DETERMINING THE FLOW RATE OF LANDFILL GAS CONSTITUENTS THROUGH A GEOSYNTHETIC CLAY LINER

A landfill cover system is designed to minimize the amount of water that can infiltrate into the waste and generate leachate. It can also function as a barrier to stop landfill gasses leaving the landfill and entering the atmosphere. Geosynthetic Clay Liners (GCL's) are known to have extremely low hydraulic conductivities, but much less is known about a GCL's effectiveness to function as an effective gas barrier.

In this study a circular GCL specimen was placed in a testing chamber where a known concentration of methane gas was introduced on the source side of the GCL and sampling ports on the receiver side of the GCL monitored the increase in gas concentration over time. With this information, the rate of flow of gas could be calculated.

Three separate tests were completed. In test number one, the flow of methane was measured for a period of 7 days. In test number two, the source gas was benzene. The last test specimen involved measuring the methane permeance of the GCL at different moisture contents.

Test results indicate that the methane flow rate of a GCL is 4 to 5 orders of magnitude less than that of a compacted clay layer when comparing these test results previous studies with a compacted clay layer.

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Determining the Flow Rate of Landfill Gas Constituents Through a Geosynthetic Clay Liner

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ABSTRACT

The primary design objective for a landfill cover system is to minimize the infiltration of precipitation, thereby minimizing the generation of leachate which could eventually threaten groundwater quality. Another cover system design objective, however, is to minimize the emission of gases generated during microbial decomposition of the underlying waste. Geosynthetic clay liners (GCLs) are known to be highly effective hydraulic barriers, yielding hydraulic conductivity values of approximately 1×10^{-11} m/sec when fully hydrated. But much less is known about their effectiveness as gas barriers. To address this issue, a series of tests was performed to quantify the flow of certain gases through a fully hydrated GCL. Similar tests were then performed to determine the moisture content at which the GCL ceases to function as an effective gas barrier. The results indicate that a hydrated GCL is a highly effective methane gas barrier and that benzene gas is actually sorbed by the GCL to the extent that it was not possible to determine a flow rate. Furthermore, it was found that the GCL can withstand significant moisture loss before the gas flow rate increases.

INTRODUCTION

The primary function of a landfill final cover system is to limit the infiltration of precipitation, so as to minimize the production of leachate that could eventually migrate offsite. While much research has been performed to investigate the ability of various barrier materials to minimize infiltration, there has been little emphasis on the design and construction of landfill cover systems as gas barriers. These two goals are not necessarily exclusive, but there should be some verification that an effective hydraulic barrier is also an effective gas barrier. The objectives of this study were to determine the rate of flow of certain landfill gas constituents through a GCL and to assess the GCL's effectiveness as a gas barrier in comparison to that of a compacted soil liner.

The composition of landfill gas generated during microbial degradation of municipal solid waste varies widely, although the principal constituents are almost always methane and carbon dioxide. Ham and Barlaz (1987) describe the typical landfill gas as 55 percent methane and 45 percent carbon dioxide, along with trace quantities of hydrogen sulfide and organic gases such as benzene, toluene, organic acids, and esters (Farquhar, 1990).

There are several reasons why a landfill cover system should contain an effective gas barrier:

1. To prevent nuisance odors from escaping the landfill. These odors are caused by the trace constituents listed above. Emissions of these trace gases may also be regulated as point sources for which air monitoring and/or permitting is required.

2. To mitigate the potential for gas-related explosions or unsafe atmospheres at the surface of a landfill. The methane fraction of the landfill gas, while odorless, represents a significant explosion hazard in the presence of sufficient oxygen.

3. To prevent the intrusion of oxygen during active gas extraction. Excessive quantities of oxygen will dilute the energy value of the collected gas and may also create an explosive atmosphere as described above.

4. To maximize the total volume of gas collected for conversion to electrical or heat energy. Many landfills with active gas collection systems can sell the energy to local utilities or industries, thus providing an economic incentive to minimize gas escape.

5. To achieve compliance with applicable air quality regulations. Federal (U.S.) landfill criteria require only that methane concentrations at the site boundary cannot exceed 25 percent of the lower explosive limit. Individual states, however, may require compliance with concentration-based criteria for certain other gases emanating from the landfill.

6. To minimize contributions to the "greenhouse effect." Landfills are responsible for approximately 10 percent of the total global methane emissions (Crutzen, 1991). Methane is a major greenhouse gas and is 20 times more sensitive to infrared absorption than carbon dioxide (Luning and Tent, 1993).

The barrier components of most modern landfill cover systems consist of either a low-permeability soil layer, a geomembrane, a geosynthetic clay liner (GCL), or virtually any combination thereof. In recent years, GCLs have often been used as substitutes for the low-permeability soil components of landfill cover systems. GCLs offer the advantages of more consistent physical properties, lower leakage rates, faster installation, and reduced construction quality assurance (CQA) requirements. Nevertheless, it is important to evaluate whether the GCL is an effective gas barrier, especially in comparison to a low-permeability soil liner.

Gas Flow Through Soil Liners. To the author's knowledge, only one study has been conducted to evaluate compacted soil liners as gas barriers. Figueroa and Stegmann (1991) performed several field tests on a soil cover 0.6 m in thickness installed at a German landfill (Table 1).

Table 1. Properties of the soil liner evaluated for gas flow by Figueroa and Stegmann (1991).

Parameter	Value
Thickness, m	0.6
Proctor Density, g/cm^3	2.0
Plasticity Index	6.5
Optimum Moisture Content, percent	9.7
Moisture content of samples taken	10.5 to 12.9
Hydraulic Conductivity, m/s	1×10^{-9}
Composition, percent	
Clay	17
Silt	23
Sand	60

Gas collection devices consisting of boxes with open bottoms were positioned at various depths within the soil layer to collect gas flow generated from beneath the cover system. By measuring the gas density, viscosity and pressure differential over a known depth interval within the soil liner, it was possible to calculate a flow rate using Darcy's Law:

$$Q = k_o \, i \, A \, \mu, \tag{1}$$

where:

Q = gas flow rate ($m^3/m^2/s$)
k_o = intrinsic permeability of soil (m^2)
i = pressure gradient (N/m^2)
A = cross-sectional area of flow collection box (m^2)
μ = gas viscosity ($N\text{-}s/m^2$)

This formula is the same Darcy's Law for calculating hydraulic flow through a porous medium, except for modifications necessary to account for the physical properties of the landfill gas. Figueroa and Stegmann found that the landfill gas flow rates at this site ranged from 5.2×10^{-6} to 9.6×10^{-5} $m^3/m^2/s$. Assuming a 55 percent methane concentration at this site, the methane flow rate would therefore range from 2.8×10^{-6} to 5.3×10^{-5} $m^3/m^2/s$. This flow rate through the soil liner was found to be roughly equal to the quantity of gas that was being collected by a gas extraction system at the site. Figueroa and Stegmann also recognized there could be significant increases in this flow rate if the soil liner were to become cracked due to desiccation or differential settlement.

GCL TESTING

A geosynthetic clay liner is defined by the American Society for Testing and Materials (ASTM) and the Geosynthetic Research Institute (GRI) as a factory-manufactured hydraulic barrier typically consisting of bentonite clay or other very low permeability materials supported by geotextiles and/or geomembranes, which are held together by needling, stitching, or chemical adhesives. The GCL used in these experiments was Bentomat®, which is comprised of a nonwoven needlepunched geotextile that is needlepunched again through a 4.9 kg/m^2 layer of sodium bentonite clay into a woven, slit-film geotextile. The overall thickness of the GCL is approximately 10 mm when hydrated. The hydraulic conductivity of this GCL is approximately 1×10^{-11} m/sec and is used as a partial or complete substitute for compacted soil liners in landfill bottom liner and cover applications.

Because GCLs are commonly used in landfill cover systems, it was desired to determine whether a GCL would be as effective as a soil liner in mitigating the flow of gas. A laboratory-scale system was used to measure gas flow through the GCL. The GCL's thinness, its anticipated low rate of flow, and the problem of constructing a gas-tight collection system would make it extremely difficult to measure flow using collection boxes as done by Figueroa and Stegmann. Therefore, it was necessary to devise a more controllable method by which gas flow through the GCL could be measured.

A series of three testing chambers were utilized for this study. The interior of each chamber was divided by a septum containing a circular GCL specimen. A known quantity of gas could be introduced into the "source side" of the chambers, and sampling ports on the "receiver side" of the chambers were used to collect the gas that flowed through the GCL. By monitoring the increase in gas concentration over time, the rate of flow can be calculated. For this study, a pressure differential of approximately 1 mbar was used to simulate that which exists across a "typical" landfill cover system (Farquhar, 1990). Previous research (Daniel, 1991; Shackelford, 1992) has shown that diffusion is the dominant transport mechanism, rather than advection as was the case with the soil liner evaluated by Figueroa and Stegmann. Therefore, the applied gas pressure in this experiment is likely exert little influence the overall gas flow rate.

Three tests were performed using methane and benzene as test gases. Methane was selected because of its large contribution to the total volume of landfill gas and because of its hazard potential. Benzene was selected because it is a representative volatile organic component of landfill gas and also because it is desirable to demonstrate adequate containment of this carcinogenic chemical. The first two tests involved the determination of the diffusive flow of methane and benzene through a hydrated GCL specimen. In the last test, flow rates were determined as a function of GCL moisture content. The objective of this final test was to determine the moisture content at which the GCL fails to perform as an effective gas barrier.

EXPERIMENTAL PROCEDURES

In order to minimize bentonite loss during the GCL preparation and mounting process, the uncut GCL was lightly wetted with deionized water. Circular GCL specimens 240 mm in diameter were cut with scissors or a sharp utility knife and were then placed into compression rings which clamped around the perimeter of the specimens (Figure 1).

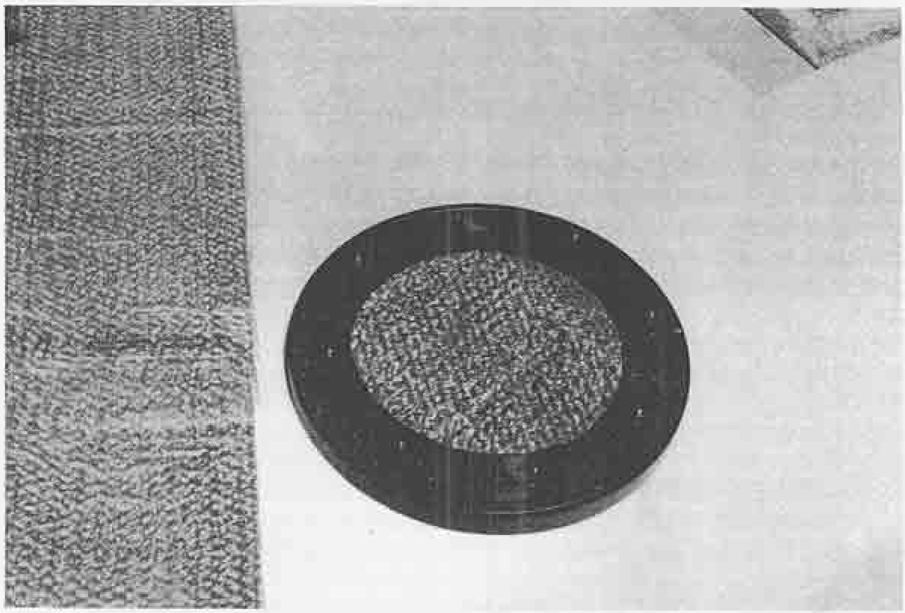

Figure 1. The GCL sample mounted in its ring holder, prior to placement in the test chamber.

O-ring seals were installed around the perimeter of the compression rings. The ring holders were designed to provide a gas-tight barrier between the source and receiver sides of the chamber. The mounted specimens were then immersed in deionized water for two days in order to hydrate. No confining stress was applied to the specimens during the hydration process. In the absence of confining stress, the bentonite in the GCL swells relatively freely, and previous testing has demonstrated that low confining stresses yield higher hydraulic conductivity values as the bentonite's porosity increases. Therefore, this hydration method represented "worst-case" gas-flow conditions.

After hydration, the GCL specimens were installed between the source and receiver sides of each chamber. The source sides of the chambers were provided with an inlet port for the introduction of the gases and an outlet port to allow the gas to cascade to the other two test chambers. The configuration of the test chambers in series allowed simultaneous testing of all three GCL specimens under identical conditions. Both sides of the chambers were equipped with sampling ports. All samples were obtained with 26-gage hypodermic needles and gas-tight syringes. The sampling ports had stopcocks between the chamber wall and the sampling septa, and the stopcocks were closed between sampling events in order to prevent diffusive gas loss through the sample port septa.

After assembly was completed, the experimental apparatus was checked for leakage by pressurizing each chamber with air at 0.1 m water head for 2-3 hours. The chambers were disassembled and reassembled as necessary until no pressure loss was observed. The fully assembled system is shown in Figure 2.

The source gases (methane and benzene) were obtained from tanks at known, certified concentrations of 23,600 and 460 parts per million (ppm), respectively, and were introduced into the chambers simultaneously. The flow rate of the source gases was kept between 3 x 10^{-5} and 3 x 10^{-4} m^3/min using a calibrated metering valve. Exhaust source gas was bubbled through water to provide a continuous, positive visual verification of flow into the source side of the chambers.

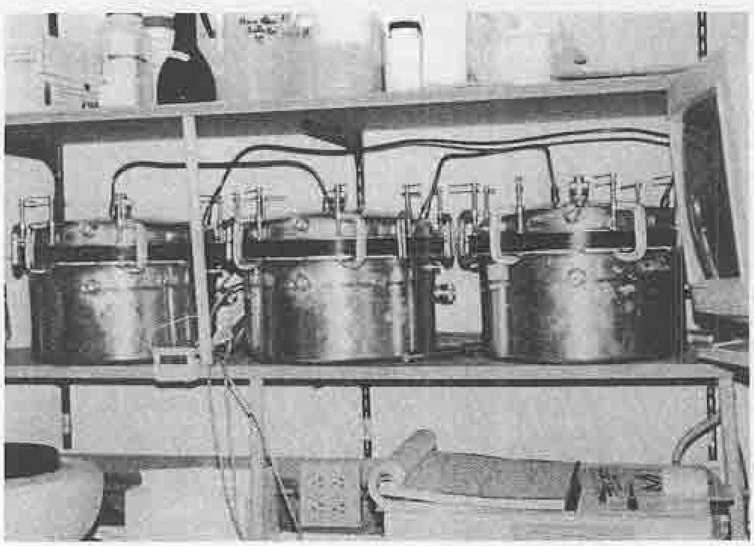

Figure 2. Fully assembled GCL test chambers.

The concentrations of methane on the receiver side of the chambers were determined with a gas chromatograph coupled with a flame ionization detector. Benzene concentrations were determined using a photoionization detector because of its superior sensitivity and selectivity for this chemical. All samples were collected from the chambers with gas-tight syringes.

RESULTS

Methane Flow. After a brief equilibration period following system start-up, the concentrations of the gases in the receiver side of each chamber were monitored for a period of 7 days. Figure 3 shows that there was a linear increase in methane concentration over time, and that a similar relationship was observed in all three chambers.

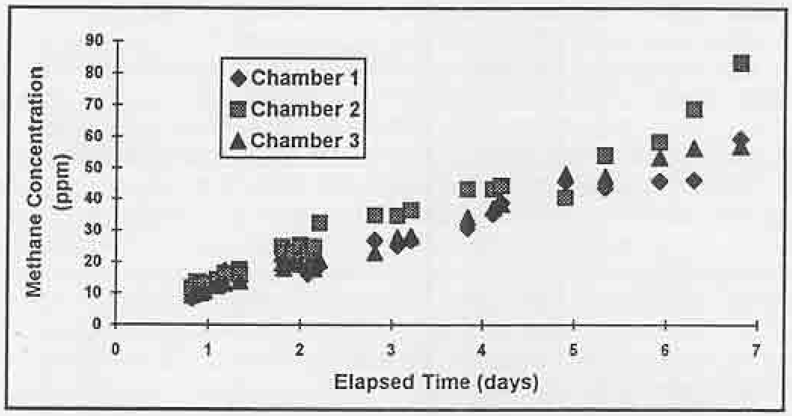

Figure 3. Methane concentration in the three test chambers as a function of exposure time.

The slopes of the lines connecting the data points represent rates of concentration change in parts per million per day. These values were determined by linear regression and were then used to determine the GCL's methane permeance as shown below:

$$P = \frac{S\ V_r}{C_s\ A} \tag{2}$$

where:

P	=	permeance, m/s
S	=	rate of gas concentration change (slope) = 8.4×10^{-5} to 1.2×10^{-4} ppm/d
V_r	=	volume of receiver side = 0.0126 m^3
C_s	=	concentration of source gas = 23,600 ppm
A	=	cross-sectional area of GCL specimen = 0.04547 m^2

The slopes of the regression lines from the three sets of data gives a permeance values ranging from 9.8×10^{-10} to 1.4×10^{-9} m/s. It should be noted that permeance is not comparable to hydraulic conductivity or to diffusive mass flux as described by Fick's second law. Nevertheless, the permeance values can be used to calculate methane flow rates as shown below:

$$Q = C_s \, P \, A \tag{3}$$

where:

Q	=	Overall gas flow rate, $m^3/m^2/s$
C_s	=	Fractional concentration of methane in gas sample
P	=	Permeance, m/s
A	=	Area over which gas is flowing, m^2

Thus, if a landfill gas is 55 percent methane, the data suggests that the areal flow through the GCL may be expected to range from 5.4 to 8.0×10^{-10} $m^3/m^2/s$.

Benzene Testing. The same experimental procedures were followed when the source gas was benzene, but remarkably different results were obtained. In all three test chambers, the concentrations of benzene in the receiver side decreased over time at a rate of at least 1.5 to 2 percent per contact minute. Leakage tests were conducted to ensure that an adequate seal was maintained at all points within the testing system, and it was confirmed that no leakage was occurring. The concentration decrease appeared to be attributable instead to sorption of the benzene onto the GCL.

In order to more conclusively determine whether sorption was actually occurring, gas flow was stopped and the seal isolating the source and receiver sides of one of the chambers was released. This allowed the source gases to flow freely into each side of the chamber. The initial methane and benzene concentrations were determined and then were periodically monitored over two days. A steady decrease again was observed, confirming that benzene sorption was occurring. Little, if any, concentration decrease was observed with methane (Table 2).

Table 2. Comparison of benzene and methane concentrations in unsealed test chamber.

Elapsed Time (days)	Benzene Concentration (ppm)	Methane Concentration (ppm)
0.01		23,900
0.17	159	24,000
0.27		22,900
0.94	5.8	24,300
1.17	2.6	24,300
1.91	0.12	21,900

Methane Flow vs. GCL Moisture Content. The third series of tests involved determining the variation in gas flow with GCL moisture content. GCL specimens were prepared and hydrated as previously described but were exposed to low-humidity air for varying times before being tested. When the GCL is in an unconfined state as in these tests, it is more susceptible to desiccation cracking than when a normal stress (typically in the form of soil cover) is provided in field use. Therefore, GCL specimens were repeatedly exposed to dry air, sealed in the testing chambers, and allowed to equilibrate until the approximate desired moisture content was reached. Gas flow rate testing was then conducted on the partially dried samples.

Methane permeance values were obtained for GCL samples at full saturation and at several reduced moisture contents. As shown in Figure 4, the methane flow rate is low until an apparent break is reached at 90 percent moisture. At moisture contents below 90 percent, the methane flow rate increases significantly.

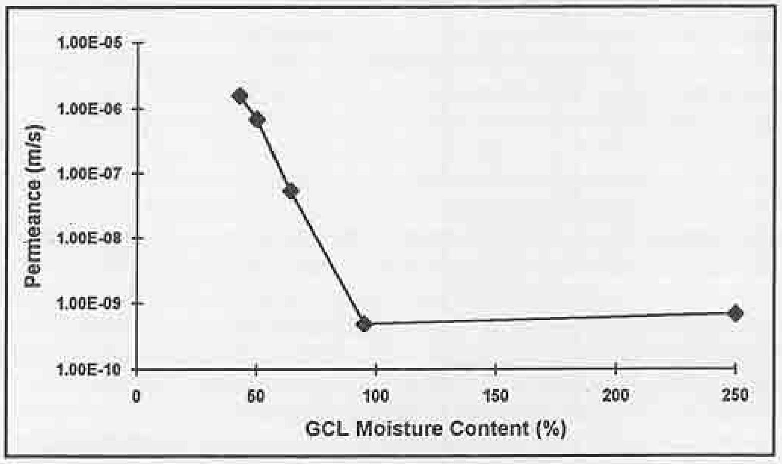

Figure 4. Variation in methane permeance with GCL moisture content.

DISCUSSION

The experimental data presented above indicate that the hydrated GCL appears to be an effective barrier to the flow of methane and benzene gases. The methane flow rates in a fully hydrated GCL specimen range from 5.4 to 8×10^{-10} $m^3/m^2/s$, whereas the flow rates for methane through the compacted soil layer investigated by Figueroa and Stegmann ranged from 2.8×10^{-6} to 5.3×10^{-5} $m^3/m^2/s$. Thus, the methane flow rate through the GCL appears to be 4 to 5 orders of magnitude less than through the compacted soil liner.

indicate that the soil may have contained cracks or other preferential flow pathways. These secondary features could have caused higher leakage rates than a soil containing more clay and greater plasticity.

Another interesting finding was that benzene concentrations decreased within the test chamber. Further testing provided evidence that this decrease was attributable to sorption. Bentonite contains little or no organic matter which would facilitate physical/chemical sorption, but Boyd (1988) has demonstrated that bentonite does have a limited ability to absorb benzene vapor. It is also possible that there was some sorption of benzene onto the rubber O-rings or other plastic surfaces of the test apparatus. A third potential explanation for the observed sorption is that biodegradation of the benzene occurred within the bentonite. However, the rate of sorption appears to have been too rapid for microbial assimilation to have occurred. The actual benzene sorption mechanism may be any one or perhaps a combination of these phenomena.

In the tests where gas flow was measured at various moisture GCL contents, it was clear that a lower moisture limit exists, below which the GCL is much less effective as a gas barrier. From the work performed to date, it appears as if this moisture content is approximately 90 percent. The question then arises as to whether the GCL could be expected to desiccate to this extent in a landfill cover application.

Based on available information, a GCL is unlikely to become desiccated. Research on the actual moisture retention capability of a GCL was performed by GeoSyntec (1989). This study involved monitoring the moisture loss of a fully hydrated GCL buried under 200 mm of sand and placed in a climate-controlled chamber. After 90 days of exposure to daytime temperatures of 35° C and nighttime temperatures of 21° C, there was essentially no decrease in the GCL moisture content. Considering that the cover layer over a GCL is likely to be much thicker than 200 mm, and considering that it has the ability to draw moisture from the subgrade (Daniel, 1993), it is unlikely that the GCL would become desiccated in a real landfill cover application. Desiccation may occur, however, in certain secondary containment applications when little cover is provided, and in especially arid areas where rehydration by natural rainfall may not occur for several months.

CONCLUSIONS

Some preliminary conclusions can be made from the results of these experiments:

1. GCLs are likely to be as effective as compacted soil liners in limiting the migration of principal landfill gas constituents such as methane. Considering the large difference in observed gas flow rates between the GCL and a soil liner, the GCL could be considered "equivalent" to the soil liner with respect to its ability to impede gas flow.

2. GCLs may also present a favorable environment for the chemical or microbial sorption of benzene.

3. A GCL has been shown to be an effective gas barrier at moisture contents ranging from full saturation (over 250 percent in the unconfined state) down to approximately 90 percent.

4. Additional research would be beneficial to more accurately quantify the gas flow rates for both GCLs and compacted soil liners, and to determine the mechanism(s) responsible for benzene sorption onto the GCL.

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