. It is only if the material is hydrated that bentonite becomes weaker.

For those GCLs that are needle-punched or sewn together, the internal reinforcement of the GCL makes the material's internal shear strength much less sensitive to the strength of the bentonite contained between the attached geotextiles. However, the reader is cautioned that for landfill covers, the GCL may be exposed to prolonged shearing stresses for periods of years, decades, or even centuries, and that the long-term shearing resistance should be carefully considered.

Interfacial Shear Strength. "Interfacial shear strength" refers to the shearing strength between two adjacent components of a liner or cover system. The GCL may be placed against soil, a geomembrane, or a geotextile. Because the range of possible materials at an interface is unlimited, the actual interfacial shearing properties are usually determined on a project-specific basis. It is the author's experience that the internal shear strength will often govern the design because, with proper selection of materials, relatively high interfacial strengths can usually be obtained.

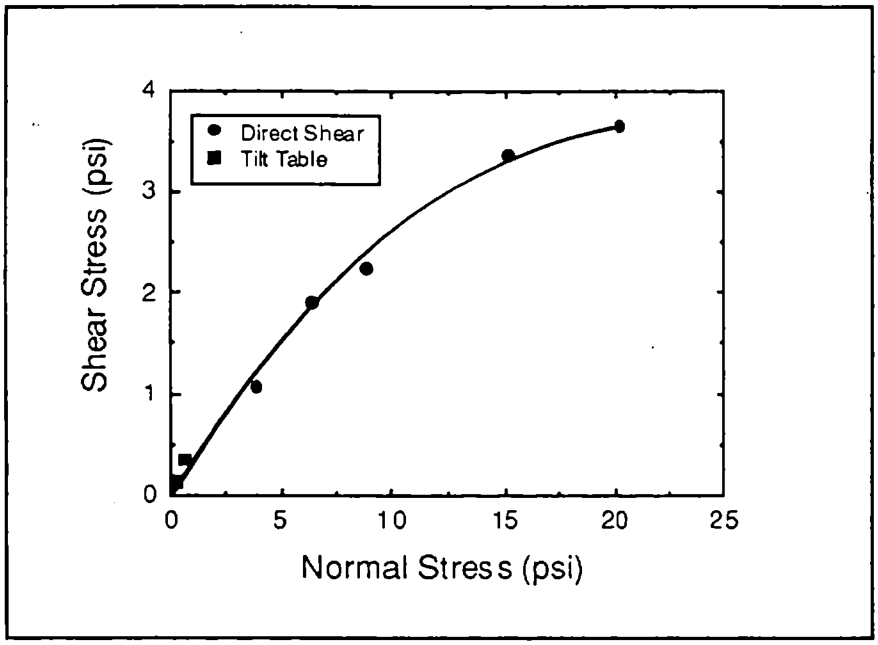

Figure 6. Failure Envelope for One Water-Saturated GCL Including Results of Tilt Table Tests.

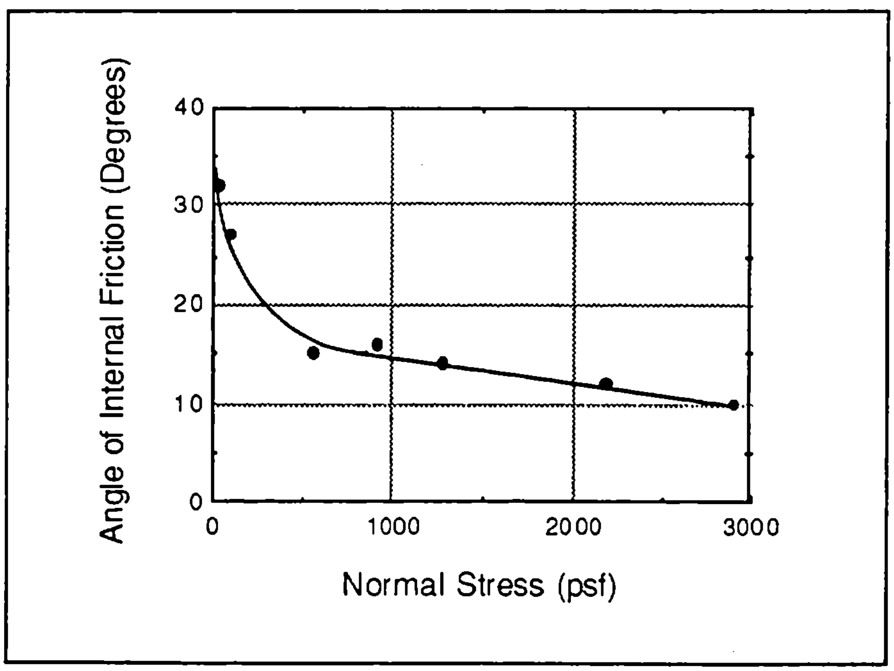

Figure 7. Influence of Normal Stress on Internal Shear Strength of One Water-Saturated GCL.

Tensile Strength

The tensile strength of a GCL is derived almost exclusively from the tensile strength of the geosynthetic components. For those GCLs that are constructed from unmodified geosynthetics (i.e., no needle-punching or other alteration of the parent geosynthetic material), the tensile strength of the GCL may be taken as the tensile strength of the geosynthetic components. For those GCLs whose geosynthetic components have been altered during the manufacturing of the GCL (i.e., needle-punched or sewn GCLs), tensile strength can be measured by performing a wide-width tensile test on the GCL material itself. Data on tensile properties of GCLs is available from the manufacturers.

Durability

Puncture Resistance. Shan and Daniel (1991) studied the effects of punctures on a geotextile-encased, adhesive-bonded GCL. The manufacturers of other GCL products have developed similar data for their particular products. The effects of punctures on the hydraulic conductivity of the GCL were studied by drilling or cutting circular holes into the dry GCL, setting the punctured GCL up in flexible-wall permeameters, and permeating the GCL slowly until steady flow was achieved. Results are summarized in the following table:

Diameter of Puncture	Hydraulic Conductivity (cm/s)
No Punctures	2×10^{-9}
0.5 in.	3×10^{-9}
1 in.	5×10^{-9}
3 in.	$> 1 \times 10^{-4}$

Small (≤ 1 in. diameter) punctures made in the dry material self-sealed upon hydration of the bentonite. These tests illustrate the self-healing capability of bentonite. Each particular GCL has a different capacity to self-heal punctures. However, all GCLs are capable of self healing small punctures in the dry GCL when the bentonite is hydrated. It should be emphasized that these tests were performed under carefully controlled conditions in which no material other than bentonite was allowed to fill the puncture. In the field, other materials may fill large punctures. Although GCLs have some capability to self-seal if punctured, there are clearly limitations in the size of puncture that could self seal in the field.

Desiccation. Concern has been expressed that the bentonite component of a GCL may swell when hydrated but may later dry out, shrink, crack, and lose its impermeability. Shan and Daniel (1991) investigated the healing capability of one geotextile-encased, adhesive-bonded GCL that was subject to wet-dry cycles. Samples of the GCL were permeated in a flexible-wall permeameter, removed from the permeameter, and allowed to air dry with a small vertical stress applied to the specimens. All specimens exhibited severe cracking upon drying. The specimens were then set back up in a flexible-wall permeameter, slowly rehydrated, and then repermeated. There was no change in hydraulic conductivity from the initial value of 2×10^{-9} cm/s, even after three wet/dry cycles. These tests reinforce the fully reversible shrink/swell nature of bentonite and suggest that any desiccation cracks will self-heal when the bentonite is hydrated.

In research recently completed at the University of Texas (Boardman, 1993), large samples of GCLs (with and without overlaps) were buried under 2 ft of gravel and subjected to a wet-dry cycle that simulates severe conditions that might occur in a final cover for a landfill. The GCLs were set up in the tanks, hydrated with water until a steady hydraulic conductivity was measured, and then severely desiccated by draining away the water on top of the GCL and circulating heated air into the gravel that was placed over the GCL. The heated air caused severe desiccation cracking in the GCLs. However, when the GCLs were rehydrated, the bentonite quickly swelled and the hydraulic conductivity eventually returned to the original, extremely low value. Thus, it appears from the available data that GCLs have an excellent capacity to self seal from desiccation-induced cracking. Geosynthetic clay liners probably possess much greater ability to self seal than conventional compacted clay liners.

Freeze/Thaw. Compacted clay liners are known to be vulnerable to damage from freezing. When water in soil freezes, the water expands, and when the water thaws, the water contracts. This expansion and contraction causes small cracks to appear in the soil and causes other alterations in the soil structure that tend to increase hydraulic conductivity.

Shan and Daniel (1991) subjected a geotextile-encased, adhesive-bonded GCL to freeze/thaw. A test specimen was set up in a flexible-wall permeameter, hydrated with water, and permeated until a steady hydraulic conductivity was obtained. Then the specimen was removed from the flexible-wall permeameter and subjected to five freeze/thaw cycles at constant water content. The specimen was repermeated, and it was found that the hydraulic conductivity did not change. Similar results have been obtained by commercial testing laboratories for other GCL products. Available data indicate that the high shrink-swell capability of bentonite gives bentonite the ability to self-heal if any alteration occurs from freeze/thaw cycles. Geosynthetic clay liners appear to have a much better capacity to remain undamaged after freeze-thaw than conventional compacted clay liners.

PERFORMANCE ASSESSMENT

Many regulatory agencies have traditionally required a low-permeability, compacted clay liner (or the equivalent) as the primary hydraulic barrier within landfill covers. The thickness of a compacted clay liner typically ranges from 1 to 2 ft (occasionally up to 3 to 4 ft), and the maximum allowable hydraulic conductivity is typically 10^{-7} cm/s. If one wishes to substitute a GCL for a compacted clay liner, one must usually demonstrate that the GCL will be equivalent in terms of meeting performance objectives. 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 are not very well defined. The lack of accepted criteria is perhaps the single greatest problem that the landfill designer and owner face in seeking regulatory approval for substitution of a GCL for a compacted clay liner.

One should not really think of a geosynthetic clay liner as being equivalent to a compacted clay liner. Indeed, a 1/4-in.-thick layer of bentonite could not possibly be equivalent to a much thicker layer of compacted clay in all respects. The critical issue is whether substitution of an alternative material such as a GCL for the more traditional compacted clay liner in a landfill cover will meet or exceed the performance objectives of the compacted clay liner. If the GCL will meet or exceed the performance objectives, then it should be considered that equivalency has been established.

Differences Between CCLs and GCLs

Some of the differences between compacted clay liners and geosynthetic clay liners are listed in Table 1.

Table 1 - Differences Between GCLs and Compacted Clay Liners.

Characteristic	Geosynthetic Clay Liner	Compacted Clay Liner
Materials	Bentonite, Adhesives, Geotextiles, and Geomembranes	Native Soils or Blend of Soil and Bentonite
Thickness	Approximately 1/2 inch	Typically 1 to 2 ft
Hydraulic Conductivity	≤ 1 to 5×10^{-9} cm/s	$\leq 1 \times 10^{-7}$ cm/s
Speed and Ease of Construction	Rapid, Simple Installation	Slow, Complicated Construction
Ease of Quality Assurance (QA)	Relatively Simple, Straight-Forward, Common-Sense Procedures	Complex QA Procedures Requiring Highly Skilled and Knowledgeable People
Vulnerability to Damage During Construction as a Result of Desiccation	GCLs Are Essentially Dry; GCLs Cannot Desiccate during Construction	Compacted Clay Liners Are Nearly Saturated; Can Desiccate during Construction
Availability of Materials	Materials Easily Shipped to Any Site	Suitable Materials Not Available at All Sites
Cost	Typically \$0.50 to \$0.60 per Square Foot for a Large Site	Highly Variable -- Estimated Range: \$0.50 to \$5.00 per Square Foot
Experience	Limited Due to Newness	Has Been Used for Many Years

Some of the potentially important (depending upon specific application) relative advantages of CCLs and GCLs may be summarized as follows:

- Key advantages of compacted clay liners (CCLs):
    - Many regulatory agencies require CCLs -- use of another type of liner may require time-consuming demonstration of equivalency to a CCL;

    - A CCL is a logical choice if large quantities of suitable clay are available locally;
    - The large thickness of CCLs makes them virtually puncture proof;
    - The large thickness of CCLs and the fact that they are constructed of multiple layers makes them relatively insensitive to small imperfections in any one layer;
    - There is a long history of use of CCLs;
    - Quality assurance procedures are reasonably well established for CCLs.
- Key advantages of geosynthetic clay liners (GCLs):
    - Small thickness of GCLs leads to low consumption of landfill space;
    - Construction of GCLs is rapid and simple;
    - GCLs can be shipped to any location -- their use is not dependent upon local availability of materials;
    - Heavy equipment is not needed to install a GCL, which is very helpful for final covers underlain by compressible waste (where compaction with heavy equipment is difficult);
    - Installation of a GCL requires less vehicular traffic and less energy use than placement and compaction of a CCL -- this also leads to less air pollution with a GCL;
    - Some inclement weather delays (e.g., freezing temperatures) that stop construction of CCLs are not a problem with GCLs;
    - Construction water is not needed with a GCL, which can be critical in arid areas where water resources are scarce;
    - Because a GCL is a manufactured material, a consistent and uniform material can be produced;
    - Because GCLs are manufactured materials, specialized performance properties can be determined and need not be repeatedly re-determined;
    - GCLs can accommodate large differential settlement;
    - Quality assurance is simpler for a GCL compared to a CCL;
    - GCLs are more easily repaired than CCLs;
    - GCLs can probably better withstand freeze/thaw and wet/dry cycles than CCLs;
    - GCLs are not vulnerable to desiccation damage during construction.

Criteria for Performance Assessment and Equivalency Analysis

Three broad issues may be addressed when one considers the equivalency of a GCL to a CCL:

1. Hydraulic issues;

2. Physical/mechanical issues;

3. Construction issues.

The specific technical issues that might have to be addressed for a particular site are listed in Table 2. For completeness, the issues are identified for both bottom liners and final covers. Only final covers are considered in the succeeding discussion.

Table 2 - Potential Equivalency Issues.

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	
	Production of Consolidation Water	X	X
	Permeability to Gas	X	X
Physical/ Mechanical Issues	Freeze-Thaw	X[1]	X
	Wet-Dry		X
	Total Settlement	X[2]	X
	Differential Settlement	X[2]	X
	Slope Stability	X[3]	X
	Erosion		X
	Bearing Capacity	X	X
Construction Issues	Puncture Resistance	X	X
	Subgrade Condition	X	X
	Ease of Placement	X	X
	Speed of Construction	X	X
	Availability of Materials	X	X
	Requirements for Water	X	X
	Air Pollution Effects	X	X
	Weather Constraints	X	X
	Quality Assurance	X	X

[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 expansions

[3]Stability of liner may not be relevant after filling, if no permanent slope remains

Hydraulic Issues. Hydraulic issues are the easiest to quantify. The criteria, which are discussed separately, include steady water flux, time to initiate release of water from the base of the liner ("breakout time"), production of consolidation water, and air permeability.

1. Steady Flux of Water

Water flux is defined as the volume of flow across a unit area in a unit time. For a barrier in a final cover system, water flux is equal to the rate of percolation of water through the barrier layer.

Water flux is usually analyzed based on the long-term, steady state water flux. The flux of water (v) through an individual layer of porous material is defined from Darcy's law as:

$$v = k \frac{H+T}{T} \tag{1}$$

where k is the hydraulic conductivity, H is the depth of liquid ponded on the liner, and T is the thickness of the liner. The water pressure on the base of the liner is assumed to be atmospheric pressure in Eq. 1.

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 considered in the equivalency analysis and in computation of water flux. The simplest way to do this is to adjust the hydraulic conductivity of the GCL to reflect the presence of a geomembrane. (Note: such a simplification does not mimic reality because water flows through a geomembrane via diffusion, and Darcy's law is not applicable to diffusion. Nevertheless, as a matter of computational convenience, one may make estimates of water flux by using appropriate values of equivalent hydraulic conductivity.) Also, Eq. 1 applies to a CCL or GCL liner alone and not to composite liners involving one or more separate geomembrane components. Composite action with a geomembrane is considered later.

The flux ratio for water, F_w, is defined as the flux through the GCL divided by the flux through the compacted clay liner (CCL):

$$F_w = v_{GCL} / v_{CCL} \tag{2}$$

or:

$$F_w = \frac{k_{GCL}}{k_{CCL}} \frac{T_{CCL}}{T_{GCL}} \frac{H+T_{GCL}}{H+T_{CCL}} \tag{3}$$

If the flux ratio is ≤ 1, then the GCL is equivalent to the CCL in terms of steady water flux. For example, for a situation with H = 1 ft (0.3 m) and a GCL with:

$$k_{GCL} = 1 \times 10^{-9}\ \text{cm/s} = 1 \times 10^{-11}\ \text{m/s}$$

$$T_{GCL} = 7\ \text{mm} = 0.007\ \text{m}$$

and a compacted clay liner (CCL) with:

$$k_{CCL} = 1 \times 10^{-7}\ \text{cm/s} = 1 \times 10^{-9}\ \text{m/s}$$

$$T_{CCL} = 2\text{ ft} = 0.6\text{ m}$$

then F_w from Eqs 3 equals 0.3, which means that there would be less water percolation through the GCL than a compacted clay liner -- equivalency is established for these conditions.

Alternatively, one can assume that water flux through the GCL is equal to the water flux through a CCL (i.e., $F_w = 1$):

$$v_{GCL} = v_{CCL} \tag{4}$$

and compute the required hydraulic conductivity of the GCL by substitution in Eq. 4:

$$k_{GCL} \frac{H + T_{GCL}}{T_{GCL}} = k_{CCL} \frac{H + T_{CCL}}{T_{CCL}} \tag{5}$$

to obtain:

$$(k_{GCL})_{Required} = k_{CCL} \frac{T_{GCL}}{T_{CCL}} \frac{H + T_{CCL}}{H + T_{GCL}} \tag{6}$$

Equation 6 may be used to determined the hydraulic conductivity of the GCL necessary to establish equivalency. So long as the job specifications require that the actual hydraulic conductivity be less than the value computed from Eq. 6, equivalency in terms of steady water flux is theoretically guaranteed. The required hydraulic conductivity of the compacted clay liner (k_{CCL}) is almost universally established as 1×10^{-7} cm/s by regulatory agencies in the U.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 liquid on the barrier layer is expected to be low in a final cover system; evapotranspiration and the nature of rainfall events makes the buildup of head on the barrier layer much less likely in final covers than in landfill liners. For illustrative purposes, three values of head of water (H) on the CCL or GCL are assumed: 0, 1 inch, and 1 foot. The required hydraulic conductivity of the GCL for equivalent performance to a compacted clay liner in terms of steady flux of water through the liner is computed as follows:

For a 1-ft-thick compacted clay liner:

- $(k_{GCL})_{Required} = 1 \times 10^{-7}$ cm/s for a negligibly small head of water on the liner
- $(k_{GCL})_{Required} = 2 \times 10^{-8}$ cm/s for a water head of 1 inch on the liner
- $(k_{GCL})_{Required} = 4 \times 10^{-9}$ cm/s for a water head of 12 inches on the liner

For a 2-ft-thick compacted clay liner:

- $(k_{GCL})_{Required} = 1 \times 10^{-7}$ cm/s for a negligibly small head of water on the liner
- $(k_{GCL})_{Required} = 2 \times 10^{-8}$ cm/s for a water head of 1 inch on the liner
- $(k_{GCL})_{Required} = 3 \times 10^{-9}$ cm/s for a water head of 12 inches on the liner

As discussed earlier, the hydraulic conductivity of the bentonite component of commercially-produced GCLs is typically ≤ 1 to 5×10^{-9} cm/s. Thus, it is clear that equivalency of a GCL to a CCL, in terms of the amount of water that passes through a GCL under conditions of steady seepage, can be established for most, if not all, landfill covers.

A GCL can also be used in conjunction with a layer of compacted soil as shown in Fig. 4d. In such cases, the compacted soil will tend to be thinner or be of higher hydraulic conductivity compared to the minimum requirements for compacted clay liners usually established by regulatory agencies. If the compacted soil liner were neither thinner nor more permeable than required by regulation, there would be no motivation to use a GCL, other than to provide redundancy.

By employing a GCL and a compacted soil liner (CSL) of hydraulic conductivity k_{CSL}, which is greater than the usual requirement for a compacted clay liner, one may be able to achieve an acceptable alternative to a conventional compacted clay liner. The equivalent hydraulic conductivity (k_{eq})of the composite GCL-CSL may be computed from the following equation:

$$k_{eq} = \frac{T_{GCL} + T_{CSL}}{\frac{T_{GCL}}{k_{GCL}} + \frac{T_{CSL}}{k_{CSL}}} \tag{7}$$

For example, if compacted soil liner has $k_{CSL} = 1 \times 10^{-6}$ cm/s and $T_{CSL} = 1$ ft, and the GCL is 7-mm-thick with a hydraulic conductivity of 1×10^{-9} cm/s, then the equivalent hydraulic conductivity (k_{eq}) is 4×10^{-10} cm/s, or roughly half the hydraulic conductivity of the GCL alone. The idea of combining GCLs with native soils is very appealing not only based on theoretical considerations but also because of the redundancy that the combination provides and the fact that a relatively low-permeability, native soil material is backing up the GCL. The situation depicted in Figure 4d and described in this paragraph is presented primarily to illustrate the options available to the designer in trying to meet regulatory agency concerns and yet use non-standard materials or designs.

A composite liner consists of a geomembrane placed in contact with a low-permeability soil. A geomembrane/GCL composite may be considered as an alternate to a geomembrane/CCL composite. If so, flow through the composite should be analyzed. The rate of flow through a flaw in a geomembrane in a composite liner depends on the size of the flaw, the hydraulic conductivity of the underlying clay component, the hydraulic gradient across the clay component, the hydraulic contact between the geomembrane and the clay component, and the presence of a geomembrane within the GCL. No equations have been published for explicit purpose of computing flow rates through a defect in a geomembrane component of a geomembrane/GCL composite liner. The presence of a geotextile between the geomembrane and bentonite may influence overall performance. This is a topic of current research. However, it is likely that equivalency can be demonstrated with reasonable assurance for some or all GCLs that are used with geomembranes to form composite liners.

2. Time to Initiate Discharge of Water from Base of Liner ("Breakout Time")

Geosynthetic clay liners and compacted clay liners are initially unsaturated with water. Geosynthetic clay liners contain essentially dry bentonite, but compacted clay liners are often very close to saturation 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.

A GCL might be compared to a CCL in terms of time to discharge of water from the bottom of the liner on the assumption that leachate production would not begin until water is discharged from the base of the barrier layer. However, many people 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 of water from the barrier layer is not important. Over the long term, the flux of water through the barrier layer (which controls the amount of leachate produced) is the important issue. As stated earlier, a liner with a hydraulic conductivity of 1 x 10^{-9} cm/s allows only about 0.01 inch of water to percolate through it per year under continuous exposure to a water source and unit hydraulic gradient. Again, for those GCLs that contain a geomembrane, the presence of the geomembrane should be taken into account in evaluation of breakout time.

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 water or may be extremely long if water 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 water from the base of the liner would have to be performed on a site and product specific basis.

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

3. Production of Consolidation Water

Application of load to a compacted clay liner tends to squeeze water out of the clay. If this were to occur in a cover, the water might eventually become leachate. Dry GCLs have no capacity to produce consolidation water loading 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 final covers. This issue is far more important for clay liners located above leak detection layers in bottom liner systems for landfills.

4. Air Permeability

The permeability of a barrier layer to gas may be very important if the barrier layer is expected to restrict the movement of gas through the cover. For porous materials, the air permeability is extremely sensitive to the water content of the soil. Dry materials are highly permeable to air, but water-saturated porous materials are practically impermeable to air.

Compacted clay liners are compacted at a water content that is wet of optimum. Any air present in the CCL tends to be present as isolated bubbles and not in continuous channels. Thus, the air permeability of CCLs tends to be very low. The air permeability of GCLs depends greatly on whether or not a geomembrane is present and how much moisture has been absorbed by the bentonite. The air permeability is high for dry bentonite that is sandwiched between two geotextiles. For GCLs that contain a geomembrane, the geomembrane dominates the material's air permeability and gives it a very low permeability to air. Equivalency in terms of air permeability probably can be demonstrated for GCLs that contain a geomembrane or for GCLs that are sufficiently hydrated to attain a low permeability to air. 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 air permeability is a critical issue.

Physical/Mechanical Issues

The physical/mechanical issues that might be considered in an equivalency analysis include freeze/thaw effects, wet/dry effects, response to total settlement, response to differential settlement, stability on slopes, vulnerability to erosion, and bearing capacity.

1. Freeze/Thaw Resistance

Compacted clay liners are known to be vulnerable to large increases in hydraulic conductivity from freeze/thaw (e.g., Kim and Daniel, 1992, and the references therein), although compacted soil-bentonite mixtures may not be as vulnerable to damage. As discussed earlier, 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.

2. Wet/Dry Effects

Wetting and drying of CCLs and GCLs can cause either type of clay liner to swell or shrink. The main concern with clay liners is that desiccation can lead to cracking and to an increase in hydraulic conductivity.

As discussed earlier, 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. Thus, GCLs appear to be superior to CCLs in terms of ability to self-heal if the material is wetted, dried, and then rewetted.

3. Response to Total Settlement

Total settlement refers to block-like settlement without significant bending or distortion. It is believed that GCLs and CCLs would both respond similarly to total settlement and that neither would be damaged if there is no bending or distortion.

4. Response to Differential Settlement

LaGatta (1992) studied the effects of differential settlement on the hydraulic conductivity of GCLs. LaGatta 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 2 ft of gravel to simulate cover material. The GCL was flooded with 1 ft 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 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 distoration 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 Fig. 8. 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 3 compiled by LaGatta (1992). Normal compacted clay materials cannot withstand tensile strains greater than approximately 0.85% without failing (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 effects from the geotextiles or geomembrane in the GCLs. In any case, the available data indicate that GCLs can withstand much greater tensile deformation than normal compacted soils without cracking, which is a very favorable characteristic for final covers. Geosynthetic clay liners are considered to be superior to compacted clay liners in terms of resistance to damage from differential settlement.

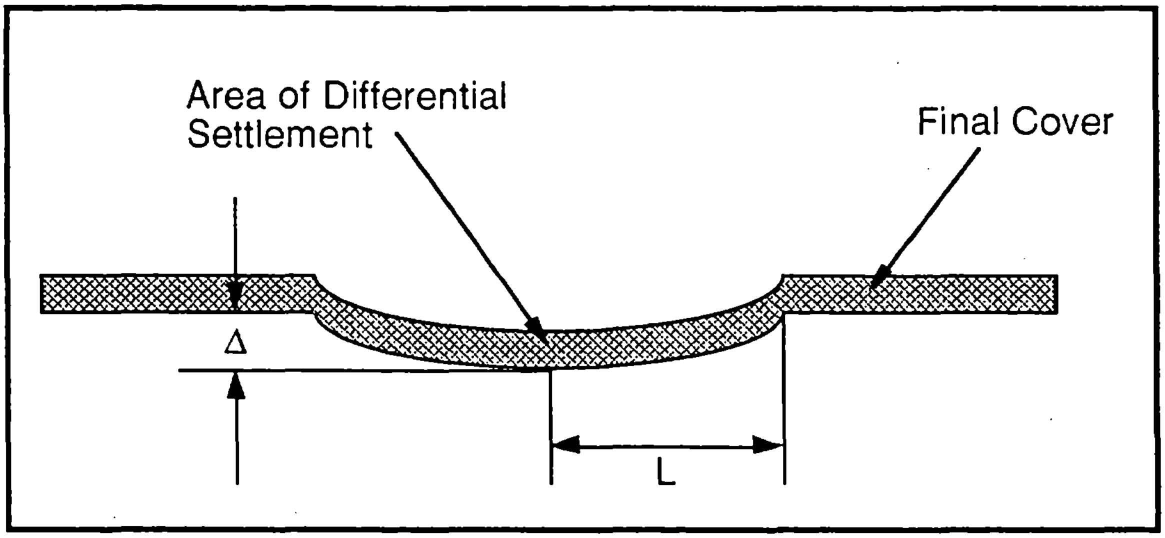

Figure 8. Definition of Distoration (Δ/L).

Table 3. Data on Tensile Strain at Failure for Compacted Clay (from 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	0.16%
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%

5. Stability on Slopes

The shear strength of GCLs is very sensitive to the water content and type of GCL (Shan and Daniel, 1991; and Daniel et al., 1993). 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 as strong as water-saturated GCLs. Also, needle-punched and stitch-bonded GCLs tend to have higher strengths, at least in the short term. The shear strength of CCLs varies widely, depending on materials, water content, and compaction conditions.

In stability analyses, one often must consider not only internal shear failure but 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 shear strength because the assessment depends on specific materials, the degree to which the bentonite can wet, slope angle, and other site-specific conditions.

6. Vulnerability to Erosion

Erosion resistance may be of concern in final covers if inadequate cover soil is 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 the clay liner is exposed to erosive forces, the bentonite may be washed out of some GCL materials. Thus, equivalency depends upon the specific materials being considered. For many sites, erosion will not be of any concern, e.g., for a GCL underlying a geomembrane or a cover with adequate cover soil.

7. Bearing Capacity

A clay liner must have adequate bearing capacity to support loads, e.g., wheel loads from construction or maintenance equipment. The clay liner must not thin or pump clay into adjacent layers under static or dynamic (e.g., traffic) loads.

Hydrated bentonite is not as strong as most materials used in constructing CCLs. However, under most circumstances, both a GCL and a CCL will provide adequate foundation bearing capacity, particularly if the GCL or CCL is buried under sufficient soil overburden. Equivalency is heavily dependent upon site-specific conditions.

Construction Issues

The construction issues that might be considered in an equivalency analysis include puncture resistance, effect of subgrade condition on constructability, ease of placement, speed of construction, availability of materials, requirements for water, air pollution effects, weather constraints, and quality assurance requirements.

1. Puncture Resistance

Geosynthetic clay liners are thin and, like all thin liner materials, are vulnerable to damage from accidental puncture during or after construction. 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 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 at the puncture.

The puncture resistance of GCLs will generally not be equivalent to that of CCLs. However, this does not mean that a GCL cannot meet or exceed the performance objectives of a compacted clay liner. Quality assurance and quality control 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 liquid, a different conclusion might 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 issue of puncture and in establishing equivalency of a GCL to a CCL for a particular project.

2. Effect of Subgrade Condition

Compacted clay liners are constructed with heavy equipment. If the subgrade is compressible (e.g, solid waste), the GCL, which can be installed with lightweight equipment, will be easier to construct. On the other hand, stones and rocks can puncture a GCL but not a CCL; if the subgrade contains stones or rocks, the integrity of the GCL may be compromised. Also, in order for the overlapped seams in a GCL to self seal properly, the overlapped panels must be placed on a reasonably smooth and even subgrade. Thus, equivalency of a GCL to a CCL in terms of the effect of subgrade depends on the condition of the subgrade and will have to be evaluated on a site-specific basis.

3. Ease of Placement or Construction

A GCL will generally be easier to place than a CCL, except under rainy conditions -- both GCLs and CCLs are difficult or impossible to construct in heavy rain. In general, GCLs are superior to CCLs in terms of ease of placement or construction.

4. Speed of Construction

Geosynthetic clay liners can be placed much more quickly than CCLs. Geosynthetic clay liners are superior to compacted clay liners in terms of speed of construction.

5. Availability of Materials

Suitable clays for construction of a CCL may or may not be available locally, depending on the site. Because GCLs are a manufactured material, 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.

6. Requirements for Water

Construction water is necessary for many compacted clay soils, which must usually be 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 2-ft-thick compacted clay liner were to be constructed over a 10-acre site, and the water content of the soil had to be increased 5% to achieve the required moisture conditions, the total amount of water used would be approximately 600,000 gal. In arid regions, this water may represent a valuable resource, and in some remote locations, it may be very expensive to provide the water.

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

7. Air Pollution Effects

Air pollution is a subject of great concern in some areas. Construction of compacted clay liners tends to be an energy intensive activity with heavy equipment excavating the soil, hauling the soil, processing the soil, spreading the soil, 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). Geosynthetic clay liners are shipped to the site, moved into position by machinery, and then unrolled (sometimes by hand). Relatively speaking, the impacts to air quality are less with a GCL than a CCL.

8. 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. Geosynthetic clay liners are difficult to construct during precipitation. Weather constraints generally favor GCLs.

Some, if not all, GCLs must be covered before they hydrate. If a geomembrane will be placed over the GCL, the GCL must be covered almost immediately with the geomembrane. Additional weather constraints, e.g., wind speed, may apply to the geomembrane and, indirectly, influence the GCL. The fact that many GCLs must be covered before they are hydrated can be a significant weather constraint for GCLs. However, CCLs have weather constraints, too: CCLs must not be allowed to freeze or desiccate, and wet weather often brings construction of compacted clay liners to a halt. GCLs cannot desiccate during construction because they are dry, and dry GCLs are unaffected by freezing temperatures.

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

9. Ease of Quality Assurance

The proper construction of a low-permeability, compacted clay liner 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, quality assurance (QA) requirements are much less extensive for GCLs compared to CCLs, but no less critical. In general, while QA for a compacted clay liner requires a number of relatively sophisticated tests and points of control by very experienced and capable personnel, QA 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. Many people are working to establish testing methods for GCLs. 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 for GCLs.

Summary of Equivalency Issues

Table 4 summarizes the preceding discussion of equivalency. Equivalency can be demonstrated generically in many categories. In several areas, geosynthetic clay liners (GCLs) are clearly superior to compacted clay liners. However, in one category, equivalency probably cannot be demonstrated: thin GCLs do not have the same resistance to puncture as much thicker compacted clay liners. Although thin GCLs can be punctured during construction, careful QA 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 a final cover. 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. In any case, the GCL enjoys several important advantages over a compacted clay liner which may more than offset greater vulnerability to puncture.

As suggested by Table 4, many equivalency issues depend on the GCL product and the particular conditions unique to a given site. Equivalency will have to be evaluated on a case-by-case basis. The most important site-specific issues are likely to be permeability to gas and slope stability. It may be difficult to provide adequate factors of safety against slope failure on relatively steeply sloping final covers that contain GCLs, but designers have a variety of reinforcement materials (such as geogrids) available for use, if necessary.

Table 4 - Potential Equivalency Issues.

		Equivalency of GCL to CCL			
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
	Production of Consolidation Water	X			
	Permeability to Gas				X
Physical/ Mechanical Issues	Freeze-Thaw	X			
	Wet-Dry	X			
	Total Settlement		X		
	Differential Settlement	X			
	Slope Stability				X
	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 Effects	X			
	Weather Constraints				X
	Ease of Quality Assurance	X			

CLUSIONS

In this paper the characteristics of geosynthetic clay liners (GCLs) have been described and potential applications of GCLs in final covers for landfills have been discussed. Current regulations typically require that a final cover contain a compacted clay liner (CCL) with a thickness of 1 to 2 ft and a maximum hydraulic conductivity of 1 x 10^{-7} cm/s. The issue is whether it is sensible to replace all or part of the compacted clay liner with a GCL in final covers at some landfill sites.

There are several advantages of GCLs over CCLs, including 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 requirement for construction water (relevant for arid areas), and easier quality assurance. Geosynthetic clay liners will probably cost less than compacted clay liners for many, and perhaps most, sites. The major draw-backs of GCLs are greater vulnerability to damage from puncture, concern over shear strength on slopes, high permeability of dry bentonite to landfill gas if the GCL remains dry (e.g., in an extremely arid location), and lack of explicit endorsement of GCLs by regulatory agencies.

A framework has been established in this paper for evaluating whether or not a GCL can meet the same performance objectives as a compacted clay liner used in a landfill cover. Three main criteria were established: hydraulic performance, physical and mechanical performance, and construction issues (including quality assurance). For landfill covers, geosynthetic clay liners can be shown to provide equivalent or superior performance to compacted clay liners in many respects. However, some performance considerations (e.g., slope stability) depend on site and product specific considerations. Thus, no generic conclusion can be reached about equivalency of a GCL to a CCL at all sites -- an equivalency assessment is needed on a project-specific basis. It is expected that GCLs can be shown to provide superior or equivalent performance at many landfill sites.

Although GCLs are not without limitations, their favorable properties are sufficiently advantageous that landfill owners, designers, and regulatory officials should give serious consideration to expanded use of GCLs in landfill covers. 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 initiate a dialogue that will ultimately lead to establishment of appropriate criteria.

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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, 109 p.

Daniel, D.E. (1991), "Geosynthetic Clay Liners," *Geotechnical News*, Vol. 9, No. 4, p. 28-33

Daniel, D.E., and P.M. Estornell (1990), "Compilation of Information on Alternative Barriers for Liner and Cover Systems," U. S. Environmental Protection Agency, EPA 600/2-91/002, Cincinnati, Ohio, 81 p.

Daniel, D.E., Shan, H.Y., and Anderson, J. (1993), "Effects of Partial Wetting on Strength and Hydrocarbon Permeability of a Geosynthetic Clay Liner," *Proceedings, Geosynthetics '93*, International Fabrics Association International, Vol. 3, pp. 1483-1496..

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

Eith, A.W., Boschuk, J., and R.M. Koerner (1991), "Prefabricated Bentonite Clay Liners," *Landfill Closures: Geosynthetics, Interface Friction, and New Developments*, R.M. Koerner (Ed.), Elsevier Applied Science, New York, pp. 193-218.

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.

Grube, W.E. (1992), "Geosynthetic Liners Offer Cover Option," *Environmental Protection*, May, pp. 29-33.

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

LaGatta, M. D. (1992), "Hydraulic Conductivity Tests on Geosynthetic Clay Liners Subjected to Differential Settlement," M.S. Thesis, University of Texas, Austin, Texas.

Maltby, V., and L.K. Eppstein (1993), "A Field-Scale Study of the Use of Paper Industry Sludges as Hydraulic Barriers in Landfill Cover Systems," *Hydraulic Conductivity and Waste Contaminant Transport in Soils, ASTM STP 1142*, D. E. Daniel and S. J. Trautwein (Eds.), American Society for Testing and Materials, Philadelphia, in press.

Scheu, C., Johannben, K., and F. Saathoff (1990), "Non-Woven Bentonite Fabrics - A New Fibre Reinforced Mineral Liner System," *Geotextiles, Geomembranes and Related Products*, D. Hoet (Ed.), Balkema Publishing, Rotterdam, pp. 467-472.

Schubert, W.R. (1987), "Bentonite Matting in Composite Lining Systems," *Geotechnical Practice for Waste Disposal '87*, American Society of Civil Engineers, New York, pp. 784-796.

Shan, H.Y., and D.E. Daniel (1991), "Results of Laboratory Tests on a Geotextile/Bentonite Liner Material," *Proceedings, Geosynthetics '91*, Industrial Fabrics Association International, St. Paul, MN, Vol. 2, pp. 517-535.

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16. ABSTRACT Low-permeability, compacted clay liners are commonly required as a barrier to water infiltration in landfill covers. A relatively new material, known as geosynthetic clay liner (GCL), has been proposed as an alternative to a compacted clay liner. A GCL has the practical advantages of relatively low cost (approximately $0.50 to $0.60 per square foot for a landfill cover, installed), rapid installation with light-weight equipment, and ease of repair. A GCL also has several technical advantages, including greater tolerance for differential settlement and better self-healing characteristics under wet-dry and freeze-thaw conditions. A potentially important disadvantage of the GCL is that, because it is thin, it is more vulnerable to damage from puncture than a compacted clay liner. The objectives of this paper are: (1) to provide an introduction to GCLs for those who may be unfamiliar with this lining material; (2) to summarize the potential applications of GCLs to landfill covers; (3) to examine the relative advantages and disadvantages of GCLs compared to compacted clay liners; and (4) to provide a generic assessment of performance equivalency of GCLs compared to low-permeability, compacted clay barriers. The fourth item will comprise the bulk of the paper. The conclusion is drawn that geosynthetic clay liners can be shown to provide equivalent performance to low-permeability, compacted clay liners for many landfill sites. The key issues concerning equivalency are ability to limit percolation of water through the barrier, permeability to gas, slope stability, and puncture resistance.

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