Gas migration through geomembrane/ geosynthetic clay liner composite liner with a defect in the geomembrane

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ABSTRACT

This paper presents the results of an experimental investigation on gas leakage through a geomembrane (GMB)/geosynthetic clay liner (GCL) composite liner where the GMB contained a circular defect and the GCL was partially hydrated. The results indicate that gas leakage rate increased with increasing gas differential pressure and increase of the GCL total suction. It was also observed that gas leakage rate reduced with the increase of the gravimetric water content of the GCL.

Keywords: Geomembrane, GCL, defect, gas leakage rate, suction, water content

1 INTRODUCTION

To effectively collect and use landfill gas, there is a need to install a suitable cover liner system to provide resistance to gas escape. This is usually achieved by the construction of a composite liner consisting of a geomembrane (GM) overlying a resistive (low permeable) liner such as a geosynthetic clay liner (GCL), and a gas collection system which reduces the driving force for gas escape. In typical cover liner configurations an intact GMB is an excellent barrier to gas migration - except where it has holes, which are extremely difficult to eliminate in practical situations. Holes may arise from any number of sources, including manufacturing defects, handling of the GMB rolls, on-site placement and seaming, traffic over the liner or the overlying protection layer, and stress cracking as the GMB ages (Bouazza et al., 2002; Rowe 2005, Bouazza et al., 2008, Abuel-Naga and Bouazza, 2014). Even one relatively small hole per hectare can result in significant leakage through a GMB if there is no hydraulic resistance adjacent to the GMB. On the other hand the performance of a GCL as a barrier to gas is intimately linked to the hydration of the bentonite component in the GCL and its resulting degree of saturation and suction.

In the field, the GCL component of the GMB/GCL composite liner is installed generally at about 10 to 20% gravimetric water content, depending on the product supplied to the site. Thus, the GCL needs to be sufficiently hydrated to provide an effective hydraulic/gas barrier. In composite cover liner systems, the GCL can be hydrated in two ways: 1) active hydration by infiltration of water through defect (s) of the GMB (if any); or 2) passive hydration by water uptake from the foundation soil. It is expected that hydration of GCL should be completed prior to significant contact with gas. However, this potentially introduces a high degree of uncertainty since there is no guarantee that the GCL will reach full hydration and will be more likely in an unsaturated condition prior to the occurrence of gas migration. This latter aspect highlights also the need to quantify the water retention of GCLs and its effect on gas leakage rate.

This paper presents the results of an experimental study conducted to quantify gas leakage rates through a GMB/GCL composite liner with a defect in the GMB. The study was conducted by mimicking the condition where hydration of the GCL occurred after a rainfall event. Thus after water has percolated through the cover system and reached the GCL through a 2 mm circular defect in the GMB. Consideration was given to the change in the gas differential pressure as well changes in the GCL gravimetric water content and total suction.

2 MATERIALS AND TESTING PROCEDURE

2.1 Materials

The commercially available GCL used in the present investigation was composed of powdered sodium bentonite sandwiched between a nonwoven geotextile (NW) cover layer and a nonwoven geotextile reinforced by a slit film woven geotextile (NW+W) carrier with the system being needle punched together and thermally treated to provide confinement of the bentonite during transport and placement. The mass per unit area of bentonite (M_{bent}) was calculated from the difference between the mass per unit area of the GCL (M_{GCL}) and the mass per unit area of the geotextiles (M_{GT}) ($M_{bent} = M_{GCL} - M_{GT}$). M_{GCL} and M_{GT} were obtained following the procedure outlined in ASTM D5993 and ASTM D5261, respectively. The mass per unit area of GCL and dry bentonite varied from 4.5 to 5.8 kg m^{-2} and 3.3 to 4.7 kg m^{-2}, respectively.

A 1.5 mm thick high density polyethelene (HDPE) geomembrane with a 2 mm circular hole at the centre was used in this study. Additionally, a 8 mm passing poorly graded gravel (D_{50}=4.4 mm) was used as both cover and foundation soil for the GMB/GCL composite liner.

2.2 Specimen preparation and hydration

GMB and GCL specimens of 125 mm diameter were cut using a sharp knife and a plastic disc as a cutting base. The initial thickness and mass of the GCL specimen were recorded prior to placing it in the cell. Then the periphery of the GCL was smeared with silicon gel to avoid loss of bentonite during handling. A hydration column cell (Figure 1) was used to hydrate the GCL. The inner column (where GMB/GCL composite needs to be assembled) was composed of two different inside diameters. The upper part of the column had a diameter of 130 mm and the lower part a diameter of 106 mm, creating a shoulder to hold the GMB/GCL composite system.

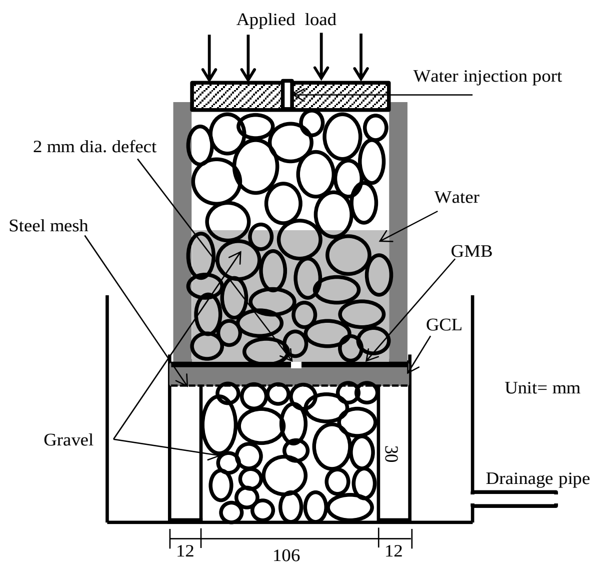

Fig. 1. Column cell for hydration of the GCL in GMB/GCL composite liner (not drawn to scale)

The bottom part of the inside cylinder was first filled with 8 mm passing gravel to the level of the shoulder and then a flat perforated steel mesh was placed on the top surface of the bottom gravel layer to avoid any sagging of the GMB/GCL system. Then a steel pipe of 110 mm inside diameter having a GMB (with 2 mm diameter defect at the center) glued at the bottom end, was placed on top of the GCL. The periphery of the GMB was then sealed with the same bentonite used in the GCL to stop any possible side wall water leakage. The upper column part was placed so that it rested on the shoulder of the bottom column part. Once its placement was completed it was filled with gravel and an axial load was applied above the gravel layer (20 kPa including gravel self-weight) to simulate the condition of 1 m thick cover soil acting above the GMB/GCL composite liner in landfill applications. Finally, a 60 mm water head was applied above the composite barrier by adding water to the gravel-filled pipe to simulate a monthly average rainfall of Melbourne, Australia as reported by the local Bureau of Meteorology. The water travelled through the gravel layer and reached the GCL through the 2 mm diameter hole in the GMB. The wet area of the GCL propagated from the hole as shown in Figure 2a.

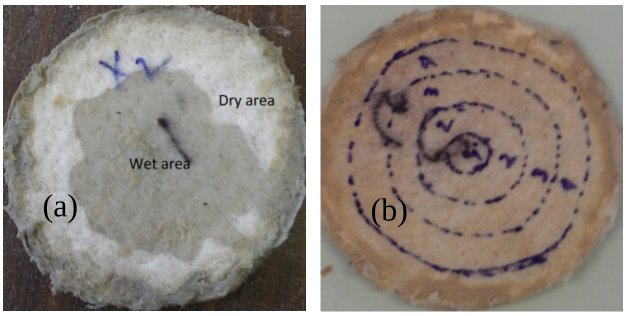

Fig. 2.(a) Hydrated GCL under 20 kPa stress (b) Hydrated GCL divided into four circular rings after 14 days equilibration period (specimen 1 in table 1)

2.3 Equilibration of GCL hydrated water

Once the target time was reached the specimens were removed from the column cell and stored in a double re-sealable plastic bag for equilibration of hydrated water under a normal stress of 20 kPa by direct loading. During hydration, the water initially hydrated the GCL below and near the defect in the GMB, then it migrated radially beneath the GMB and hydrated a larger area/volume of the GCL. After hydration, the equilibration of GCL took place gradually until all available water was absorbed by the bentonite component of the GCL as dry bentonite has a very high negative water potential. The movement of the water continued until the total potential of the bentonite throughout the GCL reached equilibrium. Two specimens were used in this study to investigate the hydrated water equilibration time (Table 1) following the hydration procedure presented earlier The first GCL specimen was divided into four circular rings as shown in Figure 2b, and the gravimetric water content of each part was measured. The results shown in Table 1 indicate that the gravimetric water content of the inner part (70%) of the specimen is higher compared to the outer part (38%) of the specimen after 14 days equilibration time. Another GCL specimen was kept for 38 days under 20 kPa stress for absorbed water equilibration. In this case, the specimen was divided into two rings only (inner ring and outer ring). The results also showed that the outer part (64%) had less water content compared to the inner part (74%) of the hydrated and equilibrated GCL (Table 1). The results of this study indicated that if the infiltrated water hydrated the GCL specimen through the defect of the GMB it will take a long time to equilibrate the absorbed water to the surrounding bentonite of the GCL. However, to expedite the experimental process an equilibration period of 15-20 days was used in the present investigation prior to the gas leakage rate tests. After the test, the average water content of the GCL specimen was measured and reported in this study.

Table 1. Gravimetric water content at different locations in GCLs for two different equilibration times

Specimen No.	Ring No.	Ring position	Hydration time (days)	Water content (%)
1	1	Inner	14	70
	2	Inner close		65
	3	Outer close		53
	4	Outer		38
2	1	Inner	38	74
	2	outer		64

2.4 Apparatus and test procedures

2.1 Leakage rate test

The GMB/GCL composite liner gas leakage rate test was conducted using the gas permeability cell used by Bouazza and Vangpaisal (2003). The cell consisted of two different parts: a base cylinder, and an upper cylinder with piston. The two parts were held together with threaded retaining rods. The piston situated in the upper cylinder was used to transmit the 20 kPa applied confining stress to the GMB/GCL composite. The connections of the upper and the base cylinders, and the piston were sealed using O-rings. The base cylinder had two different inside diameters. The upper part had a diameter of 130 mm and the lower part had a diameter of 100 mm, creating a shoulder on its wall. This shoulder was used to accommodate the GMB/GCL composite liner specimen and the upper cylinder. The effective gas flow area of the cell was 7.85×10^{-3} m^2.

To measure the gas leakage rate, nitrogen gas was supplied to the top of the cell allowing it to permeate through the GCL specimen and to flow out from the base of the cell via a gas flow meter. Five gas flow meters (GFM17 Mass Flow Meters, Aalborg, Denmark; accuracy: 1.5% of full range at 20°C and atmospheric pressure), having flow rates ranging from 0-10 mL/min up to 0-15 L/min, were used alternatively to cover the different gas flow rates. Nitrogen gas ($\mu = 1.76 \times 10^{-5}$ N s m^{-2}, $\rho = 1.165$ kg m^{-3} at 20°C and atmospheric pressure) was used in as the permeating gas because it is relatively inert and has very low water solubility. The outflow port was connected to atmospheric pressure. The differential gas pressure was estimated from the difference between the pressure supply and atmospheric pressure. The description of the gas permeability cell is presented in detail in Bouazza and Vangpaisal (2003).

2.2 Total suction measurements

A dew point potentiometer, referred to herein as WP4C, (Decagon Devices, USA) was used to measure total suction. The WP4C uses the chilled-mirror dewpoint technique to measure the total suction/water potential of a GCL specimen. The specimen was equilibrated with the headspace of a sealed chamber that contains a mirror and a system of detecting condensation on the mirror. When equilibrium is reached, the water potential of the air in the chamber is the same as the water potential of the specimen. The mirror temperature is controlled by a thermoelectric cooler and detection of the exact first appeared condensation point on the mirror is observed with a photoelectric cell. When a specimen is tested, a beam of light is directed onto the mirror and reflected into a photo detector, which senses the change in reflectance at the time of condensation on the mirror. A thermocouple attached to the mirror then records the temperature at which condensation occurs. One limitation of the WP4C is its inability to allow application of loads on the specimen. The water potential range of WP4C is 0 to -300 MPa and accuracy is ±0.05 MPa from 0 to -5 MPa and 1% from -5 to -300 MPa. In this investigation, two GCL specimens of 30 mm diameter (one from the inner ring and another from the outer ring) were used for total suction measurements. These specimens were cut from the GCL sample (125 mm diameter) at the completion of each gas leakage test. As indicated earlier, no stress was applied to the samples during the measurements of total suction. However, the samples were subjected to 20 kPa stress during the hydration/equilibration process and gas leakage rate tests.

3 RESULTS AND DISCUSSION

The GCL average gravimetric water content variation against hydration time is reported in Figure 3. It can be observed that the GCL average gravimetric water content increased from 17% to 66% when the hydration time increased from 5 minutes to 60 minutes. This indicates that the increase of GCL average gravimetric water content is mainly due to the accumulation of infiltrated water with time just below and near the 2 mm hole beneath the GMB, followed by propagation of the infiltrated water occurred at the interface between the GMB and GCL.

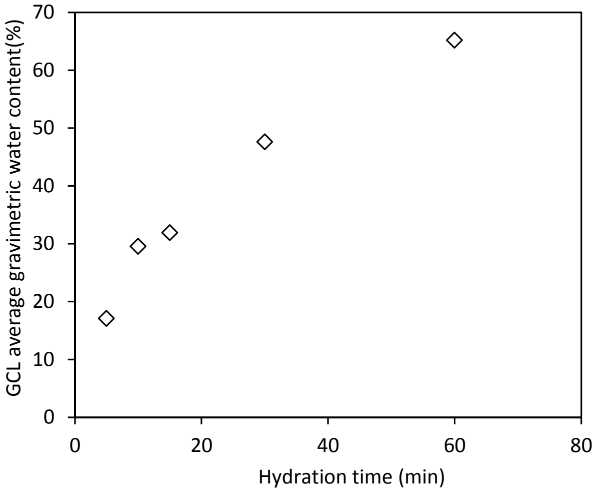

Fig. 3.Variation of average GCL gravimetric water content versus hydration time

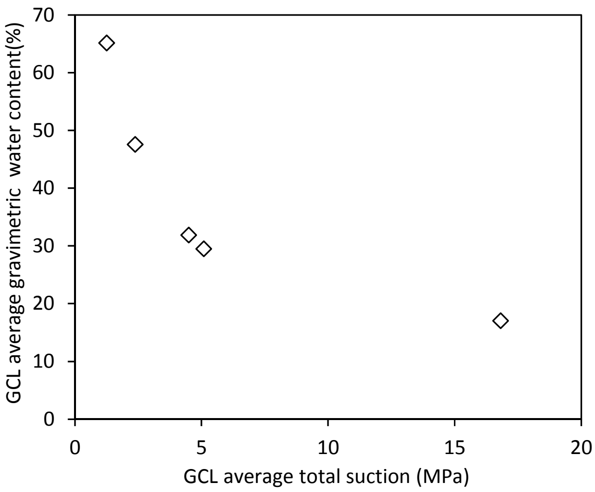

Fig. 4. GCL water retention curve under wetting path

The GCL average gravimetric water content with respect to GCL average total suction (also known as GCL water retention curve) is plotted in Figure 4 for the hydration time range used in this study. It can be observed from Figure 4 that the GCL average gravimetric water content increased by about 50% while the GCL average total suction reduced from 16.80 MPa to 1.30 MPa. The water retention curve showed a similar trend to that reported by Rouf et al. (2014) for the same GCL type. It is to be noted that during total suction measurements there was no applied stress on the specimens. However the specimen has undergone 20 kPa stress during hydration and moisture equilibration.

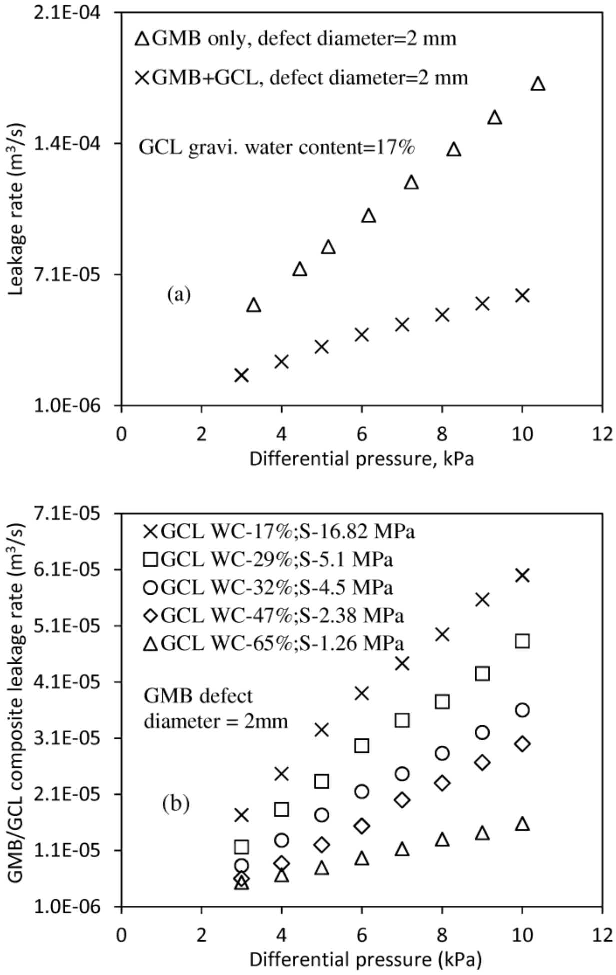

Fig. 5. Gas leakage rate against differential pressure for (a) GMB only and GMB/GCL composite at low gravimetric water content (b) GMB/GCL composite at different GCL average water contents and corresponding total suctions (WC, average gravimetric water content; S, average total suction)

Gas leakage rate variation against differential gas pressure is shown in Figure 5a. It includes the case where a GMB was used alone with 2 mm diameter defect at the center (GMB was sandwiched between two gravel layers) and a case where a GCL at low average gravimetric water content (17%) was used under the GMB to form a composite barrier. The range of differential pressure varied from 3 kPa to 10 kPa as the gas differential pressure in a municipal solid waste landfill is generally less than 10 kPa (McBean et al. 1995). Figure 5a shows that gas leakage rate increased with the increase of gas differential pressure for both cases. It can also be observed that gas leakage rate of GMB specimen only is one to two orders higher compared to a GMB/GCL system (GCL with 17% average gravimetric water content) due to the resistance to gas flow by the GCL and intimate contact at the interface of GMB and GCL caused by the 20 kPa applied stress. From this result it can be inferred that the presence of a material less porous than gravel, under a damaged GMB, can reduce the leakage rate. A similar trend was reported by Bouazza and Vangpaisal (2006).

Figure 5b shows the variation of the gas leakage rate against gas differential pressure for five different gravimetric water contents and their corresponding average total suction values. It is observed that leakage rate increased when differential pressure increased from 3 to 10 kPa at any average gravimetric water content condition. It is also observed that leakage rate decreased with the increase of average gravimetric water content as infiltrated water reduced available air filled pore spaces in the bentonite component and thereby reduced the gas flow through the GCL specimens.

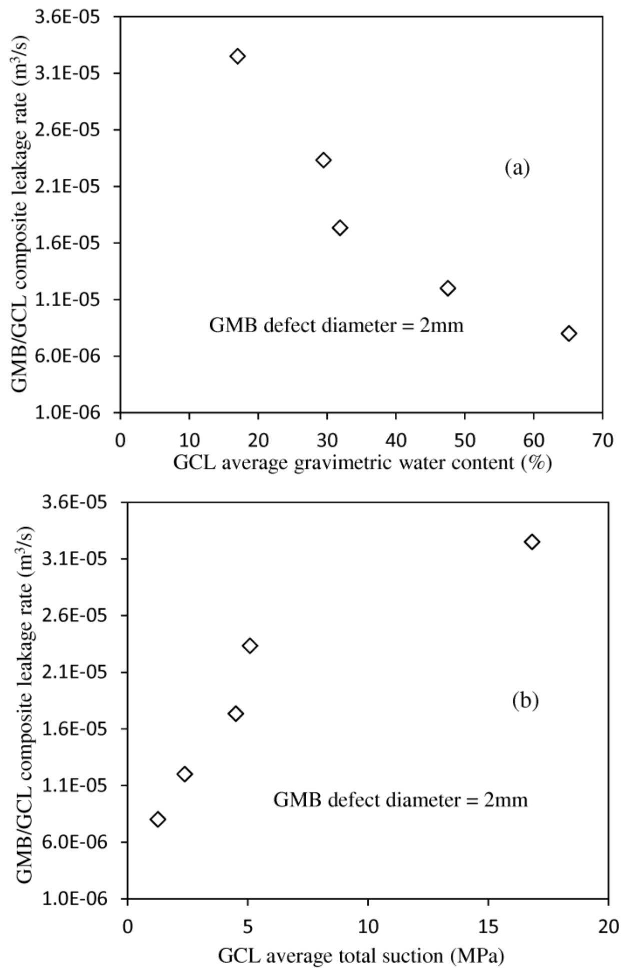

Fig. 6. Gas leakage rate with respect to (a) GCL average gravimetric water content and (b) GCL average total suction of GMB/GCL composite at 5 kPa differential pressure

Gas leakage rate is plotted against GCL average gravimetric water content in Figure 6a for the case where the differential pressure is 5 kPa. It can be observed that gas leakage rate decreased by one order magnitude when the average gravimetric water content of the GCL increased from 17% to about 66% (Figure 6a).

Figure 6b presents the variation of the leakage rate with respect to GCL average total suction at 5 kPa differential pressure. It can be seen that the gas leakage rate increased from 8 $\times 10^{-6}$ m^3/s to $3.25\times10^{-5} m^3/s$ when the average total suction of the GCL specimen increased from 1.30 MPa to 16.80 MPa. Interestingly, Rouf et al. (2014) showed that for GCL used as single barrier only and uniformly hydrated the gas flow rate was 4×10^{-7}at total suction of 1.31 MPa for the same material at same stress and differential pressure condition. This indicates that the non- uniformly hydrated GCL specimen in this study has higher suction (low water content) at the outer portion of the GCL which allowed gas to reach higher flows through the GCL.

4 CONCLUSION

Gas leakage rate tests were performed on a GMB/GCL composite liner, where the GCL was partially hydrated by infiltrated water and the GMB contained a circular defect at the center. The hydration results showed that the GCL will take more than 38 days for uniform water distribution throughout the specimen under the hydration system used in this study. The GCL average water content increased with increase of the hydration time. The results also indicated that increase of gas differential pressure can lead to larger gas leakages due to advection. Furthermore, high average water content GCL specimen in GMB/GCL composite liner can lead to lower gas leakage compared to the case where the GCL has low average gravimetric water content. This implies that the GCL in a GMB/GCL composite should be kept hydrated to high gravimetric water content in order to achieve an effective composite barrier to gas.

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