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A liner system consists of a combination of one or more drainage layers and low-permeability barrier layers (i.e., liners). The functions of the liners and drainage layers are complementary. The liner impedes the migration of leachate out of the landfill and improves the performance of any overlying drainage layer. The drainage layer limits the buildup of hydraulic head on the underlying liner and conveys to a sump the liquid that percolates into the layer. Typical components of double-liner systems are illustrated in Figure 1. These components are, from top to bottom:

- LCRS, which consists of a permeable soil and/or geosynthetic drainage system, and possibly a network of perforated liquid conveyance pipes;

- top liner, which may consist of a GMB alone or a composite liner having a GMB upper component and a CCL or geosynthetic clay liner (GCL) lower component;

- LDS, which consists of a permeable soil and/or geosynthetic drainage system, and possibly a network of perforated liquid conveyance pipes; and

- bottom liner, which may consist of a GMB alone or a composite liner having a GMB upper component and a CCL or GCL lower component.

Comparison of the rates of flow into the LCRS and LDS of a double-lined landfill can be used to quantify the performance of the top liner (in terms of ability to prevent leakage through the liner). Comparison of the chemical constituent data for LCRS and LDS liquids can be used to evaluate the sources of liquid in the LDS and to assess the ability of the top liner to contain chemicals present in the LCRS.

As part of an ongoing research investigation for the United States Environmental Protection Agency (USEPA), the authors have collected data for a wide variety of double-lined waste management cells located throughout the United States. The database includes information on 194 waste management cells at 54 double-lined landfills. The data collected includes: (i) general facility information (including location, average annual rainfall, subsurface soil types, ground-water separation distance, etc.); (ii) general cell information (including cell area, type of waste, height of waste, etc.); (iii) liner system and final cover system details (including type, thickness, and hydraulic conductivity of each layer); and (iv) LCRS and LDS flow quantities and chemical constituent data. Data analysis is currently ongoing. A subset of the currently-available database, relating to MSW landfills with

GMB/CCL composite top liners, is analyzed in this paper to draw conclusions on the performance of this type of liner.

The remainder of this paper first presents a brief review of previously published data on the field performance of composite liners. Preliminary results from the current, ongoing study are then introduced and evaluated.

REVIEW OF PREVIOUS STUDIES

Overview

The performance of top liners at double-lined landfills and surface impoundment has previously been assessed by comparing LDS and LCRS flow rate and chemical constituent data. The first general study of this type, by Gross et al. (1990), identified five potential sources of LDS flow (Figure 2): (i) leakage through the top liner; (ii) drainage of water (mostly rainwater) that infiltrates the LDS during construction but does not drain to the LDS sump until after the start of facility operation ("construction water"); (iii) water expelled from any granular component of the LDS as a result of compression under the weight of the waste ("compression water"); (iv) water expelled from any clay component of the top liner as a result of consolidation under the weight of waste ("consolidation water"); and (v) ground-water infiltration through the bottom liner ("infiltration water").

Gross et al. (1990) presented the following five-step approach for evaluating the sources of LDS liquid at a specific waste management cell:

- identify the potential sources of flow for the cell based on double-liner system design, climatic and hydrogeologic setting, and cell operating history;
- calculate flow rates from each potential source;
- calculate the time frame for flow from each potential source;
- evaluate the potential sources of flow by comparing measured flow rates to calculated flow rates at specific points in time; and

- compare LCRS and LDS chemical constituent data to further establish the likely source(s) of liquid.

Previous studies of the performance of composite liners focused primarily on a comparison of LCRS and LDS flow rate data. In a few cases, chemical data were also considered. These previous studies and their major findings are presented below.

Bonaparte and Gross (1990, 1993)

Bonaparte and Gross (1990) presented data on LDS flows from 38 double-lined landfills and surface impoundments with composite top liners. The conclusions from their study for these cells are as follows (with lphd = liters / hectare / day):

- "*The double-lined landfills and surface impoundments in this study having a layer of compacted clay as the soil component of a composite top liner almost always exhibited flows due to consolidation water. Measured flow rates attributable to consolidation water were in the range of 20 to 840 lphd. Only very small flows were observed from the leakage detection layers of cells where the soil component of the composite top liner was a prefabricated geotextile-bentonite mat.*

- *The calculation methods presented by Gross et al. [1990] for estimating consolidation water and construction water flow rates appear reasonable for the facilities reported in this study.*"

Due to the masking effects of consolidation water and the limited available data, Bonaparte and Gross (1990) were unable to quantify top liner leakage rates. The authors did conclude "*the double-liner systems evaluated in this study have performed well. Leakage rates through the top liners have been low or negligible in most cases.*" The facility database was expanded by Bonaparte and Gross (1993) as part of a USEPA-sponsored study to include data from several additional waste management cells with composite top liners. The conclusions from this more recent study were essentially the same as the earlier conclusions cited above.

Feeney and Maxson (1993)

Feeney and Maxson (1993) used a methodology similar to that of Bonaparte and Gross (1990) to evaluate LDS flows from 49 double-lined cells at eight hazardous solid waste (HSW) landfills. All but two of the cells have a GMB/CCL composite top liner on the cell base and a GMB only on the cell side slopes (i.e., Category 1 liner system). Two cells incorporate geosynthetic clay liners (GCLs) into the composite top liners on both the cell base and side slopes (i.e., Category 2 liner system). All of the cells contain a granular soil/geonet LDS on the cell base and a geonet only LDS on the cell side slopes. All cells were constructed using third-party CQA programs.

For each landfill cell in their study, Feeney and Maxson (1993) reported minimum, maximum, and average LCRS and LDS flow rates. The reporting periods for the 49 cells ranged from 4 to 60 months. At the time of the Feeney and Maxson paper, the cells were at different stages of operation, from newly constructed to closed. For 41 of the cells with Category 1 liner systems, average LDS flow rates for the monitoring periods reported in the paper ranged from 0 to 310 lphd. Average flow rates for 27 of the 41 Category 1 cells were less than or equal to 100 lphd. The authors attributed the observed LDS flows primarily to consolidation of the CCL component of the composite top liners. The LDS flow rates reported by Feeney and Maxson (1993) are in the same general range as those reported earlier by Bonaparte and Gross (1990, 1993).

LDS flow rates were temporarily higher for the two Category 2 cells and in six of the 47 Category 1 cells. Feeney and Maxson indicate that these latter eight cells initially exhibited similar behavior to the other cells. However, during operations, the top liner in each cell was damaged, usually by heavy equipment operations in the cell, and then repaired. Average LDS flow rates for the damaged cells were about an order of magnitude larger than the rates for the other cells. The authors do not provide any information for the high frequency of operational damage to the liner systems in their study and whether procedures were developed to prevent similar damage in future cells.

Workman (1993)

Workman (1993) presented monitoring results for a MSW landfill having a top liner consisting of a GMB on the side slopes and a GMB/CCL composite on the base. The LDS consists of a geonet drainage layer overlain by a geotextile filter. The portion of the landfill described by Workman contains three cells constructed between 1989 and 1992. The author does not indicate the level of CQA provided for the construction of each cell. Average LDS flow rates in the three cells initially ranged from 50 to 700 lphd, with rates at the higher end of the range being associated with the fastest rates of waste disposal. After cell filling ceased, LDS flow rates decreased to 20 to 30 lphd. Workman attributed the observed LDS flows to consolidation of the CCL component of the composite top liner on the base of the landfill. This conclusion was supported by the major ion concentrations of the LDS liquids which were different than the concentrations of major ions in leachate.

Workman reported that analyses of the LDS liquids from two of the cells (Cells 1 and 4) revealed the presence of several volatile organic compounds (VOCs), including chloroethane, ethylbenzene, and trichloroethene, at low part-per-billion concentrations, starting about one year after the start of cell operation. Workman noted that the detected compounds are common constituents of landfill gas and that testing of the LDS indicated methane gas concentrations up to 50 percent (i.e., ≈100 percent landfill gas). Workman also indicated that landfill gas was not yet actively removed or passively vented from this landfill at the time of the measurements. He attributed the VOCs to the following source: *"It is believed that methane is impacting the LDS liquids of Cells 1 and 4. No organic constituents have been detected in the Cell 2 LDS. The methane was first detected in Cells 1 and 4 about one year after each cell was placed in operation. This occurred about the same time that the waste reached ground level and totally covered the liner system. Since methane is not actively vented at this time and can accumulate under pressure in the leachate collection system, gradients can occur across the liner system. The sideslopes in this landfill are particularly vulnerable. As methane penetrated the liner and cooled, the gas began to condensate and drain small quantities of liquid to the LDS sump."*

Bergstrom et al. (1993)

Bergstrom et al. (1993) presented flow rate and chemical constituent data for the LDSs of five cells at a HW landfill. The cells have a GMB/CCL composite top liner, with the soil component of the composite liner consisting of a 1.5-m thick layer of compacted clayey till. The LDS consists of a geonet drainage layer overlain by a geotextile filter, with one layer of geonet on cell side slopes and two layers of geonet on the cell bases. All cells were constructed using third-party CQA programs.

Average LDS flow rates for the five cells ranged from approximately 200 to 700 lphd during active cell filling and 30 to 60 lphd within one to two years after waste filling ended. Bergstrom (1993) attributed the observed LDS flows primarily to consolidation of water. Bergstrom et al. (1993) also presented inorganic chemical constituent data obtained from testing of LDS liquid, LCRS liquid, and ground water. From this data, they concluded that "*each of these water sources has a unique chemical composition and the leachate does not appear to be influencing LDS liquid composition.*" The authors report that VOCs have not been detected in the LDSs of the five cells; however, details of the analyte list, analytical methods, and/or analytical detection limits are not given. They also estimated consolidation water volumes using the results of laboratory consolidation testing of the site-specific CCL material along with records of waste placement in the landfill cells. Estimated consolidation water volumes were 5 to 60 percent larger than the observed LDS flow rates.

Bonaparte et al. (1996)

Bonaparte et al. (1996) analyzed flow rate data for 26 MSW cells at six different landfills containing GMB/GCL composite top liners. These data were collected as part of the ongoing research investigation for the USEPA mentioned earlier in this paper. The authors used the data to calculate average and peak LCRS and LDS flow rates for three distinct landfill development stages: (i) the "initial period of operation"; (ii) the "active period of operation"; and (iii) the "post closure period". During the "initial period of operation", LCRS flow rates are relatively high and are largely the results of rainfall into a cell that contains little waste. To the extent rainfall occurs during this period, it will find its way rapidly into the LCRS. During the "active period of operation", the rate of flow into the LCRS decreases and eventually stabilizes. This occurs as the amount of waste in the cell increases and as daily and intermediate layers of cover soil are placed on the waste. During the "post closure period", the final cover system further reduces infiltration of rainwater into the waste, resulting in a further reduction in LCRS flow rate.

Bonaparte et al. (1996) calculated mean values of average and peak LCRS and LDS flow rates for the 26 MSW landfill cells. These mean values are presented in Table 1. They also calculated "apparent" hydraulic efficiencies for the composite top liners of the 26 landfill cells. They defined liner apparent efficiency, E_a:

$$E_a(\%) = (1 - \text{LDS Flow Rate} / \text{LCRS Flow Rate}) \times 100 \qquad \text{(Equation 1)}$$

This hydraulic efficiency is referred to as "apparent" because, as described above, flow into the LDS sump may be attributed to sources other than top liner leakage (Figure 2). If the only source of flow into the LDS sump is top liner leakage, then Equation 1 provides the "true" liner hydraulic efficiency. Liner efficiency provides a measure of the effectiveness of a particular liner in limiting or preventing advective transport across the liner.

For the landfill cells with GMB/GCL composite top liners and sand LDSs, Bonaparte et al. (1996) found that the E_a is lowest during the initial period of operation ($E_{am} = 98.60$ percent; where E_{am} = mean apparent efficiency) and increases significantly thereafter ($E_{am} = 99.58$ percent during the active period of operation and $E_{am} = 99.89$ percent during the post closure period). The lower E_{am} during the initial period of operation was attributed to LDS flow from construction water. Bonaparte et al. (1996) state that for cells with sand LDSs, "*calculated AE (E_a) values during the active period of operation and the post-closure period may provide a reasonably accurate indication of true liner efficiency for the conditions at these units during the monitoring periods.*"

For six cells with geonet LDSs, the calculated value of E_{am} for the initial period of operation was 99.96 percent. This value is higher than the E_{am} for composite liners underlain by sand LDSs for the same facility operational period (i.e., 98.60 percent). This higher apparent efficiency can be attributed to the differences in liquid storage capacity and hydraulic transmissivity between sand and geonet drainage materials. A granular drainage layer can store a much larger volume of construction water and releases this water more slowly during the initial period of operation than does a geonet drainage layer. This suggests that, during the initial period of operation, the main source of flow in a sand LDS underlying a composite top liner containing a GCL is construction water.

Bonaparte et al. (1996) concluded that "*LDS flows attributable to top liner leakage vary from 0 to 50 lphd, with most values being less than about 2 lphd. These flow rates are very low. The data shown in Table 4 suggest that the true hydraulic efficiency of a composite liner incorporating a GCL may be greater than 99.90 percent. A liner with this efficiency, when appropriately used as part of an overall liner system, can provide a very high degree of liquid containment capability.*"

Conclusions from Previous Studies

The following conclusions are drawn from the previous studies regarding the hydraulic performance of composite liners.

- LDSs underlying GMB/CCL composite liners almost always exhibit flow due to consolidation water. Measured LDS flow rates attributable to consolidation water are in the range of 0 to 1,000 lphd, with most values being less than 200 lphd. LDS flow rates attributable to consolidation water will be a function of the rate of waste placement in the overlying cell. Typically, the rate of flow will decrease with time during the latter active life and post-closure period. LDS flow rates in the range of 0 to 100 lphd have been reported within one to two years of the completion of active filling of the overlying cell.

- LDS flow attributable to leakage through GMB/CCL top liners is unquantified at present due to the masking effects of consolidation water, the very low anticipated flow rates from this source, the limited available database on the chemical constituents in LCRS and LDS liquids, and the relatively long breakthrough times for advective transport through the CCL component of the liner. While available information is encouraging, much remains to be learned.

- Flow rates from the LDSs of cells with GMB/GCL composite top liners are usually very low. From the investigation by Bonaparte et al. (1996), LDS flow rates attributable to leakage through this type of liner varied from 0 to 50 lphd, with most values being less than about 2 lphd. The true hydraulic efficiency of GMB/GCL composite liners may often exceed 99.9 percent.

- Average LDS flow rates may increase by an order of magnitude, or more, due to liner system damage induced by heavy equipment operations in the cell. Engineering and operational measures should be used to prevent this type of occurrence.

PRELIMINARY RESULTS FOR GMB/CCL COMPOSITE LINERS

Description of Data

Data for nine MSW landfill cells from seven different facilities are addressed in this portion of the paper. All of these cells contain GMB/CCL or GMB/GCL/CCL composite top liners. Descriptions of the components of the liner systems installed at these landfills are presented in Table 2 and flow rate data for the LCRSs and LDSs of the landfills are contained in Table 3. The database itself contains flow rate data reported on either a daily, weekly, or periodic basis, depending on facility. Using this source data, average daily flow rates were calculated for both systems on a monthly basis by dividing the total amount of liquid extracted from the systems during the month by the number of days in the month and the areas of the landfill cell. For this paper, these average monthly flow rates were further averaged over the approximate twelve month reporting time increments in Table 3. The flow rate units given in this table are liters/hectare/day (lphd). The volumes of flow used in the calculations were obtained from landfill operations records, with flow measurements most often measured using accumulating flow meters. The reported flow volumes should be considered approximate. Table 3 presents average and peak LCRS and LDS flow rates for the "initial period of operation" and "active period of operation". None of the cells listed in Table 2 have undergone final closure.

Table 4 summarizes average values for 30 chemical constituents for the LCRS and LDS liquids of the landfills described in Tables 2 and 3. The 30 parameters include general water chemistry parameters (e.g., pH, specific conductance, total dissolved solids (TDS), etc.) and select inorganic cations and anions, heavy metals, and volatile organic compounds (VOCs). The select metal and VOC constituents were chosen for study based on the authors' experience indicating the common occurrence of these constituents in MSW leachate. In calculating the average value for each parameter, half of the test detection limits were conservatively used for all results reported as non-detects. If more than half of the measurements for a parameter were reported as non-detects, the calculated average value is proceeded by a "<" symbol. As with the flow rate data, the chemistry data were obtained from landfill operations records. In all cases reported in this paper, the chemical constituent data were reportedly obtained using sampling and analysis procedures in accordance with USEPA protocols. USEPA protocols contain QC standards for both sampling and analysis including the use of method blanks, matrix spikes, and duplicates.

These protocols will provide accurate analytical data for samples obtained from the LCRS and LDS sumps. However, VOC losses from the sump liquids prior to sampling are unknown.

Analysis of Flow Rate Data

Table 3 shows that LCRS and LDS flow rates decrease significantly with time between the initial period of operation and later stages of the active period of operation of a landfill cell. Between these two periods, flow rates for both LCRS and LDS decreased by up to two orders of magnitude. Average LCRS flow rates ranged from about 9,900 to 27,000 lphd during the initial period of operation and from 10 to 11,000 lphd during the active period of operation. For the LDS, average flow rates ranged from 150 to 1,400 lphd during the initial period of operation and from 0 to 370 lphd during the active period of operation. Peak LCRS flow rates were up to five times the reported average, while peak LDS flow rates were up to nine times the reported average.

The flow rate data in Table 3 were used to calculate composite top liner apparent efficiencies (E_a). These calculated efficiencies are presented in Table 3. As can be seen in this table, E_a values range from 54.5 to 100.0 percent. Additional observations with respect to the LDS flow rate data and calculated E_a values are given below.

- Consolidation water flow rates are dependent on the rate of overlying waste placement. Accordingly, LDS flows from this source may increase or decrease over time. For most facilities, the waste placement schedule results in relatively larger LDS flow rates early in the active period.

- While LDS flow rates tend to decrease with time, E_a values may increase or decrease with time depending on the relative rates of decrease of LCRS flow versus LDS flow. For example, E_a values for landfill B3 were initially in the range of 96 to 99 percent. The E_a value decreased to about 80 percent after about 5 to 8 years due to steady LDS flow rates, and decreasing LCRS flow rates.

- The highest value of E_a was achieved by the GMB/CCL composite liner in Cell AM2. For this cell, an E_a value of 100 percent was achieved at a time period of about four years after the start of cell operations under a condition of very low rates of LCRS flow (i.e., < 100 lphd) during a time when overlying waste placement had ceased. Interestingly, the AM landfill is located in the western United States in a semi-arid environment. Leachate generation rates at this MSW landfill are, on average, an order of magnitude lower than the rates for the other facilities, all of which are located in the much wetter climate of the eastern United States.

The only composite top liner for which a true hydraulic efficiency (E_t) can be estimated based on flow rate data alone is that installed in Cell AM2. For this cell, an E_t value of 100 percent was achieved for the low LCRS flow rate conditions noted above. Due to the interfering effects of consolidation water, LDS flow data for the other facilities do not alone allow similar conclusions to be drawn. LCRS and LDS chemical constituent data are reviewed below to develop further insight into the containment capabilities of GMB/CCL composite liners.

Analysis of Chemical Data

Concentrations of chemical constituents in LDS liquids are compared to concentrations of the same constituents in LCRS liquids in Table 4. As indicated by the data in Table 4, the general water quality characteristics of LDS liquids are generally different than the corresponding characteristics for LCRS liquids. This is due to the different origins of the primary sources of the two liquids, leachate for the LCRS liquid and CCL pore water for the LDS liquid. The different origins of the two liquids are reflected in different general ion chemistries, as well as differences in chemical oxygen demand, biological oxygen demand, and total organic carbon concentrations. Piper (1944) trilinear diagrams for the LCRS and LDS data from each cell are presented in Figures 3 to 8. These diagrams highlight the differences in general ion chemistries. The figures show that the dominant cations and anions are often different between LCRS and LDS liquids for a given cell. Details for the construction and interpretation of Piper trilinear diagrams can be found in most hydrogeology and geochemistry textbooks.

A review of the data in Table 4 indicates that VOCs were detected in the LDS liquids in only a few instances; detections were typically at very low concentrations (i.e., in the low parts per billion (ppb) range). In comparison, VOCs were found to occur more frequently in LCRS liquids, and when they did occur, they were typically at concentrations one to two orders of magnitude larger than the concentrations of detected VOCs in the LDS liquids. Similarly, the concentrations of heavy metals (arsenic, lead, chromium, nickel, and cadmium) were generally lower in the LDS liquids than in the LCRS liquids. Concentrations of these metals in both the LCRS and LDS are generally very low. A preliminary review and comparison of the LCRS and LDS data in Table 4 does not provide any obvious indication of constituent transport through the composite liners for the monitoring periods considered. Additional analysis of this data is currently ongoing.

SUMMARY AND CONCLUSIONS

This paper presents preliminary results of a study of composite liner field performance. Performance was evaluated using LCRS and LDS flow rate and chemical constituent data from nine double-lined MSW landfill cells. The findings of this study are summarized below.

- LDSs underlying composite top liners with a CCL lower component exhibited average monthly flow rates of 150 to 1,400 lphd during the initial period of operation and 0 to 370 lphd during the active period of operation. These results are consistent with the results of previous investigations, discussed earlier in this paper. LDS flows during the initial period of operation are attributed primarily to construction water. LDS flows during the active period of operation are attributed primarily to consolidation water.

- Consolidation water flow rates are dependent on the rate of overlying waste placement. Accordingly, LDS flows from this source may increase or decrease over time. For most facilities, the waste placement schedule results in relatively larger LDS flow rates early in the active period.

- While LDS flow rates tend to decrease with time, E_a values may increase or decrease with time depending on the relative rates of decrease of LCRS flow versus LDS flow. For example, E_a values for landfill B3 were initially in the range of 96 to 99 percent. The E_a value decreased to about 80 percent after about 5 to 8 years due to steady LDS flow rates, and decreasing LCRS flow rates.

- The highest value of E_a was achieved by the GMB/CCL composite liner in Cell AM2. For this cell, an E_a value of 100 percent was achieved at a time period of about four years after the start of cell operations under conditions of very low rates of LCRS flow (i.e., <100 lphd) during a time when overlying waste placement had ceased. Interestingly, the AM landfill is located in the western United States in a semi-arid environment. Leachate generation rates at this MSW landfill are, on average, an order of magnitude lower than the rates for the other facilities, all of which are located in the much wetter climate of the eastern United States.

- Preliminary review of LCRS and LDS chemical constituent data indicates that the general water quality characteristics of these two liquids are different, confirming the different primary sources for the two liquids (i.e., leachate versus consolidation water).
- Preliminary review of the LDS liquid chemical constituent data does not provide any obvious indication of leakage through the nine composite top liners in this study for the monitoring periods considered.

The monitoring results presented in this paper are encouraging with respect to their implications for the performance levels achievable by GMB/CCL composite liners of the type being used today at U.S. MSW landfills. Further analysis of the existing database is ongoing, including more detailed analysis of the leachate and chemical constituent data to include evaluations of the temporal variations in constituent concentrations for monitoring periods that in some cases significantly exceed the estimated breakthrough time for flow through the CCL component of the composite top liner. In addition, it is recognized that the current database for the evaluation of composite liner performance is limited, in terms of both completeness and duration of monitoring. It is important that additional data be collected so that our understanding of the performance capabilities of these systems can continue to improve.

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REFERENCES

Bergstrom, W.R., Takacs, M.J., and Olson, M.A. (1993) "Behavior of Five Operating Landfill Leak Detection Systems", *Proceedings, Waste Tech '93*, Marina Del Rey, California, pp. 2.2-2.14.

Bonaparte, R. and Gross, B.A. (1990) "Field Behavior of Double-Liner Systems", *Waste Containment Systems: Construction, Regulation, and Performance*, ASCE Geotechnical Special Publication No. 26, R. Bonaparte, ed., New York, pp. 52-83.

Bonaparte, R. and Gross, B.A. (1993) "*LDCRS Flows from Double-Lined Landfills and Surface Impoundments*", report to, under contract No. 68-CO-0068, USEPA Risk Reduction Engineering Research Laboratory, Cincinnati, 65 p.

Bonaparte, R., Othman, M.A., Rad, N.S., Swan, R.H., and Vander Linde, D.L. (1996) "Evaluation of Various Aspects of GCL Performance", *Appendix F in Report of 1995 Workshop on Geosynthetic Clay Liners*, D.E. Daniel and H.B. Scrantnon, authors, EPA/600/R-96/149, USEPA National Risk Management Research Laboratory, Cincinnati, OH, pp. F1-F34.

Feeney, M.T. and Maxson, A.E. (1993) "Field Performance of Double-Liner Systems", *Proceedings, Geosynthetics '93 Conference*, Vol. 3, Vancouver, pp. 1373-1387.

Gross, B.A., Bonaparte, R., and Giroud, J.P. (1990) "Evaluation of Flow from Landfill Leakage Detection Layers", *Proceedings, Fourth International Conference on Geotextiles*, Vol. 2, The Hague, pp. 481-486.

Piper, A. M. (1944) "A Graphic Procedure in the Geochemical Interpretation of Water Analyses", *Transactions of American Geophysical Union*, Vol. 25, pp. 914-923.

Workman, J.P. (1993) "Interpretation of Leakage Rates in Double-Lined Systems", Proceedings, *7th Geosynthetic Research Institute Seminar*, Drexel University, Philadelphia, Pennsylvania, December, pp. 91-108.

Table 1. Mean LCRS and LDS flow rates for MSW landfill cells with GMB/GCL composite top liner from Bonaparte et al. (1996) (Note: m = mean value; σ = standard deviation; values are in liter/hectare/day).

LCRS	Number of Cells	Average Flow Rate		Peak Flow Rate	
		m	σ	m	σ
Initial Period of Operation	25	5,350	3,968	14,964	11,342
Active Period of Operation	18	276	165	752	590
Post-Closure Period	4	124	-	266	-

LDS	Number of Cells	Average Flow Rate		Peak Flow Rate	
		m	σ	m	σ
Initial Period of Operation	26	36.6	68.5	141.8	259.9
Active Period of Operation	19	0.7	1.1	7.7	13.7
Post-Closure Period	4	0.2	-	2.3	-

Table 2. Description of MSW landfill liner system components.

Landfill ID	LCRS		Top Liner				LDS		Bottom Liner		
	Material(1)	Thickness (mm)	Geomembrane(2) Type (and Thickness (mm))	Lower Component			Material	Thickness (mm)	Geomembrane(2) Type (and Thickness (mm))	Lower Component	
				Material(3)	Thickness (mm)	Max. Hydraulic Conductivity (m/s)				Material(3)	Thickness (mm)
B	Sand	450	CSPE(0.9)	CCL	600	1×10^{-9}	Sand	450	PVC(0.8)	NA(5)	NA
Y	Sand	600	HDPE(2.0)	CCL	450	1×10^{-9}	Sand	300	HDPE(2.0)	CCL	600
AK	Sand/GN	600/5	HDPE(1.5)	GCL/CCL	6/600	$1 \times 10^{-11}/1 \times 10^{-9}$	GN	5	HDPE(1.5)	GCL	6
AL	Sand	600	HDPE(1.5)	CCL	900	1×10^{-9}	GN	5	HDPE(1.5)	CCL	900
AM	Gravel/Sand	300/150	HDPE(2.0)	CCL	450	1×10^{-8}	GN	5	HDPE(1.5)	NA	NA
AO	Sand	600	HDPE(1.5)	CCL	900	5×10^{-10}	GN	5	HDPE(1.5)	CCL	600
AR	Gravel/TC	300/400	HDPE(1.5)	GCL/CCL	6/300	$1 \times 10^{-11}/1 \times 10^{-7}$	GN	10	HDPE(1.5)	CCL	600

Notes: (1) LCRS and LDS Material Types: GN = Geonet or Geocomposite; TC = Tire Chips.

(2) Geomembrane Types: HDPE = High Density Polyethylene; CSPE = Chlorosulfonated Polyethylene; PVC = Polyvinyl Chloride.

(3) CCL = Compacted Clay Liner; GCL = Geosynthetic Clay Liner.

(4) All material thicknesses are nominal values.

(5) NA = not applicable.

Table 3. Summary of LCRS and LDS flow data for MSW landfill cells with composite top liners.

Cell No.	Cell Area (hectare)	Start of Waste Placem. (month-year)	Initial Period of Operation[1]					Active Period of Operation[2]					E_a (Average for Active Period) (%)
			Time Period (months)	LCRS Flow[3] Avg. (lphd)	LCRS Flow[3] Peak (lphd)	LDS Flow Avg. (lphd)	LDS Flow Peak (lphd)	Time Period (months)	LCRS Flow Avg. (lphd)	LCRS Flow Peak (lphd)	LDS Flow Avg. (lphd)	LDS Flow Peak (lphd)	
B3[4]	6.4	7-87	1-4	15,304	24,858	1,394	4,250	5-16	5,700	8,935	124	266	97.8
								17-28	9,272	22,444	101	168	98.9
								29-40	7,575	13,978	262	803	96.5
								41-52	2,859	6,043	231	713	91.9
								53-64	1,189	2,280	45	152	96.2
								65-76	403	490	92	133	77.3
								77-88	560	919	102	193	81.8
								89-93	578	648	98	109	83.0
Y2	3	1-91	1-10	23,368	36,791	655	1,768	11-22	10,353	19,204	370	1,993	96.4
								23-34	11,344	25,309	90	168	99.2
								35-46	4,404	6,380	70	248	98.4
								47-54	4,397	5,199	48	56	98.9
AK1	1.4	10-93	1-12	9,867	17,986	206	804						
AL1	14.9	1990	1-29	ND[5]	ND	ND	ND	30-41	934	2,085	231	367	75.3
								42-54	1,349	5,885	103	183	92.4
AM1	3.2/2.4[6]	10-90	1-9	ND	ND	ND	ND	10-21	270	533	15	64	94.4
								22-33	236	329	10	15	95.8
								34-45	111	283	3	14	97.3
								46-57	20	77	1	1	95.0
								58-69	18	21	1	1	94.4
								70-81	11	18	5	8	54.5

Table 3. Summary of LCRS and LDS flow data for MSW landfill cells with composite top liners (cont.).

Cell No.	Cell Area (hectare)	Start of Waste Placem. (month-year)	Initial Period of Operation[1]					Active Period of Operation[2]					E_a (Average for Active Period) (%)
			Time Period (months)	LCRS Flow[3]		LDS Flow		Time Period (months)	LCRS Flow		LDS Flow		
				Avg. (lphd)	Peak (lphd)	Avg. (lphd)	Peak (lphd)		Avg. (lphd)	Peak (lphd)	Avg. (lphd)	Peak (lphd)	
AM2	4.8/2.4[6]	10-90	1-9	ND	ND	ND	ND	10-21	32	154	9	42	71.9
								22-33	35	51	9	29	74.3
								34-45	17	45	3	26	82.4
								46-57	67	274	0	0	100.0
								58-69	64	181	8	13	87.5
								70-81	112	136	9	13	92.0
AO1	1.8	1-92	1-5	ND	ND	ND	ND	6-17	1,984	4,130	184	353	90.7
								18-29	1,299	1,577	96	126	92.6
								30-37	1,144	1,371	60	102	94.8
AO2	1.8	7-92	1-5	15,881	24,541	149	191	6-17	3,027	5,266	110	158	96.4
								18-31	1,688	2,383*	33	64	98.1
AR1	9.7	3-92	1-11	27,042	65,871	292	705	12-23	11,251	23,384	181	470	98.4
								24-36	9,668	26,274	155	442	98.4

Notes:

(1) "Initial Period of Operation" represents period after waste placement has started and only a small amount of waste has been placed in the cell.
(2) "Active Period of Operation" represents period when waste thickness in cell is significant and/or an effective intermediate cover is placed on the waste.
(3) Flow rates are given in liter/hectare/day.
(4) 65 percent of Cell B3 received final cover after 60 months of start of waste placement.
(5) ND = not determined.
(6) Values given represent LCRS and LDS areas, respectively.

Table 4. Summary of liquid chemistry for the LCRS and LDS of MSW landfills with top composite liners.

Landfill ID		B		Y		AK		AL	
Cell No.-System		B3-LCRS	B3-LDS	Y2-LCRS	Y2-LDS	AK1-LCRS	AK1-LDS	AL1-LCRS	AL1-LDS
Waste Placement Period		07/87-05/92		1990-date		10/93-date		1990 - date	
Liquid Sampling Period		07/87-10/94	05/87-10/94	04/91-04/94	04/91-04/94	12/93-03/95	12/93-03/95	06/91-05/95	12/89-05/95
Parameter	Units								
pH		6.82		6.60	7.28	6.65	7.20	8.09	7.04
Specific Conductance	µmhos/cm	2,956	1,554	5,360	1,583	1,592	679	2,707	2,449
Alkalinity	mg/l			2,520	335	711	331	261	199
TDS	mg/l	4,140	1,148	4,939	881			2,892	2,482
TSS	mg/l	161	45				60	110	24
COD	mg/l	1,912	131	5,265	50	1,062	13	860	< 11
BOD_5	mg/l	422	88	2,076	3	< 2		1,134	< 2
TOC	mg/l	554	138	1,436	11	245	4	245	3
Sulfate	mg/l	131	335	108	231	45	25	219	1,028
Calcium	mg/l			1,994	179	387	116	150	465
Magnesium	mg/l				54	51	29	98	121
Sodium	mg/l	450	46	433	46	64	5	236	38
Chloride	mg/l	690	148	628	58	94	4	430	151
Arsenic	µg/l		< 24	17	4	< 3	< 1	4	< 5
Lead	µg/l	< 44	< 17	5	8	< 48	< 5	< 36	< 17
Chromium	µg/l	49	3	58	11	< 27	< 2	< 64	< 10
Nickel	µg/l	102	519	185	25	< 50	< 50	57	< 35
Cadmium	µg/l	< 20	16	8	< 2	< 19	< 3	< 11	< 7
1,1,1 - Trichloroethane	µg/l	< 107	< 6			134	3	< 8	< 4
1,1 - Dichloroethane	µg/l	< 40	< 7	45		46	< 1	< 8	< 7
1,2 - Dichloroethane	µg/l	< 5	< 6			< 2	< 1	< 6	< 2
Benzene	µg/l	< 5	< 7	10		< 5	< 1	< 6	< 2
Ethylbenzene	µg/l	15	< 6	118		< 7	< 1	< 12	< 2
Methylene Chloride	µg/l	< 80	< 17	121		603	< 5	245	< 77
Trichloroethene	µg/l			11		< 1	< 1	< 12	< 2
Toluene	µg/l	< 78	< 9	720	7	95	< 1	78	< 7
Vinyl Chloride	µg/l	< 10	< 12			< 11	< 5	< 11	< 5
Xylenes	µg/l			69		< 30	< 3	< 96	< 5
Cis- 1,2-Dichloroethene	µg/l					< 1	< 1	< 7	< 3
Trans- 1,2-Dichloroethene	µg/l					< 1	< 1	< 2	< 2

Table 4. Summary of liquid chemistry for the LCRS and LDS of MSW landfills with top composite liners (cont.).

Landfill ID		AM				AO			AR	
Cell No.-System		AM1-LCRS	AM1-LDS	AM2-LCRS	AM2-LDS	AO-LCRS	AO1-LDS	AO2-LDS	AR1-LCRS	AR1-LDS
Waste Placement Dates		10/90-02/91		10/90-02/91		01/92-date			03/92-date	
Liquid Sampling Dates		04/91-02/95	02/92-12/93	04/91-02/96	02/92-01/96	08/92-06/95	08/92-05/95	08/92-06/95	11/92-08/94	11/92-08/94
Parameter	Units									
pH		6.62	6.90	6.60	7.26	7.30	7.17	6.72	6.92	7.00
Specific Conductance	µmhos/cm	2,451	17,250	2,795	17,063	6,592	1,132	1,118	5,650	1,368
Alkalinity	mg/l	1,204	407	867	163	1,756	556	558	2,075	325
TDS	mg/l	1,709	14,330	1,413	14,363	2,178	690	722	3,923	848
TSS	mg/l					1,310				
COD	mg/l	396	184	65	76	618	142	497	1,238	22
BOD$_5$	mg/l								290	5
TOC	mg/l	108	116	22	28	414	43	8	333	5
Sulfate	mg/l	18	1,500	9	1,425	54	44	91	380	325
Calcium	mg/l	376	1,700	319	1,819	275	205	196	230	186
Magnesium	mg/l	95	283	74	299	146	66	55	153	119
Sodium	mg/l	92	1,348	88	1,929	786	19	8	850	26
Chloride	mg/l	183	2,725	332	2,659	862	38	24	1,625	35
Arsenic	µg/l	236	< 2	235	< 10	45	7	2	13	< 8
Lead	µg/l	< 2.0		< 7	< 3	< 32	< 1	< 1	< 13	< 9
Chromium	µg/l	< 30	< 30	< 57	< 30	54	< 1	< 1	62	< 10
Nickel	µg/l	< 40	< 40	< 91	< 40	108	< 50	< 50	< 20	< 100
Cadmium	µg/l	< 20	< 20	< 20	< 10	< 9	< 1	< 1	< 6	< 7
1,1,1 - Trichloroethane	µg/l	< 21	< 1	< 16	< 1	< 11	< 1	< 1	< 100	< 2
1,1 - Dichloroethane	µg/l	172	< 3	136	< 2	15	< 3	< 1	< 100	< 2
1,2 - Dichloroethane	µg/l	6	< 1	< 11	< 1	< 5	< 1	< 1	< 100	< 2
Benzene	µg/l	17	< 1	13	< 1	7	< 1	< 1	< 100	< 1
Ethylbenzene	µg/l	57	< 1	29	< 1	11	< 1	< 1	< 100	< 2
Methylene Chloride	µg/l	< 6	3	< 20	< 2	75	< 5	< 5	< 100	< 2
Trichloroethene	µg/l	3	< 1	< 12	< 1	< 4	< 1	< 1	< 100	< 2
Toluene	µg/l	267	< 1	146	< 1	167	< 86	< 1	< 100	< 2
Vinyl Chloride	µg/l	< 21	< 1	< 11	< 2	< 12	< 7	< 5	< 100	< 4
Xylenes	µg/l	122	< 1	71	< 2	34	< 3	< 3	< 100	< 4
Cis- 1,2-Dichloroethene	µg/l	324	< 1	547	< 1	< 6	< 1	< 1	< 100	< 50
Trans- 1,2-Dichloroethene	µg/l	< 5	< 1	< 8	< 1	< 4	< 1	< 1	< 100	< 2

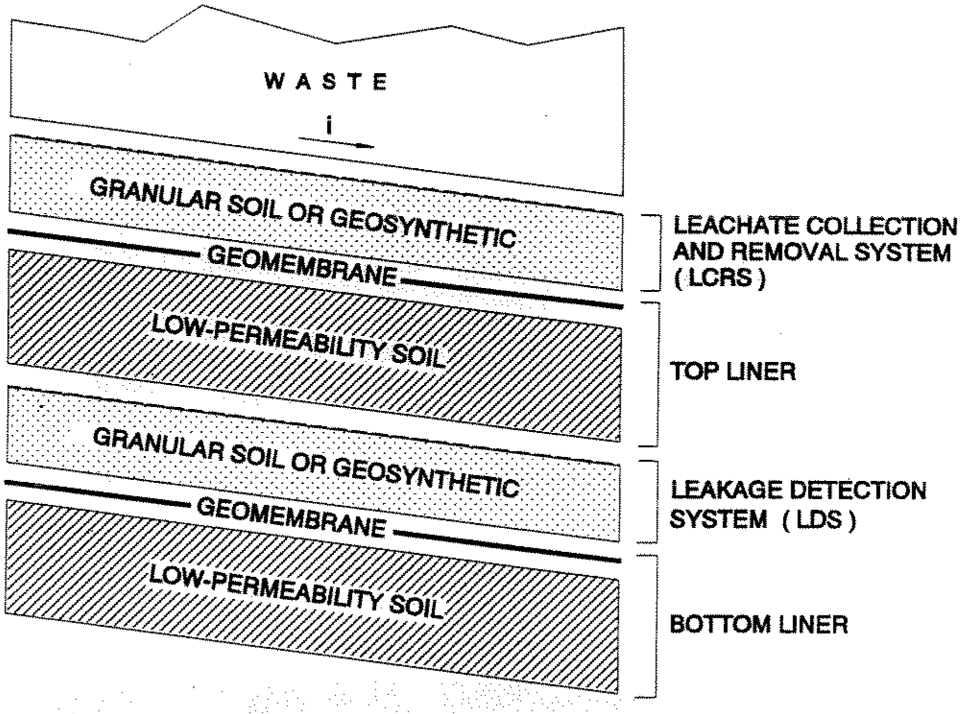

Figure 1. Components of double-liner system.

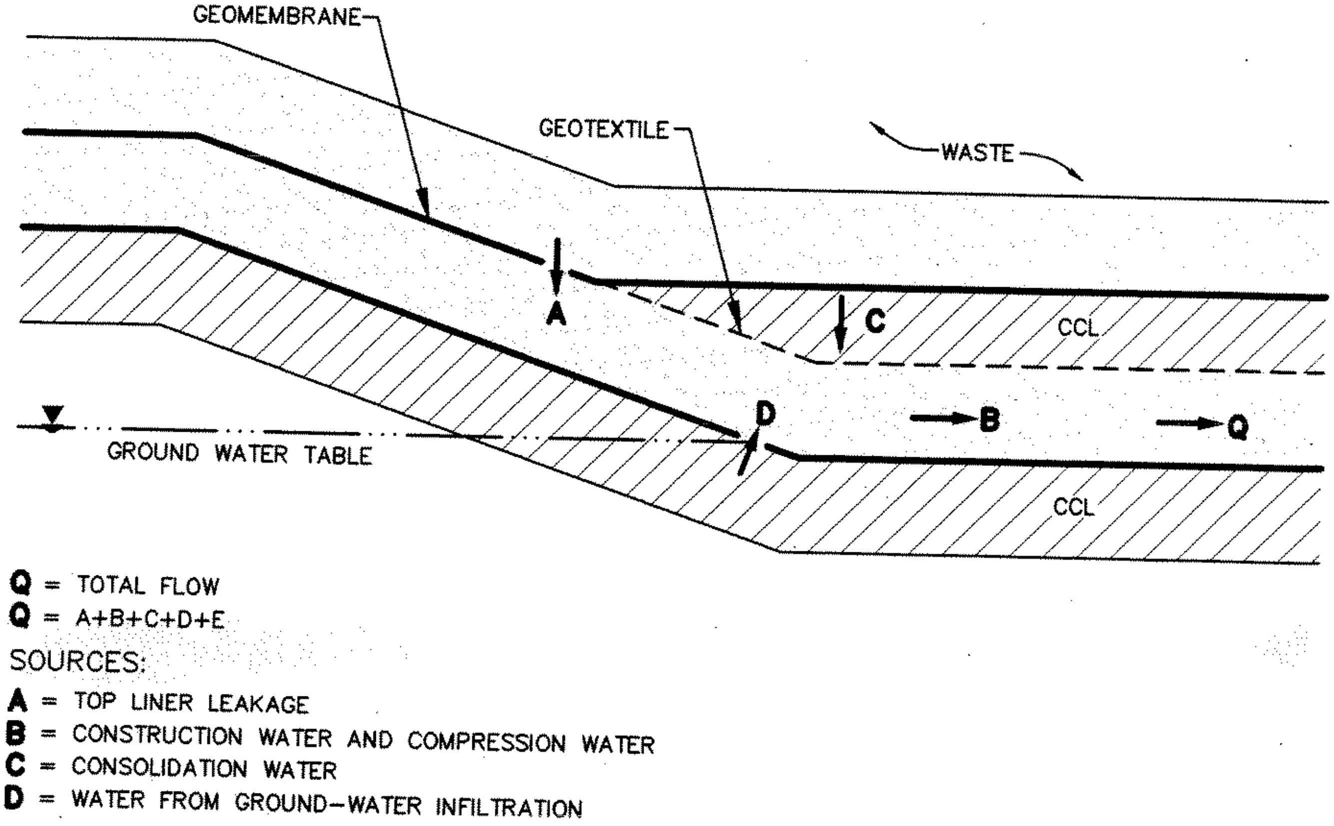

Figure 2. Sources of flow from leak detection systems (from Bonaparte and Gross (1990)).

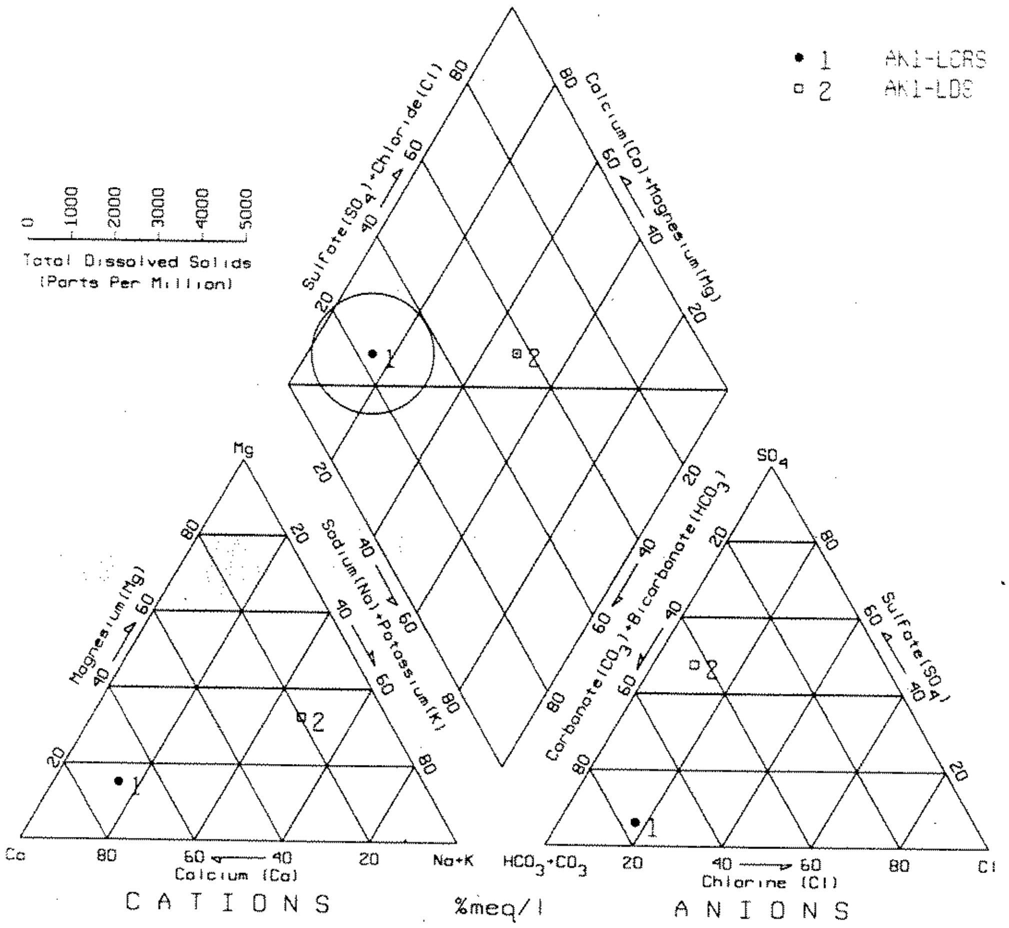

Figure 3. Piper trilinear diagram for cell AK1.

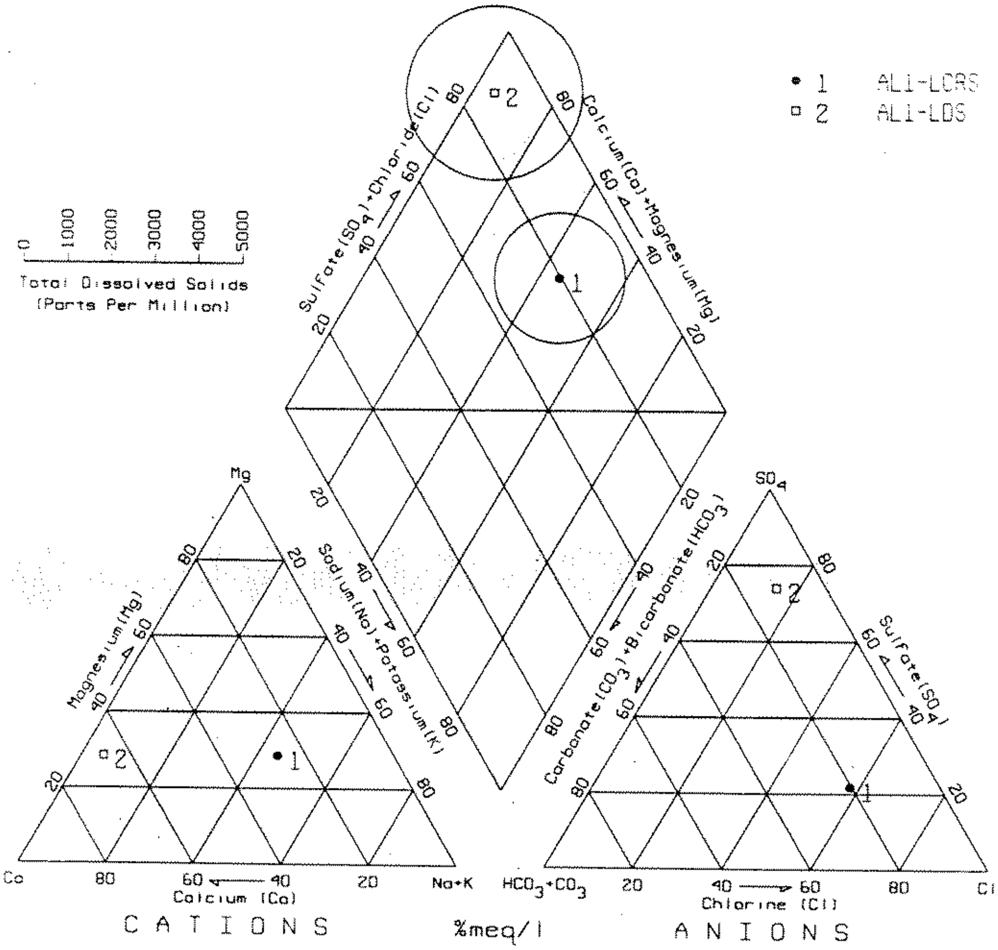

Figure 4. Piper trilinear diagram for cell AL1.

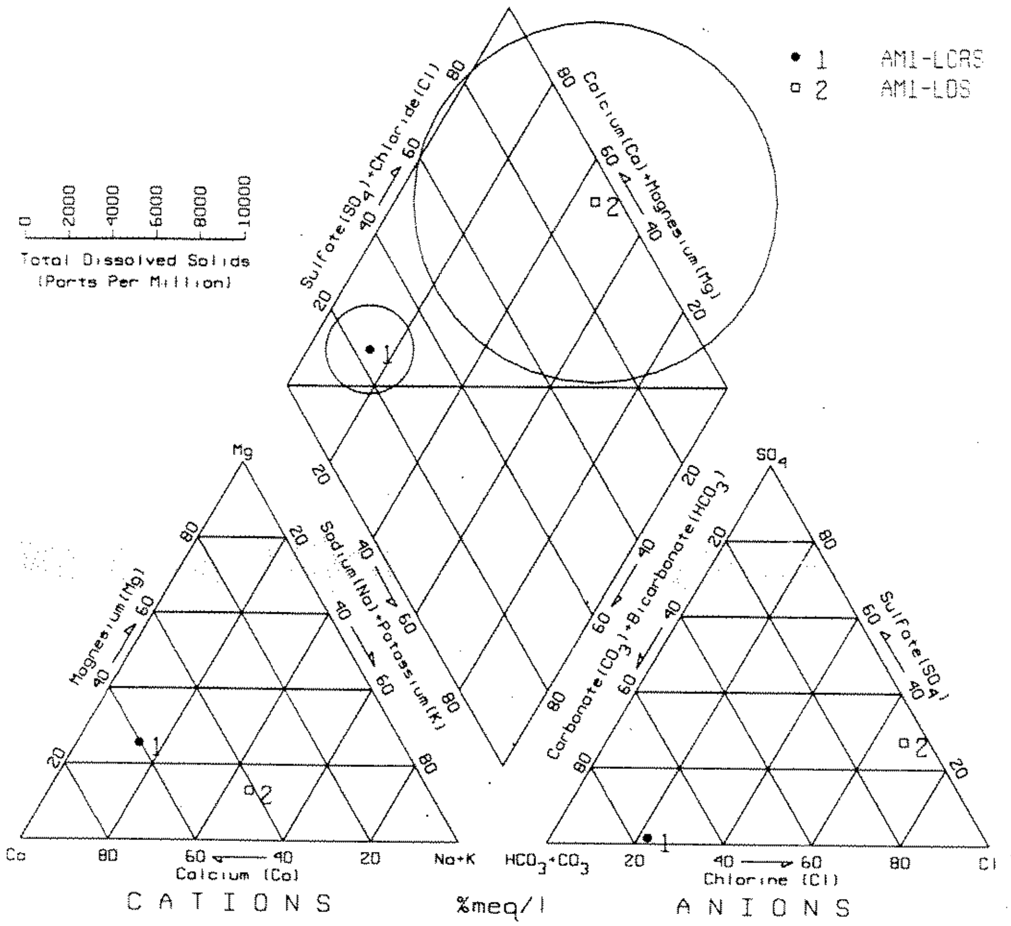

Figure 5. Piper trilinear diagram for cell AM1.

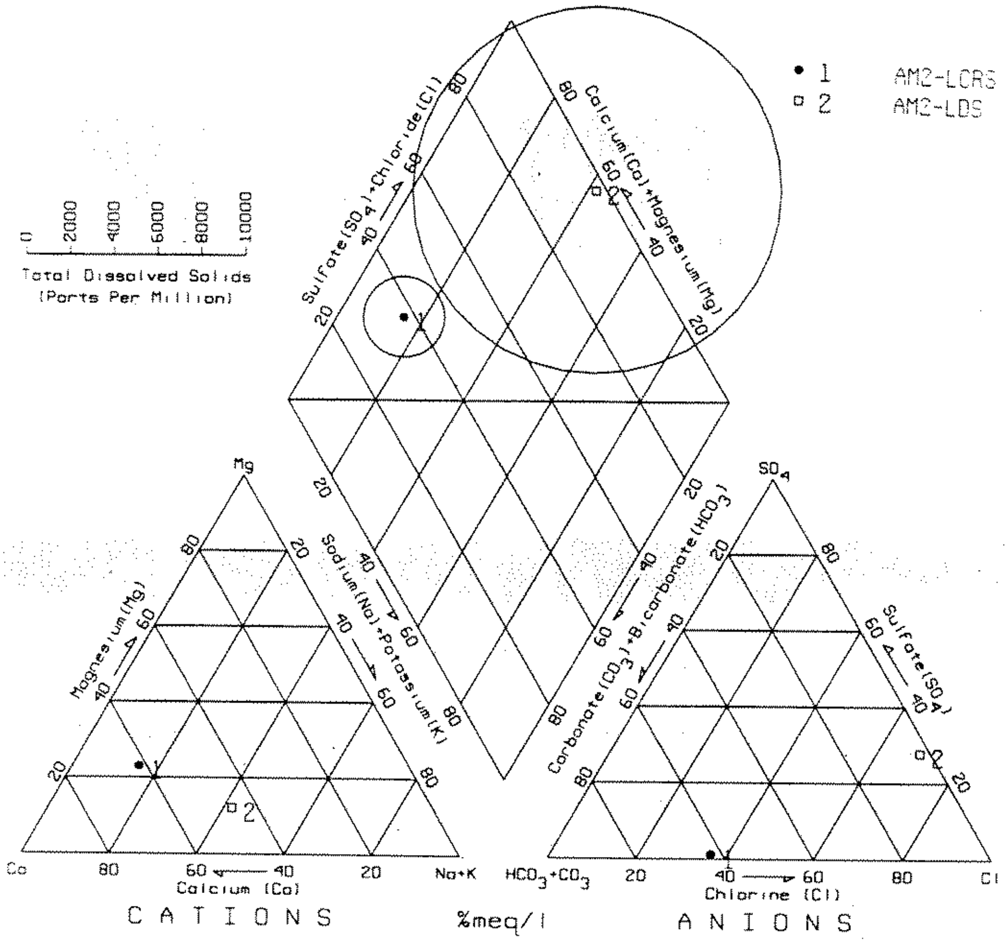

Figure 6. Piper trilinear diagram for cell AM2.

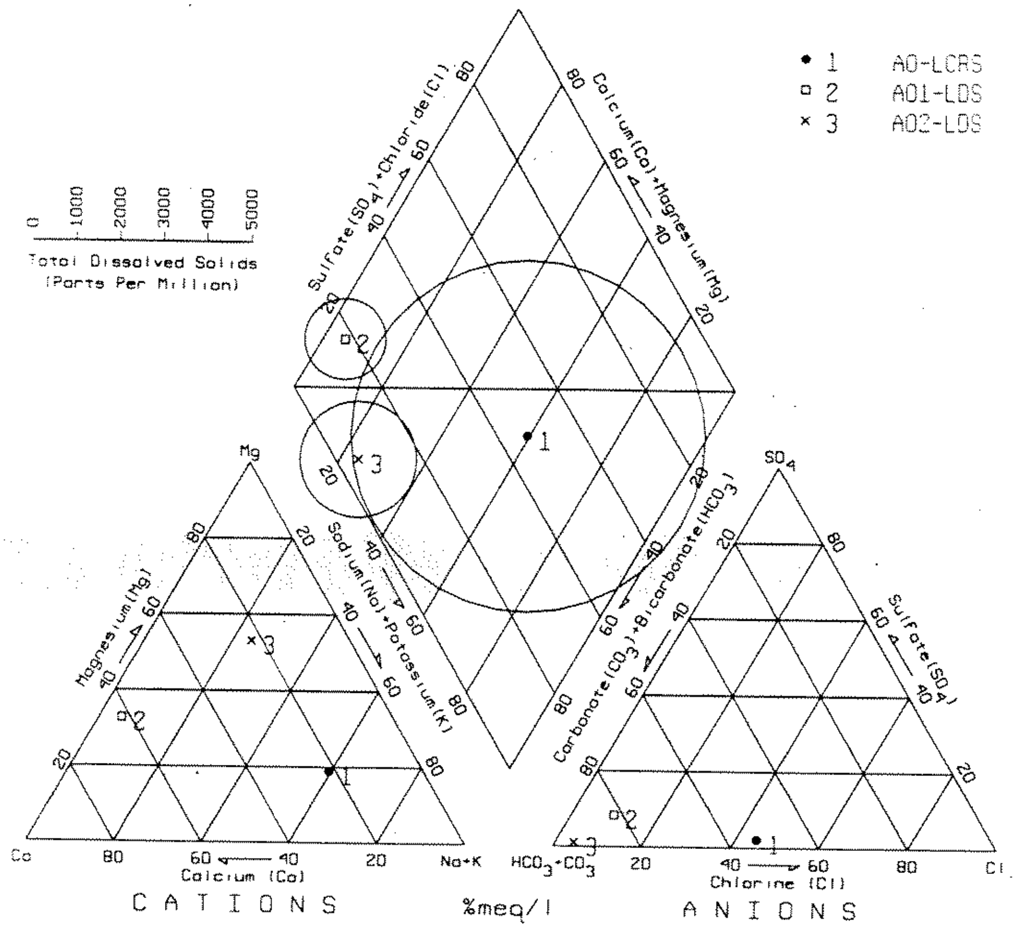

Figure 7. Piper trilinear diagram for cells AO1 and AO2.

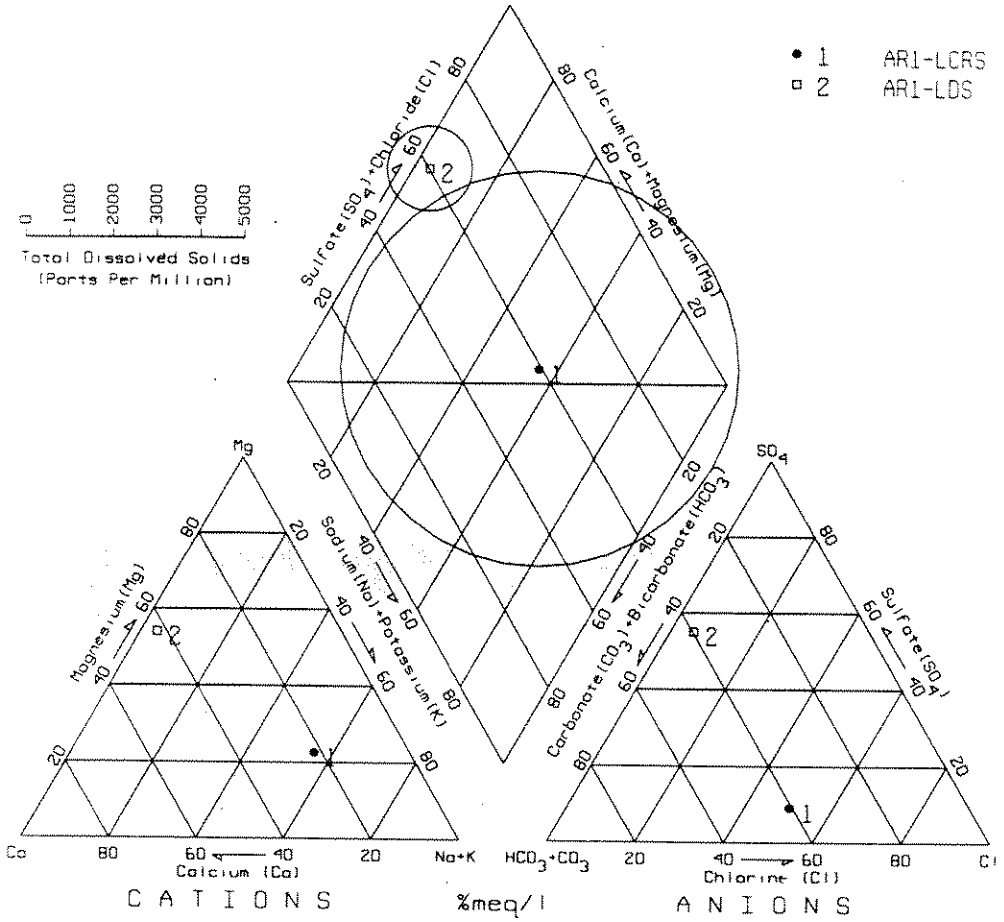

Figure 8. Piper trilinear diagram for cell AR1.

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Appendices

Appendix A — List of Attendees A-1

Appendix B — Total Down-Slope Displacement in Test Plots B-1

Appendix C — Differential Displacement in Test Plots C-1

Appendix D — Moisture Instrument Readings in Test Plots D-1

Appendix E — Results of Interface Shear Tests Performed at Drexel University's Geosynthetic Research Institute E-1

Appendix F — Evaluation of Various Aspects of GCL Performance, Prepared by GeoSyntec Consultants F-1

Appendix G — Summary of Bentomat Direct Shear Data, Prepared by CETCO G-1

Appendix H — Summary of Bentofix Shear Test Results, Prepared by National Seal Co. H-1

EVALUATION OF VARIOUS ASPECTS OF GCL PERFORMANCE

by

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and D.L. Vander Linde[1]

INTRODUCTION

The purpose of this paper is to briefly present the results of various activities that have recently been undertaken by the authors on the subject of geosynthetic clay liner (GCL) testing and performance evaluation. The subjects that are addressed are:

- field hydraulic performance of composite liners containing GCLs;
- drained shear strength of hydrated GCLs at high normal stress;
- interface shear strength between unhydrated GCLs and textured geomembranes at high normal stress;
- hydration of GCLs adjacent to soil layers; and
- causes of failure of a landfill cover system containing a GCL.

FIELD PERFORMANCE OF COMPOSITE LINERS CONTAINING GCLs

Sources of Flow in LDS of Double-Liner System

A double liner system consists of top and bottom liners with a leakage detection system (LDS) between the two liners. If the double-liner system is used in a landfill, it will also contain a leachate collection and removal system (LCRS) above the top liner. As part of an ongoing research investigation for the United States Environmental Protection Agency (USEPA), the authors have collected data

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on the rates of liquid flow into the sumps of LCRSs and LDSs for a wide variety of double-lined waste management units located throughout the United States. Comparison of the rates of flow into the LCRS and LDS of a unit can be used to quantify the performance of the top liner (in terms of the ability to impede advective transport of liquid through the liner). In essence, the LDS serves as a large lysimeter (i.e., collection pan) below the top liner.

To make the evaluation, consideration must be given to the potential sources of liquid in the LDS. Gross et al. [1990] described the potential sources of LDS flow, which are (Figure 1): (i) leakage through the top liner; (ii) drainage of water (mostly rainwater) that infiltrates the leakage detection layer during construction but does not drain to the LDS sump until after start of facility operation ("construction water"); (iii) water expelled from the LDS layer as a result of compression under the weight of the waste ("compression water"); (iv) water expelled from any clay component of the top liner as a result of clay consolidation under the weight of the waste ("consolidation water"); and (v) for a waste management unit with its base located below the water table, groundwater infiltration through the bottom liner ("infiltration water").

Gross et al. [1990] and Bonaparte and Gross [1990] presented the following five-step approach for evaluating the sources of LDS liquid at a specific waste management unit.

- Identify the potential sources of flow for the unit based on double-liner system design, climatic and hydrogeologic setting, and unit operating history.
- Calculate flow rates from each potential source.
- Calculate the time frame for flow from each potential source.
- Evaluate the potential sources of flow by comparing measured flow rates to calculated flow rates at specific points in time.
- Compare LCRS and LDS chemical constituent data to further establish the likely source(s) of liquid.

Bonaparte and Gross [1990, 1993] used this five-step approach to evaluate the sources of LDS flow for 93 waste management units. Under a contract to the USEPA Risk Reduction Research Laboratory, the authors are currently performing this evaluation using new data from the facilities in the Bonaparte and Gross studies, as well as data from a significant number of additional waste management units not included in the original studies. Preliminary results for waste management units with composite top liners containing GCLs are presented below.

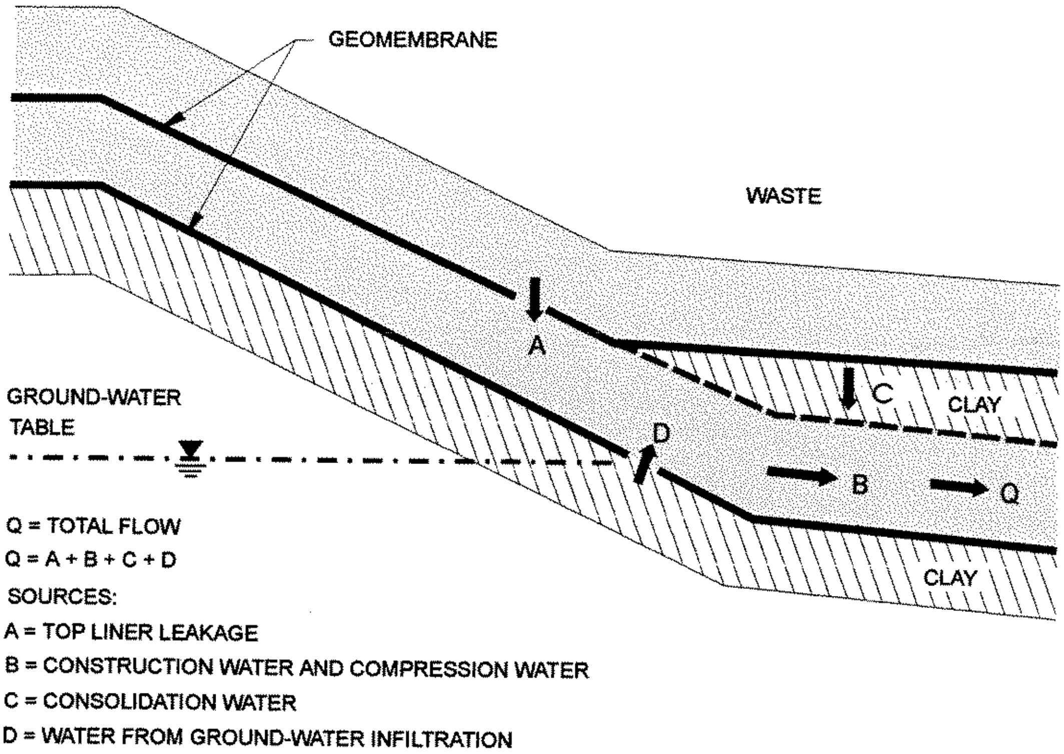

Figure 1. Sources of flow from leak detection layers.

LCRS and LDS Flow Data

Flow rate data have been collected for 26 waste management units containing composite top liners consisting of a geomembrane overlying a GCL. The 26 units are located at six different landfill sites. Descriptions of the components of the liner systems used at these facilities are presented in Table 1 and flow rate data for the LCRSs and LDSs in the units are presented in Table 2. Average daily flow rates were calculated for both systems on a monthly basis by dividing the total amount of liquid extracted from the system during the month by the number of days in the month and the area of the waste management unit. Flow rates are reported in units of liter/hectare/day (lphd). The volume of flow used in the calculation was typically obtained from the landfill operator, with flow measurements most often measured using accumulating flow meters. The reported flow volumes should be considered approximate.

Table 1. Description of landfill liner system components.

Landfill Identification	LCRS		Composite Top Liner		LDS		Bottom Liner		
	Material	Thickness (mm)	HDPE Geomembrane Thickness (mm)	GCL Thickness (mm)	Material	Thickness (mm)	HDPE Geomembrane Thickness (mm)	Layer 2	
								Material	Thickness (mm)
A	Sand	600	1.5	13	Sand	300	1.5	Clay	200
B	Sand	600	2.0	13	Sand	450	2.0	Clay	300
C	Sand	450	1.5	13	Sand	300	1.5	GCL	13
D	Sand	600	1.5	13	GT/GN[1]	5	1.5	N/A	N/A
E	Sand	600	1.5	13	GT/GN	5	1.5	Clay	900
F	GN	5	1.5	13	GT/GN	5	1.0	GCL	13

Notes: [1] GT= Geotextile, GN= Geonet.

[2] All material thicknesses are nominal values.

Table 2. Summary of flow data for the LCRS and LDS of units with composite top liners containing GCLs.

Cell No.	Cell Area	End of Cell Const. (month-year)	Start of Waste Placem. (month-year)	End of Final Closure (month-year)	Initial Period of Operation[1]					Active Period of Operation[2]					Post Closure Period[3]				
					Time Period	LCRS Flow[4]		LDS Flow		Time Period	LCRS Flow		LDS Flow		Time Period	LCRS Flow		LDS Flow	
						Avg.	Peak	Avg.	Peak		Avg.	Peak	Avg.	Peak		Avg.	Peak	Avg.	Peak
	(hectare)				(months)	(lphd)	(lphd)	(lphd)	(lphd)	(months)	(lphd)	(lphd)	(lphd)	(lphd)	(months)	(lphd)	(lphd)	(lphd)	(lphd)
A1	2.0	7-88	7-88	2-91	1-2	16,718	19,738	0.0	0.0	3-32	561	2,384	0.0	0.0	33-83	65	103	0.0	0.0
A2	2.0	7-88	7-88	2-91	1-5	15,521	58,671	15.0	44.9	6-32	281	570	1.9	20.6	33-83	178	421	0.0	0.0
A3	1.7	8-88	9-88	4-93	1-5	3,366	7,985	34.6	150.5	6-56	290	1,075	3.7	46.8	57-81	206	458	0.9	9.4
A4	1.7	8-88	9-88	4-93	1-12	2,534	12,688	101.0	860.2	13-56	75	187	0.9	13.1	57-81	47	84	0.0	0.0
A5	2.8	9-88	10-88		1-11	1,384	3,394	37.4	91.6	12-80	56	187	1.9	37.4					
A6	3.9	11-88	12-88		1-9	3,759	7,171	53.3	92.6	10-80	168	655	0.0	0.0					
A7	2.6	1-89	2-89		1-10	5,376	12,155	33.7	46.8	11-76	234	851	1.9	9.4					
A8	3.8	7-89	7-89		1-14	4,881	21,038	47.7	188.9	15-71	439	1,384	0.0	0.0					
A9	3.3	12-89	12-89		1-9	1,047	3,478	0.9	7.5	10-65	37	159	0.0	0.0					
A10	3.9	2-90	7-90		1-7	2,786	13,698	0.0	0.0	8-59	374	645	0.0	0.0					
A11	3.0	2-90	2-90		1-16	4,675	14,586	0.0	0.0	17-64	150	337	0.0	0.0					
A12	4.0	10-90	10-90		1-18	2,945	8,836	0.0	0.0	19-56	655	1,505	0.0	0.0					
A13	3.0	1-91	1-91		1-32	3,740	14,343	0.0	0.0	33-53	281	486	0.0	0.0					
A14	2.8	4-91	4-91		1-11	2,777	6,582	0.0	0.0	12-38	281	449	0.0	0.0					
A15	2.8	5-92	5-92		1-12	5,573	11,809	0.0	0.0	13-37	299	561	0.0	0.0					
A16	4.5	1-93	1-93		1-22	4,675	17,756	0.0	0.0	23-29	206	393	0.0	0.0					
B1	3.6	5-93	8-93		1-10	3,273	12,155	177.7	822.8	11-17	393	1,403	2.8	15.0					
C1	2.4	4-93	5-93		1-12	6,358	20,570	130.9	523.6										
C2	2.4	7-93	8-93		1-10	3,553	7,480	289.9	514.3										
D1	4.0	12-90	2-91		1-23			11.2	24.3	24-47			0.9	3.7					
D2	2.4	12-92	1-93		1-24	4,208	11,688	0.9	14.0										
D3	2.8	12-92	1-93		1-13	3,179	8,228	0.0	0.0	14-24	187	309	0.0	0.9					
E1	3.8	9-92	12-92		3-23	3,890		1.9	22.4										
F1	1.3	7-94	10-94		1-9	6,330	12,052	0.0	0.0										
F2	1.0	7-94	8-94		1-11	9,967	21,729	4.7											
F3	1.0	7-94	8-94		1-11	11,248	31,313	11.2											

Notes:

(1) "Initial Period of Operation" represents period after waste placement has started and only a few lifts of waste and daily cover have been placed in the cell (i.e., no intermediate cover).

(2) "Active Period of Operation" represents period when waste thickness in cell is significant and/or an effective intermediate cover is placed on the waste.

(3) "Post Closure Period" represents period after final cover system has been placed on the entire cell.

(4) Flow rates are given in liter/hectare/day.

Figure 2 shows LCRS and LDS average daily flow rate data for a municipal solid waste management unit, located in Pennsylvania, that was active for 56 months. Subsequently, a final cover system containing a geomembrane was placed over the entire unit. Flow data for the 56-month operational period and a 25-month post closure period were obtained and analyzed. As Figure 2 shows, flow rates in both systems were highest immediately after the start of waste placement and thereafter decreased with time. During the first twelve months of operation, the average rate of flow into the LCRS sump decreased from 12,700 to 180 lphd. After that time, the LCRS flow rate stabilized and during the following 44 months, the rate of flow into the LCRS sump varied between 10 and 170 lphd. After final closure, the flow rate decreased even further, to between 10 and 80 lphd.

As illustrated in Figure 2, waste management unit development can be divided into three distinct periods. During the first period, herein referred to as the "initial period of operation", LCRS flow rates may be relatively high. High flows during this period are attributed to the occurrence of rainfall into a unit that initially contains little waste. To the extent rainfall occurs during this period, it will find its way rapidly into the LCRS. Obviously, the amount of LCRS flow during this period is highly dependent on climate. A lag exists between the time liquid first enters the LCRS and when it flows into the LCRS sump. The magnitude of the lag is largely dependent on the hydraulic characteristics (i.e., the length and slope of the LCRS and the hydraulic conductivity of the LCRS drainage material). Most available data indicate a decreasing LCRS flow rate with time during the initial period of operation. During the second period, referred to herein as the "active period of operation", the rate of flow into the LCRS continues to decreases and eventually stabilizes. This occurs as the amount of waste in the unit increases and as daily and intermediate layers of cover soil are placed. This trend in flow rates is also dependent on the type of waste but is likely representative of the trends observed at most new landfills, excluding those that accept sludges or other high moisture content wastes. During the "post closure period", the final cover system further reduces infiltration of rainwater into the waste, resulting in a further reduction in LCRS flow. Final covers containing geomembranes can, if functioning properly, virtually eliminate rainwater infiltration.

LDS flow rates for the waste management unit in Figure 2 were highest (860 lphd) at the beginning of operations and decreased in the following few months, becoming very low (i.e., less than 10 lphd) within approximately 15 months after the start of unit operation. The decrease in LDS flow with time is expected because: (i) flow rates in the LCRS during this time period decreased, and therefore, the potential for leakage through the top liner also decreased; (ii) most construction water initially present in the LDS flowed to the LDS sump in the first few weeks to months of unit operation; and (iii) the volume of compression and consolidation water for this waste management unit should be very small.

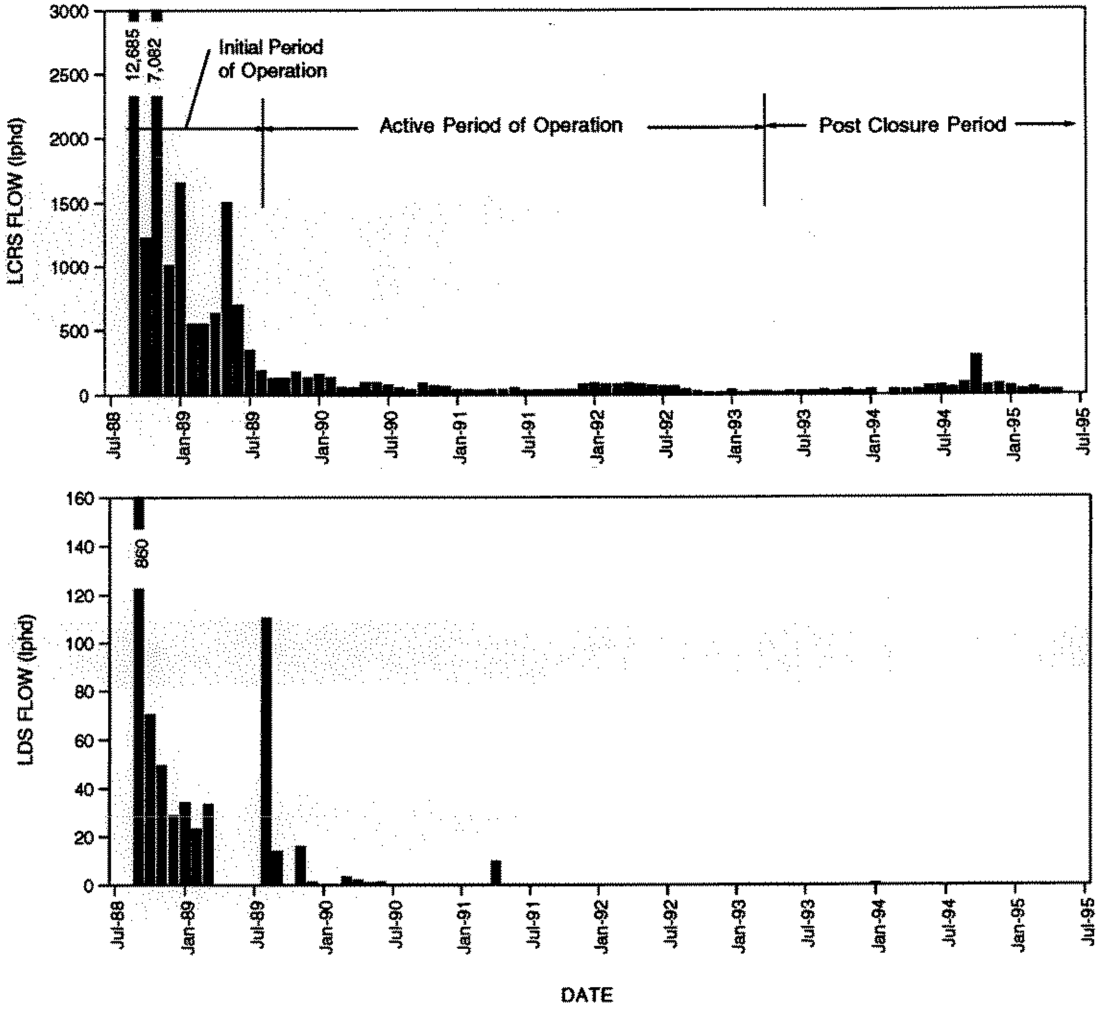

Figure 2. LCRS and LDS flow rates at a modern MSW landfill in Pennsylvania.

Table 2 summarizes LCRS and LDS flow data for the 26 waste management units containing GCLs in their composite top liners. Average and peak flow rates are reported for the three time periods described above. Table 2 shows that between the initial and active periods of operation, LCRS flow rates decreased one to two orders of magnitude and LDS flow rates decreased one to three orders of magnitude. Reported peak LCRS flow rates were up to 5 times the average, while peak LDS flow rates were up to 20 times the average. Table 3 presents the mean values of average and peak flows for the database.

Table 3. Mean values of flow for the data in Table 2 (Note: m = mean value; σ = standard deviation; values are in liter/hectare/day).

LCRS	Number of Units	Average Flow Rate		Peak Flow Rate	
		m	σ	m	σ
Initial Period of Operation	25	5,350	3,968	14,964	11,342
Active Period of Operation	18	276	165	752	590
Post-Closure Period	4	124	-	266	-

LDS	Number of Units	Average Flow Rate		Peak Flow Rate	
		m	σ	m	σ
Initial Period of Operation	26	36.6	68.5	141.8	259.9
Active Period of Operation	19	0.7	1.1	7.7	13.7
Post-Closure Period	4	0.2	-	2.3	-

Top Liner Hydraulic Efficiency

Table 4 summarizes calculated "apparent" efficiencies for the composite top liners of the 26 waste management units presented in Table 2. Liner apparent efficiency, AE, is calculated using the following equation:

$$\text{AE } (\%) = (1 - \text{LDS Flow Rate} / \text{LCRS Flow Rate}) \times 100 \qquad \text{(Equation 1)}$$

Table 4. "Apparent" efficiencies of composite liners containing GCLs(1).

Cells with Sand LDS				Cells with GT/GN LDS	
Cell No.	Initial Period of Operation (%)	Active Period of Operation (%)	Post-Closure Period (%)	Cell No.	Initial Period of Operation (%)
A1	100.00	100.00	100.00	D1	99.98
A2	99.90	99.33	100.00	D2	100.00
A3	98.97	98.71	99.55	E1	99.95
A4	96.01	98.75	100.00	F1	100.00
A5	97.23	97.50		F2	99.95
A6	98.58	100.00		F3	99.90
A7	99.37	99.20			
A8	99.02	100.00			
A9	99.91	100.00			
A10	100.00	100.00			
A11	100.00	100.00			
A12	100.00	100.00			
A13	100.00	100.00			
A14	100.00	100.00			
A15	100.00	100.00			
A16	100.00	100.00			
B1	94.57	99.29			
C1	97.94				
C2	91.84				
Number	19	17	4	Number	6
Range	91.84 - 100.00	97.5 - 100.00	99.55 - 100.00	Range	99.90 - 100.00
Mean	98.60	99.58	99.89	Mean	99.96
Median	99.90	100.00	100.00	Median	99.97

Notes: (1) Apparent Efficiency = (1 - LDS Flow / LCRS Flow) x 100 %

This liner efficiency is referred to as "apparent" because, as described above, flow into the LDS sump may be attributed to sources other than top liner leakage (Figure 1). If the only source of flow into the LDS sump is top liner leakage, then Equation 1 provides the "true" liner efficiency. Liner efficiency provides a measure of the effectiveness of a particular liner in limiting or preventing advective transport across the liner.

Table 4 presents calculated AE values for waste management units with sand LDSs (Landfills A, B, and C). For these units, the apparent efficiency is lowest during the initial period of operation (AE_m = 98.6 percent; where AE_m = mean apparent efficiency) and increases significantly thereafter (AE_m = 99.58 percent during the active period of operation and AE_m = 99.96 percent during the post closure period). The lower AE_m during the initial period of operation can be attributed to LDS flow from construction water. For units A, B, and C, calculated AE values during the active period of operation and the post-closure period may provide a reasonably accurate indication of true liner efficiency for the conditions at these units during the monitoring periods. It should be noted, however, that the true efficiency of a liner is not constant but rather a function of the hydraulic head in the LCRS and size of the area over which LCRS flow is occurring (the area is larger at high flow rates compared to low flow rates).

Table 4 also presents calculated AE values for waste management units with geonet LDSs (Landfills D, E, and F). The available data are limited to the initial period of unit operation. As shown in Table 4, AE_m for the six units with geonet LDSs is 99.96 percent. This value is much higher than the AE_m of liners of cells with sand LDSs for the same facility operational period (i.e., 98.60 percent). This higher efficiency can be attributed to the differences in liquid storage capacity and hydraulic transmissivity between sand and geonet drainage materials. A granular drainage layer can store a much larger volume of construction water and releases this water more slowly during the initial period of operation than does a geonet drainage layer. This suggests that, during the initial period of operation, the main source of flow in a sand LDS underlying a composite top liner containing a GCL is construction water.

Conclusions on Field Performance of Composite Liners Containing GCLs

From Table 2, LDS flows attributable to top liner leakage very from 0 to 50 lphd, with most values being less than about 2 lphd. These flow rates are very low. The data shown in Table 4 suggest that the true hydraulic efficiency of a composite liner incorporating a GCL may be greater than 99.90 percent. A liner with this efficiency, when appropriately used as part of an overall liner system, can provide a very high degree of liquid containment capability.

SHEAR STRENGTH OF HYDRATED GCLs

Overview

For a recent project, the authors were concerned with the long-term drained shear strength of hydrated GCLs at normal stresses in the range of 240 to 720 kPa. Drained shear strengths are applicable to long-term design and the range of considered normal stresses is applicable to conditions in a liner system at the base of a landfill. A testing program to evaluate the long-term drained shear strength of GCLs was undertaken and this program is ongoing. To develop interim values for preliminary design, the authors reviewed and analyzed available data from the technical literature on the consolidated-drained (CD) shear strength of GCLs. The findings of this review are presented below.

Required Deformation Rates to Achieve CD Conditions

To achieve consolidated drained (CD) test conditions, direct shear tests must be carried out at a very slow rate of shear displacement. The required displacement rate can be estimated using the well-known time-to-failure equation specified in American Society of Testing and Materials (ASTM) standard test method D 3080:

$$t_f = 50\ t_{50} \qquad \text{(Equation 2)}$$

where: t_f = total elapsed time to failure(s); and t_{50} = time required for the test specimen to achieve 50 percent primary consolidation under the specified normal stress, or increment(s) thereof. Using t_f from consolidation tests and an estimated failure displacement δ_t, the required shear displacement rate, d_r, can be calculated using the equation:

$$d_r = \delta_t\ /\ t_f \qquad \text{(Equation 3)}$$

Shan [1993] performed one-dimensional consolidation tests on the GCL products Claymax®, Gundseal®, Bentomat®, and Bentofix®. He evaluated t_f values for each product. The results of his evaluation are provided in Figure 3. With reference to this figure, at normal stresses in the range of 240 to 720 kPa, t_f values are in the range of about 100 to 400 hours. If it is assumed that a displacement of 25 mm is needed to achieve peak shear stress conditions, a required shear displacement rate of 0.05 to 0.25 mm/s is calculated. Only test results conducted at shear displacement rates that satisfy Equations 2 and 3 and the data from Shan [1993] should be considered to represent CD conditions. Test results at faster rates will yield lower shear strengths as a result of positive pore pressure development during the shearing phase of the test.

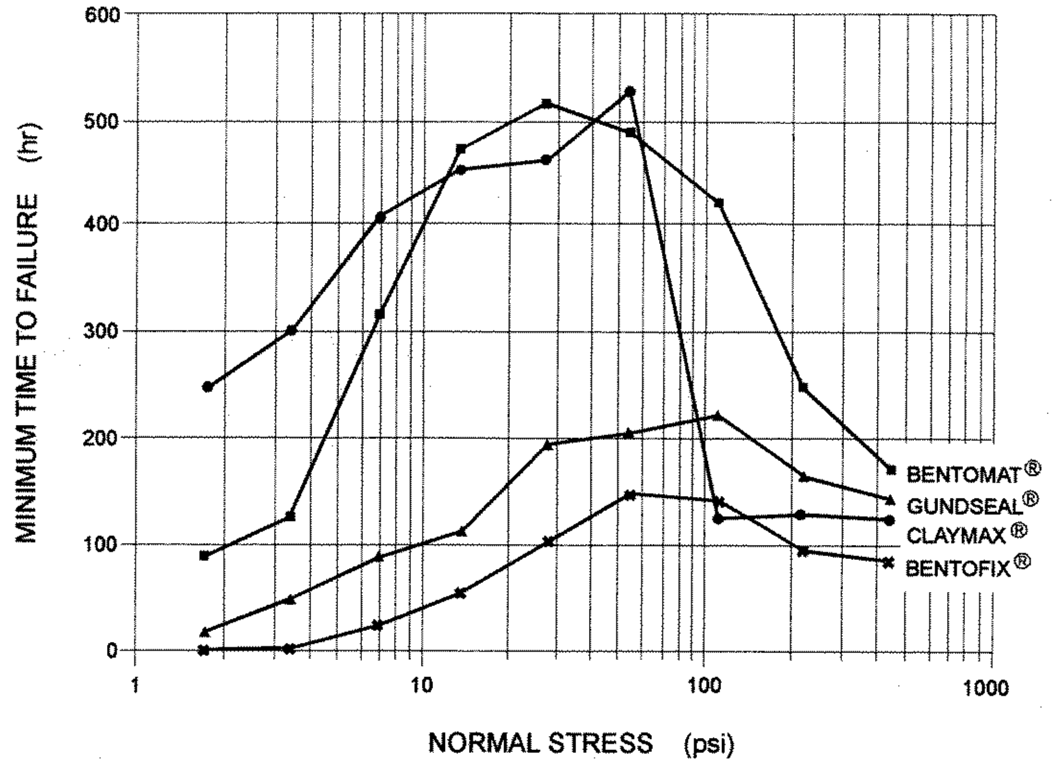

Figure 3. Relationship between time to failure of GCLs in direct shear tests and normal stress (from Shan, 1993; Note: 1 psi = 6.9 kPa).

It is noted that direct shear tests on GCLs are often performed in general accordance with the standard test method ASTM D 5321 ("*Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method*"). This method provides the following guidelines for selecting shear displacement rates for tests involving soils:

> "*11.6 Apply the shear force using a constant rate of displacement that is slow enough to dissipate soil pore pressures, as described in Method D 3080 (Note 9). If excess pore pressures are not anticipated, and in the absence of a material specification, apply the shear force at a rate of 1 mm/min (0.04 in./min).*"

The foregoing requirement calls for performing direct shear tests involving soils at a shear displacement rate in conformance with ASTM D 3080 if pore pressures are anticipated. For the soil component of GCLs (i.e., sodium montmorillonite), significant pore pressures will certainly be generated if the GCL is sheared at rates faster than those satisfying Equations 2 and 3. Interestingly, however, most test data available in the published literature were generated at the default shear displacement rate of 0.017 mm/s. Data generated at the default shear displacement rate are considered to reflect "undrained" or "partially-drained," and not "fully-drained," conditions.

Review of Available Information for Unreinforced GCLs

For purposes of shear strength characterization, two different categories of GCL can be considered: GCLs that do not contain internal reinforcement (hereafter referred to as unreinforced GCLs) and those that do (hereafter referred to as reinforced GCLs). Published information relevant to the CD shear strengths of unreinforced GCLs is very limited. The available information is summarized below.

- Daniel and Shan [1991] and Shan and Daniel [1991] reported CD direct shear test results for the GCL product Claymax®. Tests were performed using 60-mm diameter specimens and a shear deformation rate of 5 x 10^{-6} mm/s. Test results have been interpreted herein in terms of "peak (p)" and "large-displacement (ld)" normalized shear strengths. Peak displacements in these tests were 0.5 to 5 mm with the largest displacement corresponding to the lowest normal stress; the reported "ld" shear strengths correspond to shear displacements of approximately 6 to 9 mm. Results from the tests are as follows:

σ_n (kPa)	$(\tau/\sigma_n)_p$	ϕ_p	$(\tau/\sigma_n)_{ld}$	ϕ_{ld}
34	0.236	13.3°	0.236	13.3°
69	0.238	13.4°	0.209	11.8°
100	0.194	11.0°	0.165	9.4°
140	0.178	10.1°	0.137	7.8°

where: σ_n = normal stress on the shear plane at failure (kPa); τ = shear stress on the shear plane at failure (kPa); and ϕ = secant friction angle (dimensionless), calculated as the inverse tangent of τ/σ_n. It is noted that ϕ should also be interpreted as a measure of normalized shear strength and not as a "true" indication of internal friction. This data interpretation is illustrated in Figures 4 and 5.

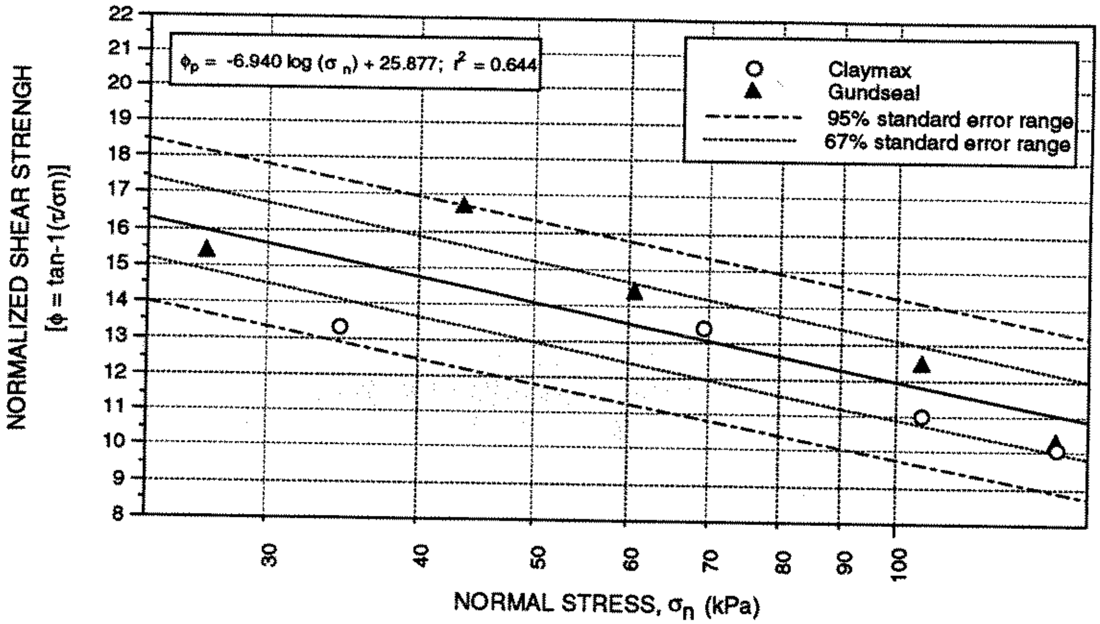

Figure 4. Log-linear regression analysis for peak CD conditions.

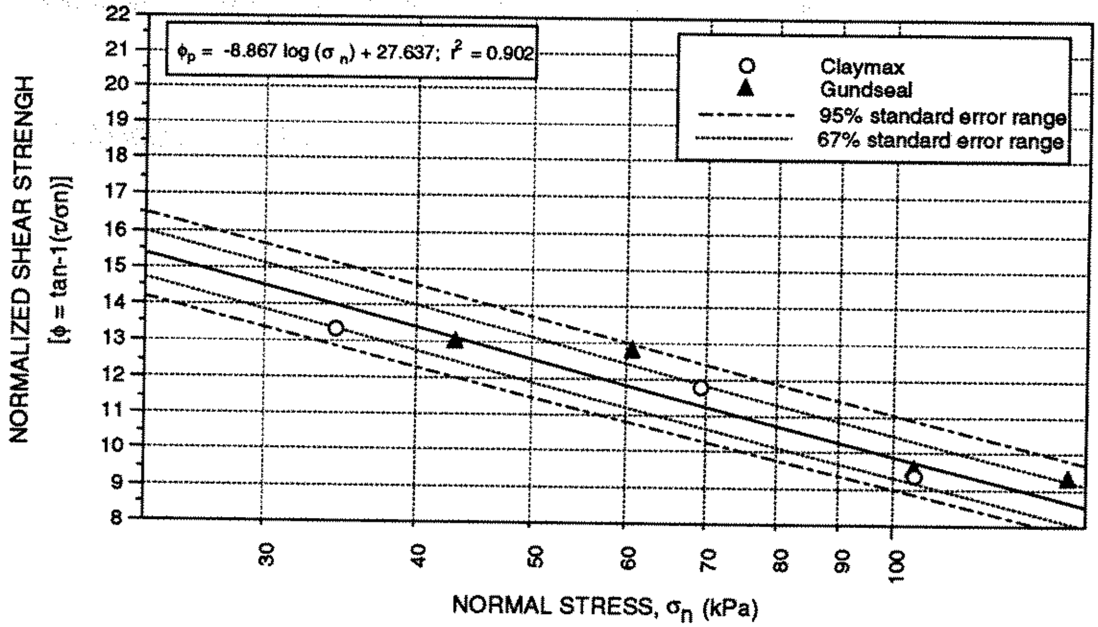

Figure 5. Log-linear regression analysis for large-displacement CD conditions.

- Daniel and Shan [1991], Daniel et al. [1993], and Shan [1993] reported direct shear CD test results for the GCL product Gundseal®. Tests were performed using 60-mm diameter specimens and a shear deformation rate of 5 x 10^{-6} mm/s. Test results have been interpreted herein in terms of peak and large-displacement normalized shear strengths. Typical peak displacements in these tests were 2 to 4 mm with the largest displacement corresponding to the lowest normal stress; the reported "ld" shear strengths correspond to shear displacements of approximately 9 to 12 mm. Results from the tests are as follows:

σ_n (kPa)	$(\tau/\sigma_n)_p$	ϕ_p	$(\tau/\sigma_n)_{ld}$	ϕ_{ld}
27	0.275	15.4°	-	-
44	0.300	16.7°	0.231	13.0°
61	0.256	14.4°	0.227	12.8°
100	0.223	12.6°	0.169	9.6°
140	0.181	10.3°	0.164	9.3°

The direct shear test results from Daniel and Shan are plotted in Figures 4 and 5 for "peak" and "large displacement" shearing conditions, respectively. Regression equations were developed to describe the test results. It is interesting to note the lesser amount of scatter in the results for the large-displacement shearing conditions compared to the peak shearing conditions.

The test results in Figures 4 and 5 only cover the stress range between 24 and 144 kPa. Even at these relatively low normal stresses, GCL CD shear strengths exhibit significant normal stress dependency. A basis is needed for extrapolating this stress dependency to higher normal stress. This basis was derived from published information from the soil mechanics literature on the shear strength of sodium montmorillonite. This information is summarized below.

- Mesri and Olson [1970] and Olson [1974] reported the results of constant rate-of-strain CD and consolidated-undrained (with pore pressure measurement) triaxial compression tests on homionic sodium montmorillonite consolidated from a slurry (Figure 6); approximate effective-stress normalized shear strengths and secant friction angles derived from the tests are as follows:

σ_n (kPa)	(τ/σ_n)	ϕ
72	0.21	12°
170	0.14	8°
340	0.10	6°
530	0.07	4°

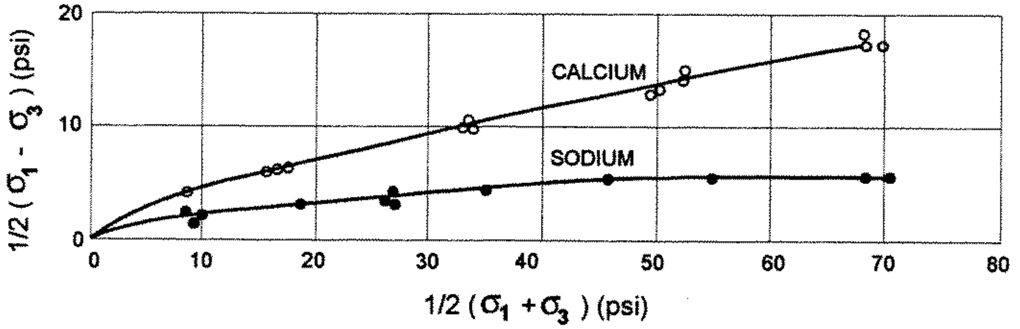

Figure 6. Effective-stress failure envelopes for calcium and sodium montmorillonite from CD and CU triaxial tests (from Mesri and Olson, 1970; Note: 1 psi = 6.9 kPa).

- Mitchell [1993] presented residual shear strength data for montmorillonite from Kenney [1967] and Chattopadhyay [1972]. Inspection of the residual shear strength data shown in Figure 7 reveals several significant points:
  - the residual friction angle exhibits significant stress dependency over a wide range of normal stress; stated differently the residual failure envelope is curved over a wide range of normal stress;
  - there may exist a normal stress above which the residual friction angle is independent of normal stress; based on Figure 7, this normal stress may be on the order of 480 kPa for sodium montmorillonite; and
  - the residual friction angle of montmorillonite is dependent on the dominant exchangeable cation and the soil pore chemistry; the smallest measured residual friction angle given in Figure 7 is 3° for homionic sodium montmorillonite in distilled water.

The GCL regression lines from Figures 4 and 5 are plotted along with the Mesri and Olson [1970] data in Figure 8. Reasonable agreement is observed between the Mesri and Olson data and the extrapolated regression lines for the unreinforced GCL. Also shown on this figure are the residual shear strengths for sodium montmorillonite developed by Kenney [1967] and Chattopadhyay [1972] as reported by Mitchell [1993]. These latter results further support the extrapolations presented in Figure 8.

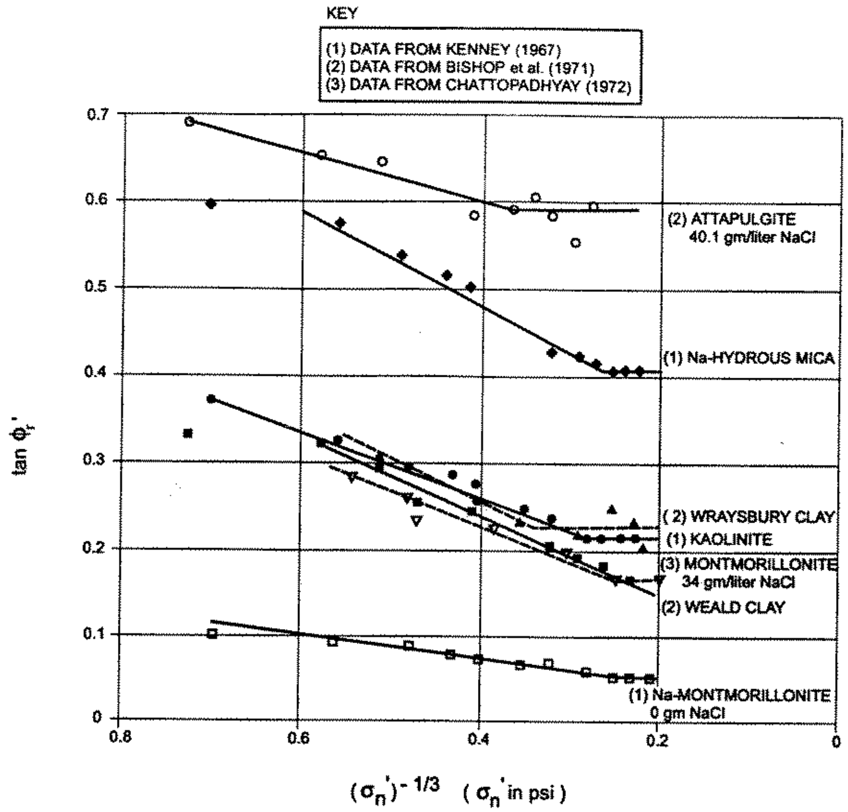

Figure 7. Residual effective-stress friction angles for clay minerals (from Mitchell, 1993; Note: 1 psi = 6.9 kPa).

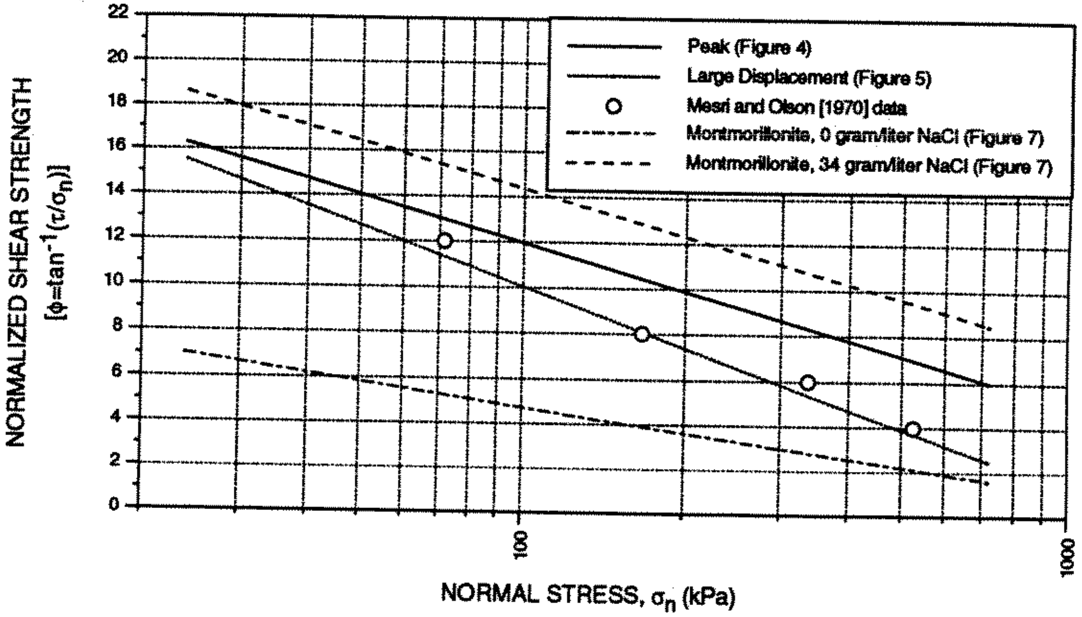

Figure 8. Comparison on montmorillonite shear strength data and GCL log-linear regression lines.

Review of Available Information for Reinforced GCLs

The authors were unable to find any information in the published technical literature on the CD shear strengths of reinforced GCLs at high normal stress. A few CD tests performed at low normal stress have been reported by Daniel and Shan [1991] for the product Bentomat®. These results cannot be extrapolated to higher normal stress, however, due to the current limited understanding of the effect of reinforcing fibers on the shear displacement-shear resistance-normal stress relationship for this type of material.

The authors have performed a limited number of consolidated-quick (CQ) direct shear tests on reinforced GCLs at normal stresses in the range of interest. Quick tests were performed at a displacement rate of 0.016 mm/s. While not "truly undrained" due to the lack of boundary drainage control in the direct shear test, the specimens in these tests will only undergo very limited pore pressure dissipation during the shear phase of the test due to the high rate of shear displacement. Due to these pore pressures, CQ tests at a given consolidation stress will result in lower GCL shear strengths than obtained from true CD tests at the same normal stress. CQ tests may therefore be considered to provide a lower bound of the CD shear strength of reinforced GCLs.

The results of the CQ direct shear tests on reinforced GCLs indicate relatively high peak shear strengths followed by a significant degree of shear softening (i.e., post peak decrease in shearing resistance). A typical test result is illustrated in Figure 9. Normalized peak and large displacement shear strengths, and the ratio of the two (ψ) for a normal stress of 480 kPa are given below:

	ϕ_p	ϕ_{ld}	τ_{ld}/τ_p
Bentomat®	29°	10°(↓)	0.32
Bentofix®	31°	16°(↓)	0.48
Claymax® 500SP	13°	6°(↓)	0.45

In the above table the downward arrow (↓) indicates that the GCL shearing resistance was decreasing at the end of the test (i.e., at a shear displacement of 40 to 50 mm). The ψ values reported above are low, generally in the range of 0.3 to 0.5. In contrast, ψ values for the CD direct shear tests on unreinforced GCLs were higher, typically in the range of 0.7 to 1.0. The ϕ_{ld} values reported above are somewhat larger than those obtained for the unreinforced GCLs. However, as noted above, observation of the shear force-displacement plots for the tests indicates that the shear stresses applied to the sample were decreasing at the ends of the tests, which typically occurred at a displacement of 40 to 50 mm. This observation, coupled with observations of the tested samples, that the GCL reinforcing fibers and stitching were still partially intact at the time the test was terminated, suggests that residual CD and CQ shear strengths of reinforced

GCLs may not be much larger than those of unreinforced GCLs. Clearly, testing is required to establish the large-displacement, high normal stress behavior of these materials, and to identify differences in product behavior based on differences in montmorillonite properties and reinforcing characteristics.

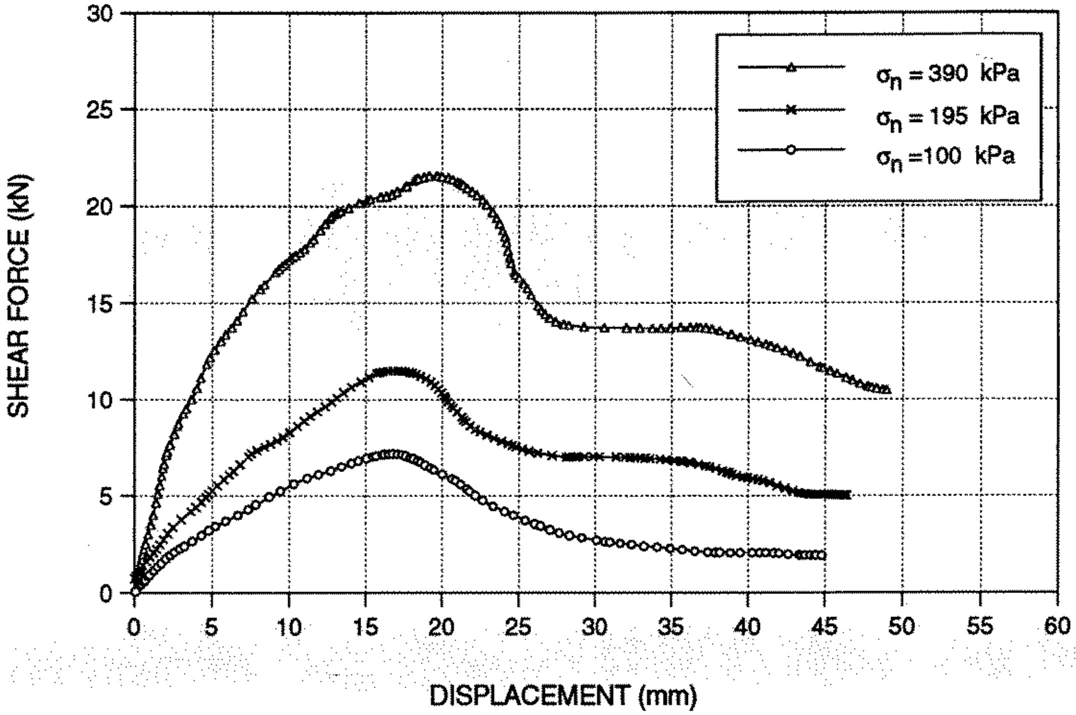

Figure 9. Results of CQ direct shear tests on reinforced Bentofix GCL.

Interim Design Values

Unreinforced GCLs: Based on the information presented in Figure 8, the authors used the following interim guidelines for performing liner system stability analyses for long-term drained conditions, for potential slip surfaces that involve internal shearing of unreinforced GCLs. These guidelines further assume that the GCL will hydrate through adsorption of water from an adjacent subgrade soil layer.

- Slope stability analyses are performed using: (i) peak internal GCL shear strengths and a minimum slope-stability factor of safety of 1.5; and (ii) large-displacement internal GCL shear strengths and a minimum slope-stability factor of safety of 1.15.

- Using the regression equation presented in Figure 4, peak normalized shear strengths are:

σ_n (kPa)	$(\tau/\sigma_n)_p$	ϕ_p
96	0.214	12.1°
240	0.157	8.9°
480	0.114	6.5°
720	0.106	6.1°

- Using the regression equation presented in Figure 5, large-displacement normalized shear strengths are:

σ_n (kPa)	$(\tau/\sigma_n)_{ld}$	ϕ_{ld}
96	0.178	10.1°
240	0.116	6.6°
480	0.070	4.0°
720	0.052	3.0°

For the large displacement strengths, a minimum friction angle cutoff of 3° was assumed based on the test results reported by Mitchell [1993], presented in Figure 7.

The normalized shear strengths given above are relatively low, and their use may be viewed by some as overconservative. This view should be tempered with the realization that the large-displacement GCL shear strengths reported in the technical literature do not represent true residual minimums (due to the limited displacement of the direct shear apparatus) and no allowance has been made for the possible effects of drained creep of the GCL under working stress conditions. Furthermore, the available CD direct shear test results for unreinforced GCLs correlate well with the triaxial compression test results for sodium montmorillonite from Mesri and Olson [1970] and Olson [1974] (Figure 6). Finally, it is noted that the foregoing approach, which utilizes a smaller slope stability factor of safety with the large displacement shear strengths than the factor of safety used with the peak shear strengths, is similar to the approaches advocated by Byrne [1994] and Stark and Poeppel [1994].

Reinforced GCLs: Recognizing the lack of data on the CD strength of reinforced GCLs at high normal stress, the complex behavior and high degree of shear-softening exhibited by these products, the authors utilized the same factors of safety and GCL long-term shear strengths for reinforced GCLs as for unreinforced GCLs. It is recognized that this assumption is conservative. However, given the limitations with respect to the available reinforced GCL test data (e.g., the technical literature does not contain any "true" CD direct shear test