Potential Solution to Pollution of Groundwater by Diffusion of Volatile Organic Compounds through the primary HDPE Geomembrane in composite lining systems of landfills

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ABSTRACT
Waste in a landfill is exposed to the chemicals and heat generated over time producing harmful fluids in the form of leachate or landfill gas that migrate from the landfill towards the liner or capping, and include organic contaminants. The High Density Polyethylene (HDPE) Geomembrane component of the landfill liner is often believed to be the primary barrier to contaminant transport, but VOCs diffuse through geomembranes at appreciable rates. The aim of this study was to obtain reliable data on the reduction in diffusion of VOCs through the HDPE geomembranes (GM) component in the composite liner systems of landfills by extracting air through the leakage detection layer or drainage layer of the composite liner. It was shown that introducing a flow of air through a pervious zone adjacent to the GM layer in a landfill liner would significantly reduce the concentrations of VOCs in the groundwater beneath landfills and waste containment facilities.

1. INTRODUCTION AND BACKGROUND

When waste materials in a landfill or any other waste body is exposed to the chemicals and heat generated over time, they produce harmful fluids in the form of leachate or landfill gas that migrate from the landfill towards the liner or capping, and include organic contaminants. These organic contaminants include a group commonly referred to as volatile organic compounds (VOCs) that have been known to migrate to and pollute the underlying groundwater (Prosser & Janechek, 1995). The High Density Polyethylene (HDPE) Geomembrane as part of a landfill liner is often believed to be the primary barrier to contaminant transport, but the clay component in the composite liner usually controls the rate of transport of VOCs since researchers have shown that VOCs diffuse through geomembranes at appreciable rates. Therefore, the effectiveness of modern landfill liner systems in minimising the migration of VOCs merits scrutiny.

2. STUDY OBJECTIVES

The aim of this study was to obtain reliable data on the reduction in diffusion of VOCs through the HDPE geomembrane (GM) component in composite liner systems of landfills by extracting air through the leakage detection layer or drainage layer of the composite liner adjacent to the HDPE component of the liner. The objective was to undertake tests in three phases.

- Phase 1 aimed to prove that the chosen VOCs diffuse from source to receptor through a GM layer and to compare to the results obtained in the literature;
- Phase 2 aimed to prove that, even if the separation between the source and receptor consisted of two GMs separated by an air-filled pervious zone, diffusion of the VOCs would still occur from the source to the receptor volumes;
- Phase 3 aimed to prove that, by introducing airflow into the pervious zone between the two GMs, the concentration of VOCs in the receptor volume (due to diffusion through the GM) could be reduced significantly. This phase’s testing also aimed to determine if the rate of air removal would play a role in the diffusive process and the resultant VOC concentrations in the receptor.

For the purposes of this study, the onsite conditions were replicated in a laboratory using stainless steel diffusion test cells.

3. LITERATURE REVIEW

3.1 Waste Disposal and Containment Barriers

In South Africa, waste disposal landfills are grouped into four classes by the waste types earmarked for disposal (Class A, B, C and D). Class A Landfills require a minimum of a double composite containment barrier system and are meant for the disposal of more hazardous wastes. The prescribed liner is a general minimum standard and every containment facility needs to have its own fit-for-purpose engineered lining
system that conforms to the Class of facility and waste type it is intended for. The layers can be replaced by other layers of equal or increased performance. The leakage detection system normally made up of granular material can be replaced by a geosynthetic equivalent such as a cuspatated HDPE drainage sheet. A fluid could pass through this layer in order to remove VOCs from the system and possibly cool the liner. Although the focus of this study was the HDPE geomembrane, in most cases the GM is used as a barrier in conjunction with other layers of a composite lining system that is designed and engineered to be fit for purpose. HDPE GM is an integral part of the composite landfill liner and in South Africa the Department of Environmental Affairs has included HDPE GM in the engineered composite lining system as a prerequisite for the successful application of any Waste License to own or operate a waste disposal facility.

3.2 Volatile Organic Compounds

Volatile Organic Compounds (VOC) are organic chemical compounds that have high enough vapor pressures under normal conditions to significantly vaporise and enter the atmosphere. Many carbon-based molecules, such as aldehydes, ketones and other light hydrocarbons are VOCs. The term may refer both to well-characterised organic compounds and to mixtures of variable composition. Sometimes, VOCs are released into the environment accidentally, where they can damage soil and groundwater, an example being the landfilling waste and waste-related products in engineered waste disposal landfills equipped with an engineered lining system. VOCs have been shown to diffuse through the lining systems of landfills resulting in, among other things, groundwater pollution (Touze-Foltz et al., 2011). Methane is the most commonly known VOC and, as a greenhouse gas, is responsible for a considerable amount of environmental pollution. Methane mostly migrates to the surface of landfills and other VOCs such as the aromatic hydrocarbons (Benzene, Chloroform, Toluene, Ethylbenzene, Xylene (BTEX)) commonly found in petroleum products that contribute most to groundwater contamination (Prosser et al., 1995).

3.3 Diffusion of VOCs

Diffusion is a net transport of molecules from a region of higher concentration to one of lower concentration by random molecular motion. Although HDPE is resistant to advective flow, they do allow movement of contaminants through them by means of molecular diffusion (Rowe, 1998). The diffusive movement of contaminants through an intact GM with no faults or holes involves a cooperative rearrangement of the penetrant molecule and the surrounding polymer chain segments. For the penetrant molecule to move into the polymer structure of the HDPE, the process requires the localization of energy to be available (Rowe, 1998). Thus the diffusive motion requires energy and depends on the relative mobility of the penetrant molecules in the waste or leachate and polymer chains in the HDPE. In turn, this will depend on temperature and concentration, the size and shape of the penetrant and the nature of the polymer itself (Rowe, 1998). Sangam & Rowe (2001) describe the molecular diffusion of penetrants such as BTEX and Chloroform through an intact GM as a molecular-activated process that occurs in a series of steps following the path of least resistance. For dilute aqueous solutions, as is the case in this study, this involves three steps (Park and Nibras, 1993). Firstly adsorption (partitioning of contaminant between the inner surface of the GM and medium containing the contaminant), then diffusion of the permeant through the GM and then desorption (partitioning of the contaminant between the outer surface of the GM and the outer medium).

For water or water-based solutions (as is the case here), the adsorption and desorption processes can be seen as similar and inverted (Sangam and Rowe, 2001). Figure 2 shows partitioning between the concentration in solution and the concentration dissolved in the GM.

![Figure 1: Schematic Diagram of Diffusion through HDPE GM (adapted from Rowe, 1998)](image)
Chloroform in aqueous solutions are equal (Sangam and Rowe, 2001). The diffusion process in the GM dimensions of \([\text{length}^2 \text{time}^{-1}]\), which result from the underlying kinetic theory. It is a proportionally constant with respect to another), the faster they diffuse into each other; thus the higher the diffusion coefficient of the VOC in question, given a certain GM and concentration profile, the faster diffusion will occur through the GM and the fluid respectively. The process ends with desorption (Step 3: Desorption), which is similar to adsorption and, for an aqueous solution in contact with a HDPE GM, it can be assumed that the above equation (Equation 1) also holds true, meaning the partitioning coefficient for adsorption and desorption of BTEX and Chloroform in aqueous solutions are equal (Sangam and Rowe, 2001). The diffusion process in the GM happen between the adsorption and desorption processes and can be explained by Fick’s first law (Equation 2). Where \(f\) is the rate of transfer per unit area [\(\text{ML}^{-2}\text{T}^{-1}\)] (typically mg per m\(^2\) per second), \(D_g\) is the Diffusion coefficient in the GM [\(\text{L}^2\text{T}^{-1}\)] (typically m\(^2\) per second), \(C_g\) is the concentration of the substance that is diffusing and \(z\) is the direction parallel to the direction of the diffusion (typically the thickness of the GM). \(\frac{\partial c_f}{\partial z}\) is thus the concentration gradient and in transient state, allowing for the conservation of mass, the governing differential equation is given by Fick’s Second Law (Equation 3) (Rowe, 1998):

\[
C_g = S_{gf} \times C_f \quad [\text{Equation 1}], \quad f = -D_g \times \left(\frac{\partial c_g}{\partial z}\right) \quad [\text{Equation 2}], \quad \frac{\partial c_f}{\partial t} = D_g \times \left(\frac{\partial^2 c_f}{\partial z^2}\right) \quad [\text{Equation 3}]
\]

This equation needs to be solved for the appropriate boundary and initial conditions to obtain the Diffusion coefficient of the solution/GM system at equilibrium. To measure the concentration change in the GM when doing diffusion tests is difficult so it is useful to express the diffusion equations in terms of the concentration in adjacent solutions (Sangam and Rowe, 2001). Equation 1 gives the relationship between the concentrations in the GM and the adjacent fluid. Equation 3 gives the flux (diffusion) within the GM, so substituting Equation 1 into Equation 2 gives the flux on one side of the GM to a similar fluid on the other side of a GM (Rowe, 1998).

\[
f = -D_g \times \frac{d c_g}{d z} = -S_{gf} D_g \times \frac{d c_f}{d z} = -P_g \times \frac{d c_f}{d z} \quad [\text{Equation 4}]
\]

Where \(P_g = S_{gf} \times D_g \quad [\text{Equation 5}]
\]

\[
f = S_{gf} \times D_g \times \left(\frac{\Delta c_t}{t_a m}\right) \quad [\text{Equation 6}]
\]

\(P_g\) gives the relationship between the Diffusion coefficient and the Sorption coefficient and is referred to in polymer literature as the Permeability Coefficient (Sangam et al, 2001). Based on Equation 5, the mass flux across a GM of thickness \(t_a m\) is thus given by Equation 6 where \(S_{gf} D_g\) can be replaced by \(P_g\) (Equation 5) and where \(\Delta c_t\) is the difference in concentration in the fluid on either side of the GM (\(c_{t1}\) and \(c_{t2}\) in Figure 2). The purpose is thus to determine the \(S_{gf}\) and \(D_g\) (and thus \(P_g\)) values of the system in question and compare them to the values found in the literature, before trying to prove that VOCs can be extracted successfully through a pervious zone in the liner system.

3.4 Calculating Coefficients in Diffusion Process

When undertaking diffusion tests the Sorption (\(S_{gf}\)) and Diffusion (\(D_g\)) coefficients need to be calculated in order to understand and comment on the diffusion process. \(S_{gf}\) is most often unitless and, when doing diffusion tests where the concentration of contaminants in the source and receptor is monitored over time, can be calculated using Equation 7 and can then be used to infer the diffusion coefficient (\(D_g\)) using the computer software programme POLLUTE© which implements a one-and-a-half dimensional solution to the advection-dispersion equation (Equation 3). The Diffusion coefficient (\(D_g\)), or so-called diffusivity, has the dimensions of \([\text{length}^2 \text{time}^{-1}]\), which result from the underlying kinetic theory. It is a proportionally constant between the molar flux due to molecular diffusion and the gradient in the concentration of the species (or the driving force for diffusion). Generally, it is prescribed for a given pair of species, but for a multi-component system, it is prescribed for each pair of species in the system. The higher the diffusivity (of one substance with respect to another), the faster they diffuse into each other; thus the higher the diffusion coefficient of the VOC in question, given a certain GM and concentration profile, the faster diffusion will occur through the GM.
into the underlying groundwater. The $S_{gf}$ can be determined using the diffusion test method, which is the diffusion from solution on one side of the GM to solution on the other side and monitoring the change in concentration in the source and receptor over time until equilibrium is reached (no significant change in the concentrations in the source and receptor volumes). The value for $S_{gf}$ is then calculated using the following equation (Rowe, 1998):

$$S_{gf} = \frac{(C_{fo}V_{s} - C_{F}(V_{s}+V_{r}) - \Sigma V_{i}C_{i})}{(At_{GM}C_{F})}$$

[Equation 7]

Where $C_{fo}$ is the initial concentration of fluid in the source reservoir [ML$^{-3}$], $V_{s}$ and $V_{r}$ are the volumes of the source and receptor reservoirs [L$^3$], $C_{F}$ is the final equilibrium concentration in the source and receptor reservoirs [ML$^{-3}$], $\Sigma V_{i}C_{i}$ is the mass removed by sampling events [M] ($V_{i}$ and $c_{i}$ being the volume and concentration removed at each sampling event), $A$ is the area of the GM through which diffusion occurs [L$^2$] and $t_{GM}$ is the thickness of the GM [L]. The Diffusion coefficient ($D_{g}$) is then inferred by using Equation 3 and the variation in source and receptor concentrations with time (Fick’s second law) at the given boundary conditions. This is done using POLLUTEv7®, which solves the one-dimensional contaminant migration equation subject to boundary conditions at the top and bottom of the GM being modelled.

1. EXPERIMENTAL METHODOLOGY

1.1 Sorption Tests

Sorption tests (all tests carried out at University of Pretoria) were done to determine the sorption coefficient ($S_{gf}$) for the GM and permeant in question. Sorption tests were done using glass vials with sampling caps, about 80-mm high and 50-mm diameter as shown in Figure 4. Tests were done on both the 1-mm and 2-mm GM using an aqueous solution containing BTEX and Chloroform. The tests were done in duplicate for both the 1-mm and the 2-mm GMs and two control cells were included to measure and assess losses. The control vials were identical to the test vials except that they contained no GM. Experiments were performed at room temperature in the laboratory (24 ± 2°C) and 1 ml samples were taken at days 0, 2, 5, 12 and 21. Samples were placed into glass Gas Chromatograph (GC) sampling vials for testing in the GC (GC-MS). The concentrations of contaminants were monitored until the equilibrium concentration was reached. The system was deemed to be in equilibrium if no significant attributable change in concentrations occurred for consecutive sampling events. The sorption coefficient of each contaminant was then calculated.

1.2 Diffusion Tests

Diffusion tests were done to determine the rate of diffusion of the VOCs through the GM by measuring the change in concentrations of solutions on either side of the GM. Diffusion tests were carried out in three phases.

Phase 1 – Diffusion tests using one GM: This test would replicate work already done by others in order to prove that by using the equipment and laboratory setup for this project, diffusion would take place across a 2 mm intact HDPE GM separating a source and receptor volume (see Figure 2) of a diffusion test cell.

Phase 2 – Diffusion tests using two GMs: The second phase of testing replicated the first, with the 2 mm GM being replaced by 2 x 1 mm GMs separated by a 0.8 cm gap filled with air to replicate the top and bottom of an HDPE cusped leakage detection system. The purpose was to prove that diffusion would take place across both GMs (separated by air in the pervious zone) and still reach groundwater beneath the liner system. The two GMs are assumed identical and when there is no flow through the system the VOC concentration in the water above and below the GMs will reach equilibrium with the concentration of the VOC in the air layer, resulting in the $S_{gf}$ and $D_{g}$ values being the same for the two GMs.

Phase 3 – Extraction of air: The third phase replicated phase 2, with air being extracted through the gap between the two GMs to represent the flow of a fluid through the leakage detection system of a landfill liner. The purpose was to prove that by removing the air between the two GMs at regular intervals, the VOCs would be removed from the system and would not reach the groundwater. The two GMs were assumed identical, but since there would now be a flow of air through the gap between the two GMs, the concentration profile would change resulting in a change of flux, which could result in a change in the $D_{g}$ values of the two GMs. Stainless steel was used to manufacture the diffusion cells. Dimensions and properties shown in Figure 5:
Five cells were made so that tests could be done in triplicate (for each phase of testing) with one control cell and one blank cell to measure losses and outside influences. The receptor reservoir represented the groundwater beneath lined landfill facilities and was filled with deionized water at the start of testing. The source reservoir represented the leachate in a lined landfill and was filled with a prepared synthetic leachate solution using the filling port.

For the phase 1 diffusion tests, the source and receptor cells were separated only by the HDPE GM and during phases 2 and 3, a centerpiece was added to introduce the pervious zone into the liner system. The centerpiece was separated from the source and receptor reservoirs by HDPE GMs so that the configuration was Source-GM-Pervious Zone-GM-Receptor. During phase 3 testing the holes in the centerpiece were used to introduce air flow to the system. Using four test cells (A to D), different air flow rates were introduced in three of the cells, leaving one cell permanently closed as for phase 2 testing in order to provide a control. The air flows were achieved by replacing the air in the pervious zone between the GMs with clean ambient air once every 24 hours, 72 hours and 7 days. In addition to the sorption test described earlier, the $S_{gf}$ value was also obtained from the diffusion test using Equation 7 after the completion of Diffusion tests at equilibrium. The Diffusion coefficient ($D_g$) was then inferred using Equation 3 and the variation in source and receptor concentrations with time (Fick’s second law) at the given boundary conditions using the software POLLUTE®.

2. RESULTS

2.1 Phase 1 – Diffusion tests using one GM

Concentrations in the source and receptor cells were measured averaged and plotted (initial concentration over measured concentration) against time for the source Figure 6 and receptor Figure 7 volumes.
Figure 6 and 7: Phase 1 – VOC concentration in source (left) and receptor volume (right)

The concentration versus time output graphs that POLLUTE® produces if the methodologies described earlier were correctly followed, were combined with the actual laboratory test results and is shown on Figures 8 and 9 for phase 1 testing (only Benzene and Toluene shown).

Figure 8 and 9: Phase 1 combined output graph for Benzene (left) and Toluene (right)

Table 1 summarizes the averaged and corrected Sgf values obtained from the sorption tests and the phase 1 diffusion coefficients obtained are then given in Table 2.

Table 1: Summary of Sgf Values Obtained Using Different Test Methods

<table>
<thead>
<tr>
<th>VOC</th>
<th>Aqua Sorption</th>
<th>Diffusion Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1mm</td>
<td>2mm</td>
</tr>
<tr>
<td>Benzene</td>
<td>27.8</td>
<td>14.1</td>
</tr>
<tr>
<td>Toluene</td>
<td>61.9</td>
<td>198</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>87.2</td>
<td>326</td>
</tr>
<tr>
<td>p-Xylene</td>
<td>80.2</td>
<td>102</td>
</tr>
<tr>
<td>Chloroform</td>
<td>25.1</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Table 2: Calculated Diffusion Coefficients (Dg) for phase 1 testing

<table>
<thead>
<tr>
<th>VOC</th>
<th>Diffusion Coefficient in m²/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>9.26 x 10⁻¹³</td>
</tr>
<tr>
<td>Toluene</td>
<td>8.68 x 10⁻¹³</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>1.39 x 10⁻¹²</td>
</tr>
<tr>
<td>p-Xylene</td>
<td>2.32 x 10⁻¹²</td>
</tr>
</tbody>
</table>
2.2 Phase 2 – Diffusion tests using two GMs

Concentrations in the source and receptor cells were measured, averaged and plotted (initial concentration over measured concentration) against time for the source Figure 10 and receptor Figure 11 volumes.

![Figure 10 and 11: Phase 2 VOC concentration in source (left) and receptor (right) volumes](image)

As for phase 1 testing, the Diffusion coefficient $D_g$ was determined using POLLUTE®. The concentration versus time output graphs that POLLUTE® produced were combined with the actual laboratory test results and then plotted as shown in the example for Benzene in Figure 12. The phase 2 diffusion coefficients obtained are given in Table 3.

<table>
<thead>
<tr>
<th>VOC</th>
<th>Diffusion Coefficient in $m^2/s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>$8.10 \times 10^{-13}$</td>
</tr>
<tr>
<td>Toluene</td>
<td>$8.10 \times 10^{-13}$</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>$5.79 \times 10^{-13}$</td>
</tr>
<tr>
<td>p-Xylene</td>
<td>$8.10 \times 10^{-13}$</td>
</tr>
<tr>
<td>Chloroform</td>
<td>$5.79 \times 10^{-13}$</td>
</tr>
</tbody>
</table>

![Figure 12: Phase 2 combined output graph for Benzene](image)

2.3 Phase 3 – Extraction of Air

Concentrations in the source and receptor cells were measured and plotted (initial concentration over measured concentration) against time for the source and receptor volumes of each cell. The results showed that the VOC concentrations in the source gradually decreased while concentrations in the receptor gradually increased over the 48 day testing period. When looking at the graphs of concentrations (initial concentration over measured concentration) against time per individual VOC in the various cells, another trend becomes clear. Figures 13 and 14 shows this trend for Benzene but the trend was also the same for the other VOCs.
Figure 13 and 14: Concentrations of Benzene in source (left) and receptor (right) volumes.

These figures show that concentrations of the VOCs increase more significantly in the receptor volume of Cell A where no air extraction took place, compared to the other cells’ charts that represent various air extraction rates. The concentration versus time output graphs that POLLUTE® produced, were combined with the actual laboratory test results and are shown on Figures 15 to 18 for Phase 3 testing, again using only Benzene as an example.

Figure 15 to 18: Phase 3 combined output graphs for Cell A to D (Benzene)

For Phase 3 testing the diffusion coefficients obtained through POLLUTE® is given in Table 4.
Table 4: Calculated Diffusion Coefficients ($D_g$) for Phase 3 testing

<table>
<thead>
<tr>
<th>VOC</th>
<th>Diffusion Coefficient in m$^2$/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cell A</td>
</tr>
<tr>
<td>Benzene</td>
<td>$D_{GM1+GM2}$</td>
</tr>
<tr>
<td>Toluene</td>
<td>$1.04 \times 10^{-12}$</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>$1.15 \times 10^{-12}$</td>
</tr>
<tr>
<td>p-Xylene</td>
<td>$1.15 \times 10^{-12}$</td>
</tr>
<tr>
<td>Chloroform</td>
<td>$9.26 \times 10^{-13}$</td>
</tr>
</tbody>
</table>

3. DISCUSSION

Phase 1 results show that the VOC concentrations in the source decreased and the VOC concentrations in the receptor increased. The detection of VOC concentrations in the receptor started on day 8 and increased to between 10% and 30% of the original source concentration at day 22. The VOC concentrations in the source immediately decreased as the VOC sorbed onto the GM, and gradually decreased over the 22-day testing period to between 5% and 30% of the original source concentration. Measured losses can be attributable to sorption of the VOCs onto items such as the stainless steel cell, the septa, the gaskets or the screw in the filling port, but since great care was taken to limit losses due to sorption to these areas, the most plausible reason for the losses would be due to the sampling process. Phase 1 testing met its objective of proving that the VOCs in question diffuse from the source, through the 2 mm GM, into the receptor that represents the groundwater and the diffusion coefficients obtained compare well with those from literature.

Phase 2 results show that the VOC concentrations in the source decreased and the VOC concentrations in the receptor increased. The detection of VOC concentrations in the receptor were evident from the samples taken on day 5 already, and increased to between 15% and 32% of the original source concentration at day 86. The trend in the data shows an increase in the receptor and a decrease in the source concentrations over time, indicating that diffusion took place across the divide between the source and receptor. The VOC concentrations in the source immediately decreased as the VOC sorbed onto the GM, and continued to decrease gradually over the 86-day testing period to between 80% and 20% of the original source concentration. For diffusion to occur through GM separating the receptor from the pervious zone, the concentration of the VOCs in the pervious zone had to be higher than in the receptor to drive the diffusive process. Phase 2 testing proved that the diffusion of BTEX and Chloroform takes place from source to receptor across a divide consisting of two 1 mm GMs separated by an air filled pervious zone.

Phase 3 results show that concentrations in the source volumes decreased over the testing time to about 20% of the original source concentration. This is very similar to the data shown on the source graph of Cell A (no air flow), indicating that the reduction in source concentrations are comparable regardless of air flow through the pervious zone and that the assumption to use the same sorption coefficient in the modelling of phase 2 and 3 work was sound. Results also show that VOC concentrations in the receptor volumes of Cells B, C and D increased over the testing period, indicating that even with airflow through the system, concentrations of BTEX and Chloroform were observed in the receptor. However, the concentrations of the VOCs in the receptor volumes were at most 0.9% (average 0.4%) of the original source concentrations compared to 20% found during phase two tests. This indicates that airflow resulted in diffusion taking place significantly slower. Due to the very low VOC concentrations measured in the receptor volumes of Cells B, C and D, the graphs look slightly distorted and trend identification is difficult. The receptor graphs showing the concentration profile per Cell for each individual VOC against time indicate that the concentrations measured in the receptor volumes of Cell A, where airflow was not introduced, is much higher than the concentrations measured in the receptor volumes of Cells B, C and D, again indicating that diffusion took place significantly slower in the cells where airflow was introduced. The aim of phase 3 was to prove that by introducing airflow into the pervious zone between the two 1 mm GMs, the concentration of VOCs in the receptor volume (due to diffusion through the GM) could be reduced significantly and the results indicate that this aim was comfortably achieved.
4. CONCLUSIONS AND RECOMMENDATIONS

Various studies have shown that VOCs can penetrate even the most well-designed liners of waste containment facilities to pollute the groundwater. The method of penetration is advection and/or diffusion with the main contributor to pollution of groundwater beneath landfills being diffusion. Phase one of the tests undertaken for this study showed that BTEX diffuses through a 2 mm HDPE GM over time with significant concentrations found in the receptor volumes of diffusion test cells specially made for this project. This confirmed studies undertaken by many researchers in the past. Phase two testing proved that diffusion of BTEX and Chloroform takes place from a source to a receptor reservoir separated by two 1 mm GMs with an air-filled pervious zone. Phase three proved that by extracting air through a pervious zone beneath the GM component of a landfill liner, the concentration of VOCs present in the underlying groundwater can be reduced, since the air removed from the system also removes the majority of VOCs. This phase of testing also confirmed that more frequent removal of air further reduces the VOC concentrations in the receptor thus implying that a constant airflow through a pervious zone in a landfill liner can significantly reduce concentrations of VOCs in the groundwater beneath landfills and waste containment facilities.

To add to the work done for this study it is recommended that extraction fluids other than air be used at more frequent rates. This could include the use of a GCL in testing to understand whether continuous hydration of the bentonite in the GCL will benefit the reduction in contaminant transport. Also, the VOCs that were extracted from the system in the tests undertaken for this study were not captured or measured. If the VOCs are removed from beneath the liner, they need to be routed somewhere and releasing it into the atmosphere does not protect the environment. It needs to be further investigated how to trap the VOCs and treat them after removal.

REFERENCES:


