

Evaluation of the performance of bituminous geomembranes (BGMs) as vapour barriers

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Abstract. Vapour barriers (VBs) are essential in maintaining the indoor air quality of home basements or industrial facilities, especially when subsurface contamination poses a risk to human health. It is of utmost importance that the material installed as VB has the capacity to prevent contaminant migration into the indoor air space and reduce its concentration to an acceptable limit. Bituminous geomembranes (BGMs) have been used as contaminant barriers in spite of the gap in research regarding the permeation of volatile organic compounds (VOCs) through BGMs. This study examines the performance of a 4.1mm thick elastomeric BGM as a diffusive barrier to four commonly found VOCs; benzene, toluene, ethylbenzene, and xylenes (BTEX), utilizing computer modelling of contaminant migration from a contaminated soil source to a hypothetical warehouse building constructed on a brownfield site. The effectiveness of BGM in preventing vapour intrusion is evaluated based on its capacity to keep the indoor air concentration of the contaminant below the recommended exposure limits (RELs). Based on the modelling results, the BGM can be expected to perform as a very efficient VB for the simulated warehouse if quality control can be ensured during installation. This modelling approach can be adopted to investigate BGMs' performance in different remediated site scenarios to make scope for a robust decision-making process regarding the construction and the engineering control requirements.

1 Introduction

Bituminous geomembranes (BGMs) have found extensive applications within the engineering sector, serving a diverse range of purposes. They have been employed for various functions such as liner material for geoenvironmental protection in waste disposal facilities like landfills and mine tailing ponds, as hydraulic barriers in dams, canals, and water reservoirs, and in minimizing the loss of valuable metals through the heap leach pads [1-4]. They have also been installed in different transportation projects for their waterproofing characteristics, relatively high resistance to aggregate puncture and low thermal expansion coefficient [5]. Notably, the utility of BGMs has expanded in recent times to encompass new roles as vapor barriers (VBs). Apart from their conventional usage, BGMs have been used as

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vapour and gas barriers in different countries like Canada, France, and Ireland [6]. The primary objective of installing BGMs in these cases was to inhibit the migration of contaminants into residential and commercial buildings situated close to sites previously used as oil fields, landfills, or industrial areas. Intrusion of volatile organic compounds (VOCs) is a valid concern in all these cases, but there is no available data regarding the effectiveness of BGMs to ensure their proper use as a VB to provide the desired environmental protection against the diffusive migration of these contaminants.

The VBs, usually installed below building foundations, are typically made of polymeric materials [7,8]. They are widely used as contaminant barriers in the redevelopment of brownfield sites with a persistent low level of residual contamination [7]. While redevelopment can transform underutilized areas into valuable assets for the community leading towards economic growth, the presence of VOCs in the subgrade becomes a health issue due to the potential risk of vapour intrusion and subsequent exposure to contaminants [8]. Traditional single-material polymeric geomembranes (GMBs) like HDPE, LLDPE and PVC have very low diffusive resistance to VOCs [6, 8, 9]. Modified and co-extruded GMBs have been found to perform better in this respect [7, 10]. However, thin polymeric VBs (minimum thickness of 0.15 mm by NYSDOH [6]) are susceptible to puncture and other installation-related mechanical damage. BGMs, being much thicker (commonly 3-5 mm) compared to conventional GMBs, have a scope to bring additional advantage in this regard due to their high puncture resistance [2, 4] only if they can perform as an effective barrier material against the migration of VOCs.

Thus, the objectives of this paper are: (1) to assess the performance of BGM as a VB with respect to the diffusion of benzene, toluene, ethylbenzene, and xylenes (BTEX); four commonly found VOCs and (2) to compare its performance with that of single-material monolayer and co-extruded polymeric GMBs in controlling the BTEX intrusion.

2 Materials and Methods

2.1 BGM

This study examined an elastomeric BGM (thickness 4.1 mm, trade name TERANAP 431 TP 4M) reinforced with a polyester nonwoven geotextile (NW-GTX) (mass per unit area 235 g/m²) and a glass fleece layer (mass per unit area 50 g/m²) [11]. The reinforcement layer is completely impregnated in bitumen and then additional bitumen is added as a coating layer. The bitumen used in the production of this BGM is stabilized with Styrene-Butadiene-Styrene (SBS) copolymer. The top surface of the BGM is coated with sand for higher friction and the bottom surface adheres to an anti-root polyester (PET) film. The thin PET film (the non-bituminous component) and the modified BGM sample without the film (the bituminous component) were also examined for this study alongside the as-received BGM samples.

2.2 Organic compounds

BTEX are typically used to examine the diffusion characteristics of VOCs through GMBs [6-10, 12]. The organic compounds used in this study were purchased through Sigma-Aldrich and Chromatographic Specialties Inc., ON, Canada. Aqueous solutions, made from 99% pure laboratory-grade chemicals, were used to perform the tests.

2.3 Experimental procedures

Stainless steel double-compartment cells were used to perform the diffusion tests [11]. The source and receptor compartments were separated by a circular sample of membrane examined. Teflon (PTFE) gaskets and silicone sealant were used to secure the sample and seal the junction of the cell. Double deionized water (DDI) was used to fill both compartments and then a solution of known concentration was injected into the source compartment to initiate the test. All tests were performed at room temperature ($24\pm 1^\circ\text{C}$).

The source and receptor solution concentrations were monitored by taking samples through the sampling ports. Sampling was done more frequently at the earlier stage while the changes were more prominent than the later stages of the test. The samples were analysed using a gas chromatographer (7890B GC from Agilent, Santa Clara, CA, USA) with an autosampler (PAL 80). Calibration checks were performed, and quality control standards were used to verify the analysis for each set of samples collected at a specific time.

2.4 Modelling in POLLUTE

2.4.1 Inferring diffusion parameters

The diffusion parameters were inferred by modelling the transient diffusion from the source to the receptor using the finite layer analysis program POLLUTE v7 [13]. Finite layer contaminant transport models were developed through this program to match the experimental data collected during the diffusion tests. The theoretical curves for the source and the receptor were established based on the diffusion theories explained by Sangam and Rowe [12] with finite mass boundary conditions. Additional considerations were given to the approach proposed by McWatters and Rowe [10] while modelling a GMB as a multilayer system.

2.4.2 Predicting vapour intrusion

A hypothetical warehouse, constructed on a hydrocarbon-contaminated site, was examined for the effectiveness of BGM as a vapour barrier to maintain indoor air quality. The vapour barrier was installed below the concrete slab of the warehouse building to minimize the concentration of contaminants in the indoor air. To assess the relative performance of a BGM to that of a PE-based geomembrane as a vapour barrier, the same case was modelled with different types of membrane materials in POLLUTE v7 [13] and the peak indoor concentration (c_{peak}) of the contaminant was evaluated. To be able to utilize the previously published data for vapour barrier assessment for BTEX, the POLLUTE model was built to be similar to the case presented by Jones and Rowe [6] where the warehouse was a 100x100x5m building on a 0.3m thick concrete slab with crack porosity of 0.005. The foundation gravel layer was also 0.3m thick and was assumed to be dry. The contaminated soil below the foundation layer was assumed to have a constant concentration at the solubility limit of the contaminant of interest in the aqueous phase [11]. For the base scenario, it was assumed that 25% of the total air inside was exchanged every hour i.e., an air exchange rate (AER) of 0.25 h^{-1} . Under this setup, the contaminant migration pathway would be established by diffusion from the contaminated soil, through the foundation layer, the geomembrane, the concrete slab and into the building's indoor atmosphere. The maximum contaminant concentration would be at the interface of the concrete slab and the indoor air, and thus the peak indoor concentration (c_{peak}) was examined at zero air height i.e., the interface. The peak concentrations (c_{peak}) were then compared to the occupational exposure limits [14].

3 Results and discussion

3.1 Diffusion parameters for BGM components

The changes in contaminant concentrations monitored during the diffusion test with the as-received BGM showed a significant difference in the behaviour compared to traditional polymeric BGM with low diffusive resistance to aromatic hydrocarbons [11]. The source concentration decreased rapidly during the first few days since the initiation of the test, but the receptor concentration increased at a very slow rate i.e., a very small value of increment in a very long time. Additionally, the individual diffusion test results with the modified BGM and the PET film demonstrated the difference in diffusion characteristics between the bituminous and the non-bituminous components of the BGM [11]. Based on the diffusion parameters inferred for the modified BGM and the PET film, it could be comprehended that in the diffusion test with the as-received BGM, there was relatively rapid diffusion of contaminant molecules into the bituminous portion from the source but their release into the receptor was significantly repressed by the very low diffusion coefficient in the PET film layer. This process can not be modelled with one single set of diffusion parameters. Thus, a two-layer model was established in POLLUTE v7 using the diffusion parameters inferred for the modified BGM and the PET film [11]. The theoretical data were compared to the experimental data from the diffusion test results with the as-received BGM sample with all the components. The trials conducted showed the two-layer theoretical model closely matched the experimental data and hence modelling BGM as a two-layer system and underlying theoretical assumptions were validated for all BTEX [11].

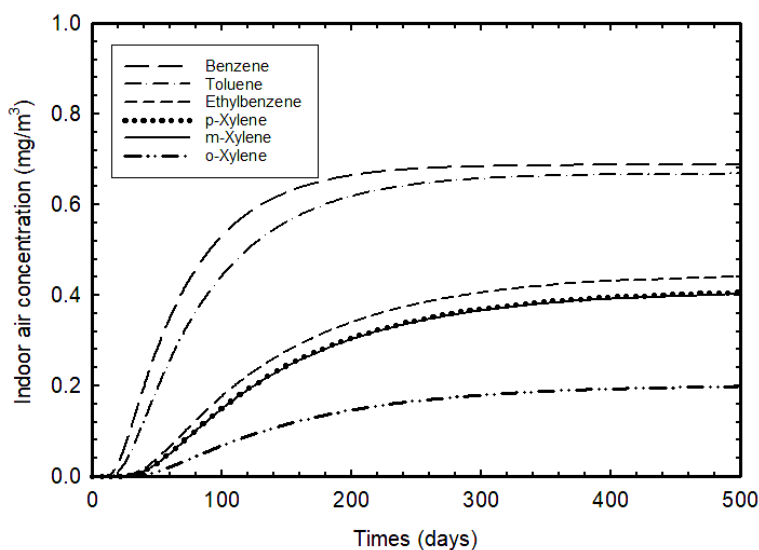


Fig. 1. Change in BTEX concentration in indoor air with time at the interface between the concrete floor and the building air in a simulated warehouse with a 4.1 mm BGM installed as a vapour barrier.

3.2 BTEX concentration in indoor air for BGM VB

Based on the modelling results, the contaminant concentrations increased with time until they reached the peak concentration, c_{peak} at a certain point and then stabilized due to the dilution by air exchange. Among all BTEX, the increase in the concentrations was in the order of benzene > toluene > ethylbenzene > m&p-xylenes > o-xylene (Fig.1). As the diffusion of the

permeant molecule through a GMB decreases with increasing molecular weight and molecular volume [12], the benzene and toluene concentrations increased the most in the indoor air. In contrast, ethylbenzene and xylenes concentrations increased the least.

The National Institute for Occupational Safety and Health (NIOSH) recommends that the exposure to BTEX must be controlled and suggests the recommended exposure limit (REL) for these contaminants as a time-weighted average (TWA) concentration over an 8-hour work shift and the short-term exposure limit (STEL) in any 15-minute sampling period [11]. BGM was able to keep the c_{peak} below the NIOSH REL TWA level for all BTEX other than benzene (Table 1) for an AER of 0.25h^{-1} . However, it was able to maintain c_{peak} well below the NIOSH REL STEL level and the requirements set by the American Conference of Governmental Industrial Hygienists (ACGIH) [11]. Based on this, BGM performance at 0.25h^{-1} AER could be considered acceptable for an establishment in Canada since the ACGIH requirements match the maximum exposure limits for BTEX in many Canadian jurisdictions [11].

Table 1. Peak indoor air concentration for BTEX at the interface between the concrete floor and the building air for different GMBs as vapour barriers at an AER of 0.25h^{-1}

Contaminant (NIOSH REL TWA ^a)	Thick ness (mm)	Vapour Barrier				Co-extruded LLDPE/EVOH/ LLDPE ^d
		PVC ^b	LLDPE ^c	HDPE ^b	BGM	
		1.02	0.76	0.79	4.1	0.53
Benzene (0.32 mg/m ³)	c_{peak} (mg/m ³)	370	110	22	0.69	0.19
	c_{peak} (GMB) / c_{peak} (BGM)	540	160	32	1	0.28
Toluene (375 mg/m ³)	c_{peak} (mg/m ³)	230	72	14	0.67	0.11
	c_{peak} (GMB) / c_{peak} (BGM)	340	110	21	1	0.16
Ethylbenzene (435 mg/m ³)	c_{peak} (mg/m ³)	100	25	9.9	0.44	0.034
	c_{peak} (GMB) / c_{peak} (BGM)	230	57	23	1	0.077
m-Xylene (435 mg/m ³)	c_{peak} (mg/m ³)	87	20	11	0.4	0.029
	c_{peak} (GMB) / c_{peak} (BGM)	220	50	28	1	0.073
o-Xylene (435 mg/m ³)	c_{peak} (mg/m ³)	67	14	6.7	0.2	0.019
	c_{peak} (GMB) / c_{peak} (BGM)	340	70	34	1	0.095
p-Xylene (435 mg/m ³)	c_{peak} (mg/m ³)	130	20	16	0.41	0.029
	c_{peak} (GMB) / c_{peak} (BGM)	320	49	39	1	0.071

^a According to CDC [14]

^b Reported by Jones and Rowe [6]

^c Modelled using diffusion parameters reported by McWatters and Rowe [9]

^d Modelled as a multilayer system based on McWatters and Rowe [10]

3.3 Comparison among different GMB materials

Similar to the BGM VB, single-material polymeric GMBs examined in this study through the model were also able to meet the requirement of keeping the c_{peak} below the NIOSH REL TWA level, except for benzene (Table 1). The order of the c_{peak} among BTEX was also the same i.e., $c_{\text{peak}}(\text{benzene}) > c_{\text{peak}}(\text{toluene}) > c_{\text{peak}}(\text{ethylbenzene}) > c_{\text{peak}}(\text{m\&p-xylenes}) > c_{\text{peak}}(\text{o-xylene})$. Among the GMBs, the LLDPE VB (0.76 mm thick) outperformed the PVC VB (1.02mm thick) even though the PVC VB was much thicker than the LLDPE VB. A similar thickness HDPE VB (0.79 mm thick) outperformed the LLDPE VB. The 4.1 mm thick elastomeric BGM performed better than all these three traditional GMBs, e.g., it showed a 540-fold reduction relative to the PVC VB, a 160-fold reduction relative to the LLDPE VB, and a 32-fold reduction relative to the HDPE VB, in the c_{peak} for benzene in the indoor air.

The only VB that was able to maintain the c_{peak} for benzene below the NIOSH REL TWA level was a 0.53 mm co-extruded LLDPE/ethyl-vinyl alcohol(EVOH)/LLDPE vapour barrier [10]. It was also the only polymeric VB examined to outperform the BGM VB. Based on the modelling results, the LLDPE/EVOH/LLDPE VB reduced the c_{peak} for BTEX from 72% (for benzene) to 93% (for m&p-xylenes) compared to the 4.1 mm BGM. Although, the coextruded VB is predicted to show a significant difference in performance, the issue with the thickness still prevails, since it meets the minimum thickness requirement by NYSDOH (0.15 mm [6]) but does not meet the recommendation of USEPA. USEPA recommends a minimum thickness of 0.75mm for VB for minimizing the risk of puncture [6]. The thickness and puncture resistance of BGM examined [11] make it a more suitable material in this regard for this particular application where BGM is not exposed to heat or any degradation chemicals.

3.4 Effect of air exchange rate (AER) on BGM performance

If adding a VB is not enough to maintain the contaminant concentration in indoor air below the required level, the percentage of the total air exchanged every hour could be a more economical option to maintain the air quality guideline than other remediation options such as excavation of the contaminated soil to eliminate the subsurface vapour source or reconstruction of the building foundation layer with higher performance materials. Since the BGM could not meet the NIOSH REL TWA requirement for benzene at an AER of 0.25h^{-1} for the hypothetical warehouse model, the indoor air concentration of benzene was evaluated for different AER for the same warehouse model with a BGM installed as a vapour barrier to assess the effect of AER on BGMs performance. Previous researchers have reported that AER values typically fall between 0.2 to 1.2 air exchanges per hour (h^{-1}), with most values being clustered around the mean of 0.6h^{-1} [15]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends an AER of 0.35h^{-1} but not less than 15 cubic feet of air per minute (cfm) per person [16]. Thus, the BGM's performance was examined at these specific AERs and plotted together with the base case (AER 0.25h^{-1}) for clear comparison (Fig. 2).

The peak indoor air concentration for benzene decreased with an increase in AER (Fig. 2) and it went below the NIOSH REL TWA requirement (0.32 mg/m^3) for the average AER 0.6h^{-1} or higher (e.g., 1.2h^{-1}). In all cases examined, the peak concentration was below both the NIOSH REL STEL specified limit (3.2 mg/m^3), and the ACGIC specified limits (TWA 1.6 mg/m^3 and STEL 8 mg/m^3) [11, 14].

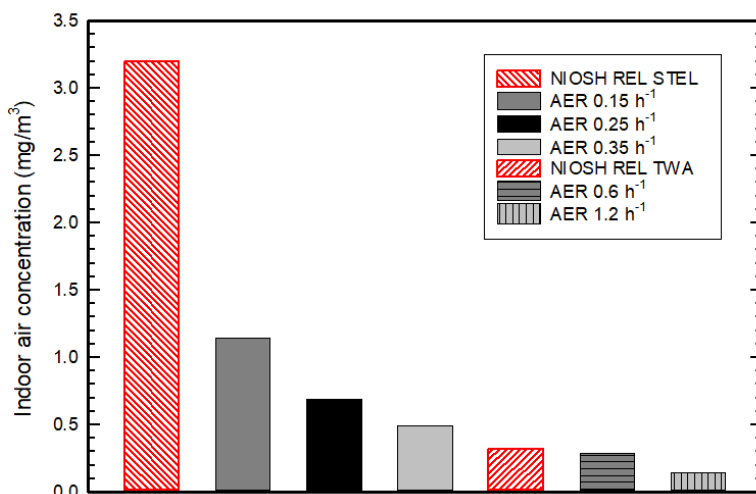


Fig 2. Peak indoor air concentration for benzene at the interface between the concrete floor and the building air for different air exchange rates in a simulated warehouse with a 4.1 mm BGM installed as a vapour barrier.

Based on these results, the BGM could be accepted to perform as a very efficient vapour barrier for the simulated warehouse if the AER could be maintained at 0.6 h⁻¹ or higher. A similar modelling approach can be adopted to evaluate the relative effectiveness of BGM in other contaminated site scenarios to optimize the combination of VB performance and engineering control measures.

4 Conclusions

The performance of a 4.1 mm elastomeric BGM as a VB was examined for a hypothetical case of a warehouse constructed on a hydrocarbon-contaminated site. The diffusion parameters deduced experimentally for BTEX were used to investigate its capacity to prevent vapour intrusion, which was then compared to that of polymeric GMBs. For the specific case and materials explored in this study, the following conclusions were reached:

1. The BGM VB significantly reduced the c_{peak} of BTEX in indoor air compared to the traditional single-material and monolayer HDPE (0.79 mm thick), LLDPE (0.76 mm thick) and PVC (1.02 mm thick) GMBs.

2. Except for benzene, BGM was able to maintain the contaminant concentration below the NIOSH REL (TWA) with an AER of 0.25 h⁻¹. To achieve the requirements for both TWA and STEL by NIOSH and ACGIC, a minimum of 0.6 h⁻¹ AER was required for the BTEX group.

3. Although a 0.53 mm co-extruded LLDPE/EVOH/LLDPE did not meet the minimum thickness requirement (0.75 mm) by USEPA, it was the only polymeric VB that was able to perform better than the BGM in reducing the vapour intrusion into the indoor air.

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