InterLoK, a new GCL with K = 1 x 10^{-9} cm/s

The purpose of this technical reference is to evaluate the hydraulic performance of a new GCL, InterLoK, compared to standard GCLs and traditional compacted clay liners (CCLs). InterLoK is manufactured by adding non-biodegradable, high-viscosity polymers to high-swell, low-fluid loss sodium bentonite. The combination of polymer, high-quality clay, and selected manufacturing adjustments increases the tortuous flow path for water moving through the GCL, resulting in a lower hydraulic conductivity value of 1 x 10^{-9} cm/s, at standard ASTM D5887 testing conditions (5 psi confining stress and 2 psi hydraulic head with deionized water). Independent laboratory test data verifying this performance are presented in Figure 1.

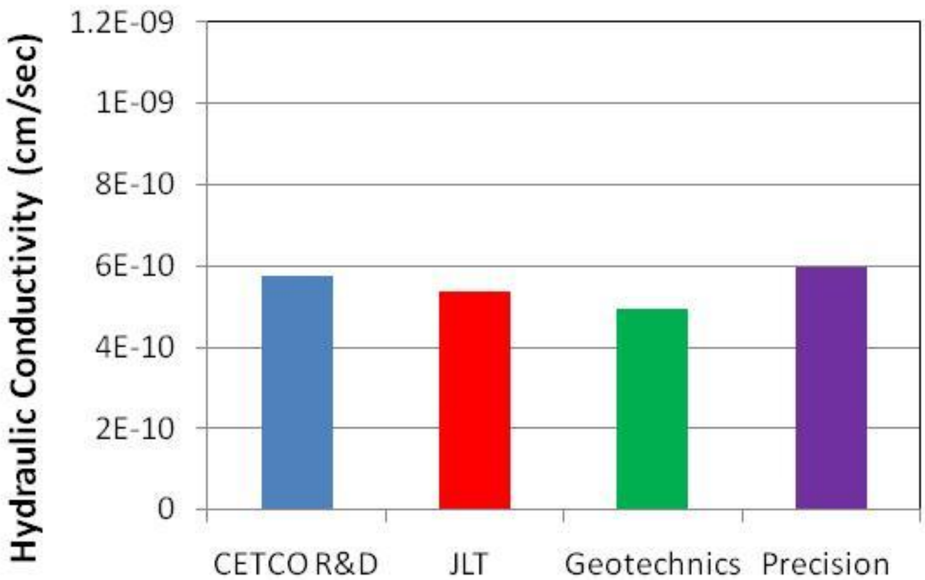

Figure 1. Summary of InterLoK GCL Hydraulic Conductivity Values Reported by Various Independent Laboratories

The InterLoK GCL hydraulic conductivity value of 1 x 10^{-9} cm/s **is five times less than that of a standard GCL, and one hundred times less than a CCL.** The benefit of the lower hydraulic conductivity offered by InterLoK can be best demonstrated by evaluating hydraulic performance of these barrier materials in the following cases:

1. Soil layer (e.g., GCL alone vs. CCL alone)
2. Composite liner (e.g., Geomembrane/CCL vs. Geomembrane/GCL)
3. Composite liner over Structural Fill Layer (e. g., Geomembrane/CCL vs. Geomembrane/GCL/Soil)

Each of these cases is evaluated separately below.

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1. Flow through Single Soil Layer or GCL

Although in practice most containment applications involve composite liners (i.e., a geomembrane placed over a low-permeability soil or GCL), for simplicity, many designers opt to ignore the geomembrane component of the liner system, and focus only on the soil components in their equivalency calculations. In such cases, the hydraulic equivalency demonstration is a comparison of the expected leakage through a GCL to the expected leakage through a CCL (the results of calculations where the geomembrane is included are presented later in this document).

The water flow rate through a single soil liner or a GCL can be described using Darcy's Law:

$$Q = k \times i \times A$$

$$Flux = \frac{Q}{A} = k \times i = k \times \left(\frac{h+t}{t}\right) \quad (1)$$

where:
K = hydraulic conductivity
A = area perpendicular to flow
i = hydraulic gradient
h = hydraulic head
t = barrier layer thickness

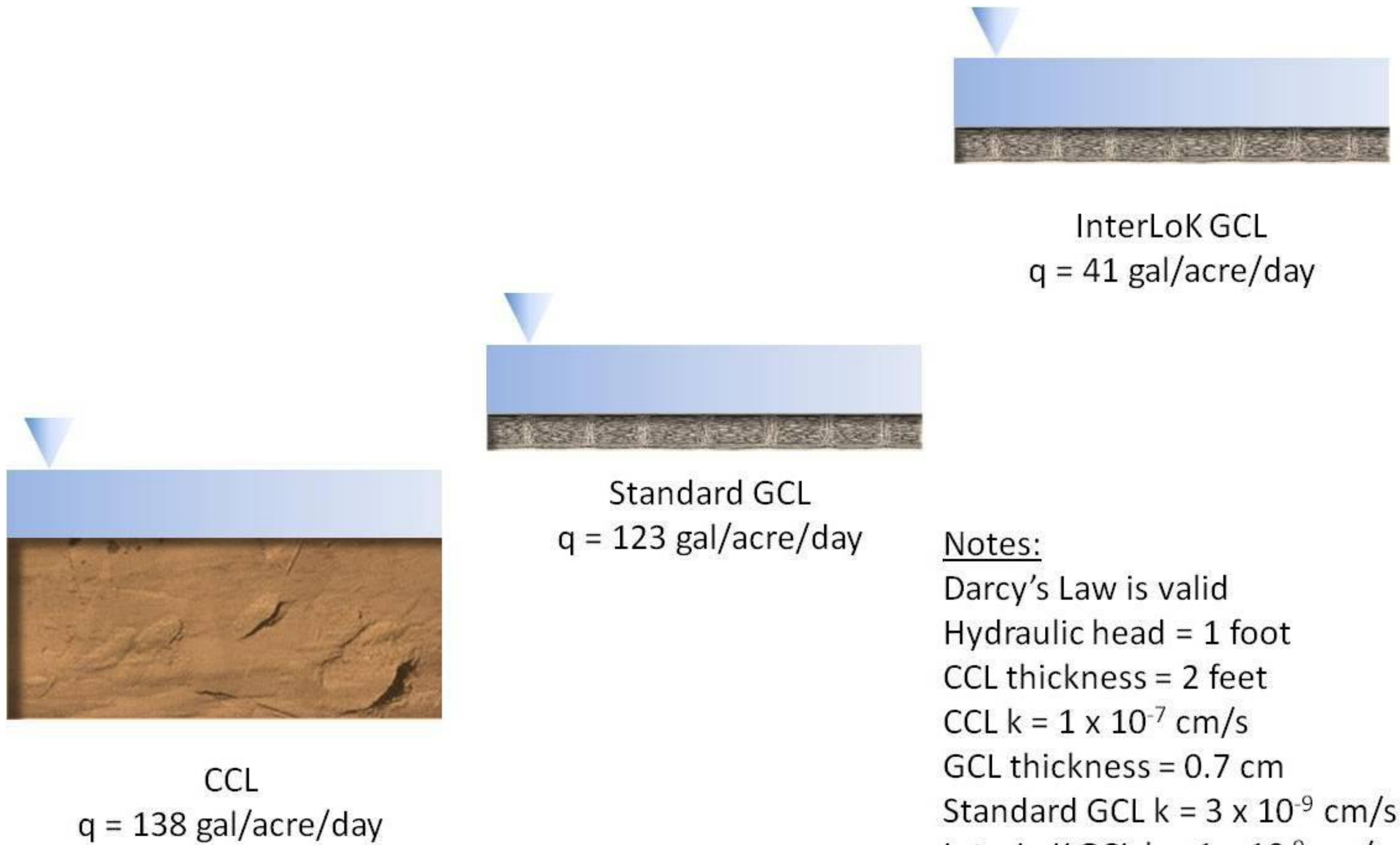
Figure 2 presents a summary of Darcy flux calculations for several single liner options: CCL alone, standard GCL alone, and InterLoK GCL alone. The calculations show that while a standard GCL alone is roughly hydraulically equivalent to a conventional CCL, **the InterLoK GCL is superior to both options, allowing less than one-third as much water flux.** Since the water flux through a given barrier layer is directly proportional to the contaminant transport through that liner due to advection, the InterLoK GCL is also expected to allow less than one-third as much contaminant transport due to advection. (Note that contaminants can also migrate through a liner system through diffusion, a process which is independent of hydraulic flow. While outside the scope of this paper, diffusion is an important design consideration, discussed in detail in TR-247 and TR-310).

<u>"What-If" Scenarios Involving Single Liner Options</u>

If one wants to evaluate "what-if" scenarios (e.g., what GCL hydraulic conductivity will achieve hydraulic equivalency with a certain CCL hydraulic conductivity and thickness?), they can simply set the flux through a GCL equal to the flux through a CCL, to produce the following expression (from Koerner and Daniel, 1993):

$$k_{GCL} = k_{clay}\left(\frac{t_{GCL}}{t_{clay}}\right)\left(\frac{h+t_{clay}}{h+t_{GCL}}\right) \quad (2)$$

Figure 2. Hydraulic Performance Comparison of Single Barrier Options



<u>Notes:</u>

Darcy's Law is valid
Hydraulic head = 1 foot
CCL thickness = 2 feet
CCL $k = 1 \times 10^{-7}$ cm/s
GCL thickness = 0.7 cm
Standard GCL $k = 3 \times 10^{-9}$ cm/s
InterLoK GCL $k = 1 \times 10^{-9}$ cm/s

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where:
k_{GCL} = GCL saturated hydraulic conductivity (cm/sec)
k_{clay} = CCL saturated hydraulic conductivity (1×10^{-7} cm/sec)
t_{GCL} = thickness of GCL (0.7 cm)
t_{clay} = thickness of GCL
h = hydraulic head on top of the liner (1 foot, or 30.48 cm)

The following table summarizes the maximum GCL hydraulic conductivity values needed to achieve equivalency with common CCL thicknesses.

Table 1. Maximum GCL K Needed to Achieve Hydraulic Equivalency with Various CCL Thicknesses

GCL K (cm/s)	Equivalent CCL (10^{-7} cm/s) thickness (feet)
6.8×10^{-9}	0.5 feet
4.6×10^{-9}	1 foot
3.4×10^{-9}	2 feet
3.0×10^{-9}	3 feet
2.8×10^{-9}	4 feet
2.7×10^{-9}	5 feet
2.3×10^{-9}	∞

Since the hydraulic conductivity of standard GCLs ranges from 2×10^{-9} to 5×10^{-9} cm/s, hydraulic equivalency between a standard GCL and a typical 2-foot thick CCL can be established in most cases.

Although a 2-foot CCL is the minimum CCL thickness required by RCRA Subtitle D landfill liner regulations, many individual states require thicker CCLs, with some states requiring CCLs as thick as 5 feet. A review of Table 1 shows that whereas standard GCLs may not be hydraulically equivalent to a 4- or 5-foot thick CCL, InterLoK is hydraulically equivalent to CCLs that are 5-feet thick or more. In fact, Table 1 shows that for GCL hydraulic conductivity values $\leq 2.3 \times 10^{-9}$ cm/s, there is no 1×10^{-7} cm/s CCL thickness that will give equivalent hydraulic performance. **At one-foot of hydraulic head, InterLoK, a GCL with a maximum hydraulic conductivity of 1×10^{-9} cm/s, is therefore hydraulically superior to any 1×10^{-7} cm/s CCL, regardless of the CCL thickness.**

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The realization that mathematically, with 1 foot of head, all 10^{-7} cm/s CCLs are hydraulically inferior to an InterLoK GCL with k = 1 x 10^{-9} cm/s, leads to another interesting "what-if" scenario: What combination of CCL hydraulic conductivity and thickness will achieve hydraulic equivalency with a 1 x 10^{-9} cm/s GCL? This question can be evaluated by re-arranging equation 2 to solve for the CCL hydraulic conductivity:

$$k_{clay} = k_{GCL}\left(\frac{t_{clay}}{t_{GCL}}\right)\left(\frac{h + t_{GCL}}{h + t_{clay}}\right) \quad (3)$$

Table 2 summarizes calculations using equation 3 for various CCL thicknesses.

Table 2. CCL K and Thickness Needed to Achieve Hydraulic Equivalency with a GCL with K = 1 x 10^{-9} cm/s

Equivalent CCL K (k_{clay}) needed to show equivalency with InterLoK (10^{-9} cm/s) (cm/s)	CCL thickness, t_{clay} (feet)
1.5 x 10^{-8}	0.5 feet
2.2 x 10^{-8}	1 foot
2.9 x 10^{-8}	2 feet
3.3 x 10^{-8}	3 feet
3.5 x 10^{-8}	4 feet
3.7 x 10^{-8}	5 feet

Table 2 shows that in order for a 2-foot thick CCL to match the hydraulic performance of an InterLoK GCL, it would have to be constructed at a hydraulic conductivity of 2.9 x 10^{-8} cm/s, or three times tighter than the typical CCL target value of 1 x 10^{-7} cm/s. Even at an optimum combination of compactive effort, dry density, and moisture content, it would be extremely difficult to consistently meet this value with most fine-grained soils. Table 2 shows that increasing the CCL thickness does not provide much relief; even a 5-foot thick CCL would still need to meet 3.7 x 10^{-8} cm/s (more than two times less than the typical CCL target) to be equivalent to the InterLoK GCL.

In summary, in terms of single soil layer equivalency, a standard GCL, with a typical hydraulic conductivity of 3 x 10^{-9} cm/s, has been shown to be hydraulically equivalent to CCLs up to approximately 2 to 3 feet thick. Conversely, an InterLoK GCL, with a maximum hydraulic conductivity of 1 x 10^{-9} cm/s, can be shown to be superior to all CCLs with hydraulic conductivity of 1 x 10^{-7} cm/s, regardless of thickness, and hydraulically equivalent to 3 foot thick CCLs with hydraulic conductivity less than 3.3 x 10^{-8} cm/s.

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2. Flow through Composite Liner System (Geomembrane /soil or Geomembrane/GCL)

As mentioned previously, most waste containment applications involve composite liners (i.e., a geomembrane placed over a low-permeability soil or GCL). Since geomembranes are virtually impermeable, Darcy's Law does not apply. Instead, in composite liner systems, the leakage will occur through geomembrane defects, which can be evaluated using Giroud's equations (Giroud, 1997). The semi-empirical Giroud equation for leakage through circular defects in a composite liner is:

$$Q = 0.976 \cdot C_{qo}\left[1 + 0.1 \cdot \left(h/t_s\right)^{0.95}\right] \cdot d^{0.2} \cdot h^{0.9} \cdot k_s^{0.74} \qquad (4)$$

where:

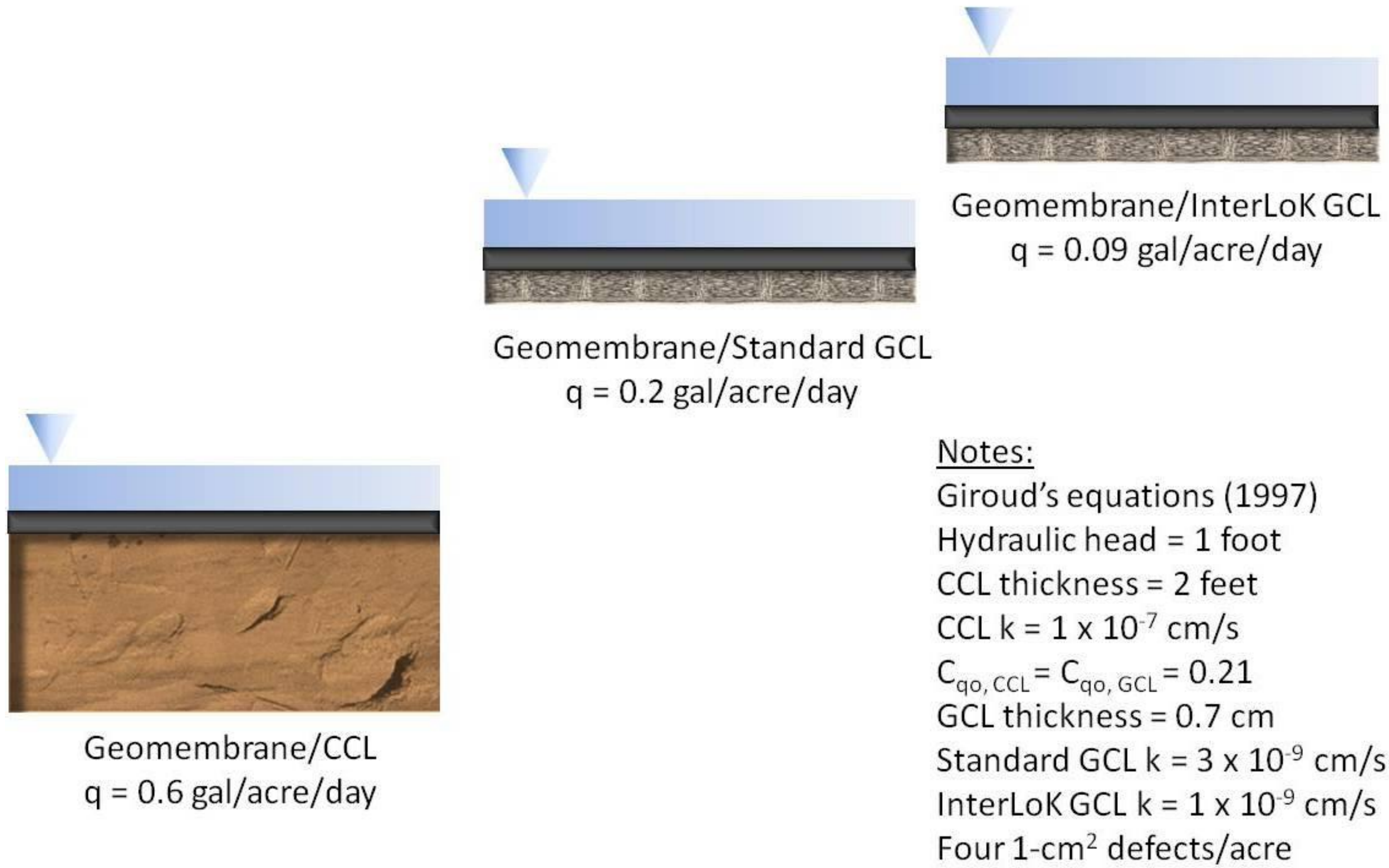
C_{qo} = contact quality factor (dimensionless, 0.21 for good quality or 1.15 for poor quality)
h = hydraulic head on top of the liner (assumed at 1 foot, or 0.3048 m)
t_s = thickness of low-permeability soil layer (0.007 m for GCLs; 30.48 cm for compacted clay)
d = defect diameter (m)
k_s = Hydraulic conductivity of low-permeability soil layer (m/s)

The Giroud equations are similar to the equations used in the Hydrologic Evaluation of Landfill Performance (HELP) model, which were also developed by Giroud. The HELP model, which is the state of practice in the solid waste industry for simulating flow through liners and caps, estimates that, when installed using good installation practice and QA/QC, the number of installation defects (caused by installation quality, equipment, and surface preparation), is 1 to 4 per acre. Each installation defect is assumed to have an area of 1 cm^2. For ease of comparison, 4 installation defects/acre will be used in the leakage calculations presented in this analysis.

Where defects are present, the liquid will pass through the defect, and then flow laterally in the space between the geomembrane and low-permeability soil layer before infiltrating through the soil. The amount of this "interface flow" is dependent upon the quality of contact between the geomembrane and the low-permeability soil. Composite liner components that are in good contact (no geomembrane wrinkles, well-prepared, smooth subgrade) will permit less interface flow (and therefore, less overall leakage) than components with poor contact. The contact quality factor, C_{qo}, is a coefficient introduced to account for the effects of interface flow. Giroud provides estimates of C_{qo} for good (0.21) and poor (1.15) contact quality. Giroud states that good contact should be assumed with GCLs, since they are usually installed flat and, when under pressure, bentonite will exude through the surrounding geotextiles, forming a hydraulic seal with the geomembrane. For ease of comparison, good contact quality (0.21) will be assumed in the leakage calculations for both CCLs and GCLs in this analysis.

Figure 3 presents a summary of Giroud calculations for several composite liner options: geomembrane/CCL, geomembrane/standard GCL, and geomembrane/InterLoK GCL. The calculations show that a composite liner system consisting of a geomembrane over a standard GCL is expected to allow less than one-half as much leakage as a geomembrane/CCL composite liner system, and **a geomembrane/InterLoK GCL composite system is expected to allow one-sixth, or less than 17 percent, as much leakage as the geomembrane/CCL.**

Figure 3. Hydraulic Performance Comparison of Composite Liner Options



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As with the simplified examples presented earlier, since the water flux through a given barrier layer is directly proportional to the contaminant transport through that liner due to advection, the InterLoK GCL is also expected to allow less than 17 percent as much contaminant transport due to advection.

3. Flow through Composite Liner System with Multiple Soil Layers (Geomembrane/GCL/Soil)

In many applications, the GCL is underlain by a compacted soil layer, which can serve as either structural fill, puncture protection, or a chemical diffusion attenuation layer. This additional soil layer is not typically subject to the same strict hydraulic conductivity requirement as CCLs, since it's function is not as a hydraulic barrier. It is common practice in the waste containment industry to model such multiple soil layers as a single "effective" soil layer whose properties are a weighted average of the individual barrier layers:

$$k_{effective} = \frac{t_1 + t_2}{\frac{t_1}{k_1} + \frac{t_2}{k_2}} \qquad (5)$$

$$t_{effective} = t_1 + t_2 \qquad (6)$$

This approach is commonly seen in hydrogeology textbooks (e.g., Freeze and Cherry, 1979) and in the HELP model user's guide (Schroeder et al, 1994). However, Giroud et al (1997) showed mathematically that the GCL's hydraulic conductivity is so low, virtually any soil type placed underneath the GCL will serve as a drainage layer, and will not become saturated or contribute to the effectiveness of the hydraulic barrier. They also showed that using this approach results in an "effective" hydraulic conductivity higher than the GCL hydraulic conductivity, unnecessarily penalizing liner systems containing a GCL.

Despite these facts, the weighted-average approach of evaluating multiple barrier layers is still commonly used. Accordingly, a discussion of the expected performance of composite liner systems with standard GCLs and InterLoK GCLs both placed over structural fill layers, is warranted.

Figure 4 presents the results of a series of calculations using the Giroud equations to evaluate several composite liner options: geomembrane/CCL, geomembrane/standard GCL/structural fill, and geomembrane/InterLoK GCL/structural fill. In both of the GCL cases, the structural fill layer is assumed to be 2 feet thick and have a hydraulic conductivity of 1 x 10^{-5} cm/s. Using equation 5, the calculated "effective" hydraulic conductivity values are 2.6 x 10^{-7} cm/s (combined standard GCL/structural fill layer) and 8.7 x 10^{-8} cm/s (combined InterLoK GCL/structural fill layer).

Figure 4 shows that a composite liner system consisting of a geomembrane/standard GCL/structural fill is expected to allow more leakage than a geomembrane/CCL composite liner system, and **a geomembrane/InterLoK GCL/structural fill composite system is expected to allow approximately 10 percent less leakage.**

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Figure 4. Hydraulic Performance Comparison of Composite Liner/Structural Fill Options

Geomembrane/CCL
q = 0.6 gal/acre/day

Geomembrane/GCL/fill
q = 1.2 gal/acre/day

Geomembrane/InterLoK GCL/fill
q = 0.55 gal/acre/day

<u>Notes:</u>
Giroud's equations (1997)
Hydraulic head = 1 foot
CCL thickness = 2 feet
CCL k = 1×10^{-7} cm/s
$C_{qo,\,CCL} = C_{qo,\,GCL} = 0.21$
GCL thickness = 0.7 cm
Standard GCL k = 3×10^{-9} cm/s
InterLoK GCL k = 1×10^{-9} cm/s
Four 1-cm^2 defects/acre
Fill thickness = 2 feet
Fill k = 1×10^{-5} cm/s

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The fact that the leakage rates shown in Figure 4 are greater than those in Figure 3 is a paradox, consistent with the conclusions of Giroud et al (1997). In reality, the weighted average approach is not appropriate for waste containment liners, and the flow through the systems in Figure 4 should be no different than the flows shown in Figure 3, since the GCL is the limiting layer. Nonetheless, since several designs and permits continue to use a weighted average calculation to evaluate multiple barrier layers, an example was included here.

4. Summary

The purpose of this technical reference is to evaluate the hydraulic performance of a new GCL, InterLoK, compared to standard GCLs and traditional CCLs. InterLoK is manufactured by adding non-biodegradable, high-viscosity polymers to high-swell, low-fluid loss sodium bentonite. The combination of polymer, high-quality clay, and selected manufacturing adjustments increases the tortuous flow path for water moving through the GCL, resulting in a lower hydraulic conductivity value of 1×10^{-9} cm/s, at standard ASTM D5887 testing conditions. The InterLoK GCL hydraulic conductivity value of 1×10^{-9} cm/s is five times less than that of a standard GCL, and one hundred times less than a CCL. The practical benefit of the lower hydraulic conductivity offered by InterLoK can be summarized as follows:

- In terms of flux, or leakage through single soil liners, an InterLoK GCL is expected to allow three times less leakage than both a traditional CCL and a standard GCL.
- InterLoK can be shown to be superior to all CCLs with hydraulic conductivity of 1×10^{-7} cm/s, regardless of thickness, and hydraulically equivalent to 3 foot thick CCLs with hydraulic conductivity less than 3.3×10^{-8} cm/s. Lower permeability provides hydraulic equivalence to a greater thickness of compacted clay, reducing construction material and installation costs.
- A composite liner system consisting of a geomembrane over an InterLoK GCL is expected to allow less than 17 percent as much leakage as a geomembrane/CCL composite liner.
- A composite liner system consisting of a geomembrane over an InterLoK GCL placed over 2 feet of structural fill with hydraulic conductivity of 1×10^{-5} cm/s, when evaluated using a weighted-average approach commonly used to evaluate multiple barrier layers, is expected to be hydraulically equivalent or superior to a geomembrane/CCL composite liner. The use of an InterLoK GCL allows for less stringent subgrade soil permeability requirements when using a weighted average approach of evaluating equivalency.
- Since the water flux through a given barrier layer is directly proportional to the contaminant transport through that liner due to advection, the InterLoK GCL is also expected to allow proportionally less contaminant transport due to advection in each of the scenarios above. Less contaminant transport results in more protective designs that may allow waste containment facilities to be placed closer to property boundaries, groundwater, surface water, or other sensitive receptors.

Please note that, due to limited information about the actual design, several assumptions were made as part of these analyses. The equations and calculations presented here are only for the purpose of comparing the relative performance of different lining systems. Actual field performance of these systems depends on other factors, such as subgrade condition, installation quality, construction quality assurance program, and operations practices at the site.

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5. References

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