A gas flow unified measurement system for measuring sequentially gas diffusion and gas permeability of partially hydrated geosynthetic clay liners

<table>
<thead>
<tr>
<th>Journal:</th>
<th>Canadian Geotechnical Journal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>cgj-2015-0123.R2</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Article</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>28-Nov-2015</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Rouf, Md; Monash University, Civil Engineering Bouazza, A.; Monash University, Civil Engineering Singh, R.M.; University of Surrey, Civil and Environmental Engineering Gates, Will; Monash University, Civil Engineering Rowe, R. Kerry; Queens University,</td>
</tr>
<tr>
<td>Keyword:</td>
<td>geosynthetic clay liner, gas flow, diffusion, advection, gravimetric water content</td>
</tr>
</tbody>
</table>
A gas flow unified measurement system for measuring sequentially gas diffusion and gas permeability of partially hydrated geosynthetic clay liners

by

Md A. Rouf1, Abdelmalek Bouazza2*, Rao M. Singh3, Will P. Gates4 and R. Kerry Rowe5

*Corresponding Author

1 PhD Student, Department of Civil Engineering, 18 Alliance Lane, Monash University, Vic. 3800, Australia, phone: +61 3 9905 8901, Fax: +61 3 9905 4944. email:md.rouf@monash.edu

2*Professor, Department of Civil Engineering, 23 College Walk, Monash University, Vic. 3800, Australia, phone: +61 3 9905 4956, Fax: +61 3 9905 4944 email:malek.bouazza@monash.edu

3 Lecturer, Department of Civil and Environmental Engineering, 24 AA 02, University of Surrey, Guildford, GU2 7XH United Kingdom, phone: + 44 (0)1483 68 9280, Fax: +44 (0) 1483 68 6041, email: r.singh@surrey.ac.uk

4Senior Research Fellow, Department of Civil Engineering, 23 College Walk, Monash University, Vic. 3800, Australia, phone: +61 3 99054664, Fax: +61 3 9905 4944. email:will.gates@monash.edu

5Professor and Canada Research Chair in Geotechnical and Geoenvironmental Engineering, Department of Civil Engineering, Queen’s University, Ellis Hall, Kingston ON, Canada K7L 3N6, phone: +1 613 533-3113; Fax: +1 613 533-2128; email:kerry@civil.queensu.ca.
ABSTRACT

A gas flow unified measurement system (UMS-G) for sequential measurement of gas diffusion and gas permeability of geosynthetic clay liners (GCLs) under applied stress conditions (2 to 20 kPa) is described. The measurements made with the UMS-G are compared with measurements made with conventional experimental devices and are found to give similar results. The UMS-G removes the need to rely on two separate systems and increases further the reliability of the gas properties measurements. This study also shows that the gas diffusion and gas permeability reduce greatly with the increase of both gravimetric water content and apparent degree of saturation. The effect of applied stress on gas diffusion and gas permeability is found to be more pronounced at gravimetric water content greater than 60%. These findings suggest that at a nominal overburden stress of 20 kPa, the GCL used in the present investigation needs to be hydrated to 134% gravimetric water content (65% apparent degree of saturation) before gas diffusion and gas permeability drop to $5.5 \times 10^{-11} \text{ m}^2/\text{s}$ and $8.0 \times 10^{-13} \text{ m/s}$ respectively and to an even higher gravimetric water content (apparent degree of saturation) at lower stress.

*Keywords*: geosynthetic clay liner, gas flow, diffusion, advection, gravimetric water content
### Notation List

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>one-dimensional volumetric flow rate of gas in porous media (m$^3$s$^{-1}$)</td>
</tr>
<tr>
<td>$k$</td>
<td>intrinsic permeability of the porous material (m$^2$)</td>
</tr>
<tr>
<td>$A$</td>
<td>cross sectional area of the porous material (m$^2$)</td>
</tr>
<tr>
<td>$dP/dz$</td>
<td>pressure gradient (Nm$^{-1}$)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>dynamic viscosity of gas (N s m$^{-2}$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density of the N$_2$ gas (kg m$^{-3}$)</td>
</tr>
<tr>
<td>$g$</td>
<td>gravitational acceleration (m s$^{-2}$)</td>
</tr>
<tr>
<td>$K$</td>
<td>gas permeability (m s$^{-1}$)</td>
</tr>
<tr>
<td>$L$</td>
<td>length of specimen (m)</td>
</tr>
<tr>
<td>$P_1$</td>
<td>inlet pressure (Nm$^2$)</td>
</tr>
<tr>
<td>$P_2$</td>
<td>outlet pressure which is atmospheric pressure (Nm$^2$)</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$W$</td>
<td>gravimetric moisture content of GCL (%)</td>
</tr>
<tr>
<td>$w_{ref}$</td>
<td>maximum gravimetric moisture content that GCL can reach during hydration (%)</td>
</tr>
<tr>
<td>$C(L, t)$</td>
<td>gas concentration in the diffusion chamber at time $t &gt; 0$ (g m$^{-3}$), at $z &gt; L$</td>
</tr>
<tr>
<td>$C_0$</td>
<td>gas concentration in the atmosphere (source) (g m$^{-3}$), at $z &lt; 0$</td>
</tr>
<tr>
<td>$C_g$</td>
<td>concentration difference in the gaseous phase (g m$^{-3}$)</td>
</tr>
<tr>
<td>$C_i$</td>
<td>gas concentration in the diffusion chamber at $t = 0$ (g m$^{-3}$), at $z &gt; L$</td>
</tr>
<tr>
<td>$C_r$</td>
<td>relative gas concentration in diffusion chamber (g m$^{-3}$)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>air-filled porosity (m$^3$ m$^{-3}$)</td>
</tr>
<tr>
<td>$\alpha_l$</td>
<td>first positive root of $hL = \alpha_n L_n \tan(\alpha_n L_n)$ (n = 1, 2, ...........)</td>
</tr>
<tr>
<td>$J$</td>
<td>mass diffusive flux of the gas (g m$^{-2}$ s$^{-1}$)</td>
</tr>
<tr>
<td>$D_p$</td>
<td>gas diffusion coefficient (m$^2$s$^{-1}$)</td>
</tr>
<tr>
<td>$z$</td>
<td>thickness, height, etc. (m)</td>
</tr>
<tr>
<td>$\partial C_g / \partial z$</td>
<td>gas concentration gradient (g m$^{-4}$)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>volumetric water content of bentonite (m$^3$ m$^{-3}$)</td>
</tr>
<tr>
<td>$D_a$</td>
<td>gas diffusion coefficient in free air (m$^2$s$^{-1}$)</td>
</tr>
<tr>
<td>$D_w$</td>
<td>gas diffusion coefficient in water phase (m$^2$s$^{-1}$)</td>
</tr>
<tr>
<td>$M_{GCL}$</td>
<td>mass per unit area of GCL (kg/m$^2$)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$M_{bent}$</td>
<td>mass per unit area of bentonite (kg/m²)</td>
</tr>
<tr>
<td>$M_{UG}$</td>
<td>mass per unit area of upper geotextiles (kg/m²)</td>
</tr>
<tr>
<td>$M_{LG}$</td>
<td>mass per unit area of lower geotextiles (kg/m²)</td>
</tr>
<tr>
<td>$M_{GT}$</td>
<td>mass per unit area of geotextile (kgm⁻²)</td>
</tr>
<tr>
<td>$H_{UG}$</td>
<td>thickness of upper geotextiles (m)</td>
</tr>
<tr>
<td>$H_{LG}$</td>
<td>thickness of lower geotextiles (m)</td>
</tr>
<tr>
<td>$H_{GCL}$</td>
<td>thickness of GCL (m)</td>
</tr>
<tr>
<td>$S_r^*$</td>
<td>apparent degree of saturation (%)</td>
</tr>
<tr>
<td>$S_r$</td>
<td>bentonite degree of saturation</td>
</tr>
<tr>
<td>$h$</td>
<td>ratio of air content in GCL specimen to length of free space below GCL specimen including diffusion chamber length ($m^{-1}$)</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

Evaluation of gas migration is important in engineered cover systems of waste containment facilities to prevent or minimize possible contamination of the environment following their closure due to gas build up. The movement of gases in porous media occurs by two major transport mechanisms: advective and diffusive flow. Gases such as methane, carbon dioxide, generated as a result of anaerobic decomposition of organic materials in municipal solid waste landfills, tend to move in response to a gradient in total pressure (i.e., advective flow) (Vangpaisal and Bouazza 2004; Rouf et al. 2015a) whereas atmospheric methane oxidation and uptake tend to be controlled by oxygen ($O_2$) diffusion (Gebert et al. 2011; Yao et al. 2015). In mining waste storage facilities, the gas transport mechanism is more diffusion dominated. For example, oxidation of reactive sulphide bearing mine residues leading to acid drainage is caused by the diffusive influx of oxygen through the cover (Aubertin et al. 2000; Johnson and Hallberg 2005; Bouazza and Rahman 2007). In the case of uranium tailings diffusive efflux of radon gas needs to be controlled to reduce its impact on human health (Ferry et al. 2002; Mudd 2008).

The design of these cover systems is, in most cases, site specific and depends usually on the prevailing climatic conditions. In areas with humid climates, the conventional approach to cover systems (usually multi-layered systems) is to construct a “resistive barrier” that utilises a liner with a low saturated hydraulic conductivity (i.e., compacted clay liner or geosynthetic clay liner) or composite liners (i.e., compacted clay liner or geosynthetic clay liner + geomembrane), in combination with a number of other soil layers, to reduce or control water infiltration and gas ingress/egress into/from the waste. Geosynthetic clay liners (GCLs) are now increasingly used in landfill covers as the resistive barrier as an alternative to compacted clay liners (Didier et al. 2000; Bouazza 2002; Kim and Benson 2004; Bouazza and Bowders 2010; Scalia and Benson, 2011; Buckley et al. 2012; Bouazza et al. 2013; Makusa et al. 2014). Their use has also been included in the construction of mine cover systems as replacement to soil resistive barriers, at least in humid or wet climates (Aubertin et al. 2000; Kim and Benson 2004; Renken et al. 2005; Bouazza and Rahman 2007; Rowe and Hosney 2013; Hosney and Rowe 2013, 2014).
There is a wide body of work available on GCL hydraulic performance and the measurements of GCL permeability and diffusivity to fluids are well documented in literature (Rowe 1998; Shackelford et al. 2000; Lake and Rowe 2000; Bradshaw and Benson 2013; Bouazza and Gates 2014; Bouazza et al. 2014; Shackelford 2014; Abuel-Naga and Bouazza 2014; Rowe et al. 2014; Liu et al. 2014, 2015), thus it will not be the focus of this paper. However, experimental measurements of GCL permeability and diffusion to gases are less widely available and information on GCL gas advective and diffusive flow performance has become available only in the last decade (Bouazza et al. 2006, 2008; Bouazza and Vangpaisal 2004, 2007; Vangpaisal and Bouazza 2004; Bouazza and Rahman 2007; Abuel-Naga and Bouazza 2009; Mendes et al. 2010; Pitanga et al. 2011; Rouf et al. 2014). Gas permeability of GCLs has been shown to be affected by changes in gravimetric/volumetric water content (Didier et al. 2000; Bouazza and Vangpaisal 2003; Vangpaisal and Bouazza 2004; Pitanga et al. 2011; Rouf et al. 2013, 2014), amount of straining (Bouazza and Vangpaisal 2004), distribution of needle punched fibres in GCLs (Bouazza and Vangpaisal 2007) as well as the form of bentonite (powdered or granular) used in GCLs (Vangpaisal and Bouazza 2004). Additionally, bentonite impregnation of the geotextile component was found to reduce the gas permeability of GCLs considerably (Vangpaisal and Bouazza 2004). It was also reported by previous researchers (Bouazza et al. 2006; Mendes et al. 2010) that when a GCL lost the absorbed water, its gas permeability significantly augmented due to shrinkage of the bentonite component and, in severe cases, due to the formation of desiccation cracks which provided preferential gas flow paths due to pressure gradient. Earlier work has also shown that an increase in degree of saturation greatly attenuated the gas diffusion coefficient of GCLs (Aubertin et al. 2000; Bouazza and Rahman 2004, 2007). Furthermore, Bouazza and Rahman (2007) indicated that the way that GCLs are held together as a composite material (i.e., stitch bonded versus needle punched) had a significant effect on the variation of gas diffusivity.

Traditionally, two separate devices are used to quantify the gas advective and diffusive properties of GCLs, a gas permeameter to measure the gas permeability (Bouazza and Vangpaisal 2003) and a diffusion cell to measure gas diffusion (Aubertin et al. 2000; Bouazza and Rahman 2007). This process makes it cumbersome to evaluate the gas flow properties of GCLs. Furthermore such method is fraught with uncertainties since specimens used in both devices may differ substantially (i.e., different mass per unit area (Ali et al. 2014; Rouf et al.
2015b), thickness (Meer and Benson 2007; Rouf et al. 2015a, 2015b) even if they are from the same roll. This paper presents a gas flow unified measurement system (UMS-G) which allows the measurement of gas diffusion and permeability sequentially on the same specimen, thus removing the need to rely on two separate systems and increasing further the reliability of the gas properties measurements.

2. MECHANISM OF GAS TRANSPORT

The movement of gas in porous media such as soil or GCLs is mainly governed by two physical transport mechanisms: diffusion and advection. A brief description of diffusion and advection process is given:

2.1. Diffusion

Diffusion is a physical process where gas movement occurs due to molecular interactions and mass flow (Troeh et al. 1982; Aubertin et al. 2000; Allaire et al. 2008; Barral et al. 2010). When a gas is more concentrated in one region of a mixture than another, gas tends to diffuse into the less concentrated region. Thus the molecules move in response to a partial pressure, or gas concentration gradient. The movement of gas molecules will occur through the air filled pores in the case of unsaturated porous media while for the highly saturated porous media it partly will occur through the gas phase and partly in the liquid phase implying in this latter a solubilisation process (Aubertin et al. 2000; Bouazza and Rahman 2004, 2007). The primary driving force for gas transport in mine tailings cover is the $O_2$ concentration gradient formed between the atmosphere and mine tailings (Lundgren 2001; Bouazza and Rahman 2007).

Fick’s laws can be used to model gas diffusion in a similar way to diffusion transport of dissolved contaminants through porous media (Aubertin et al. 2000; Bouazza and Rahman 2007). The mass diffusive flux for the one-dimensional diffusion process is given by Fick’s first law:

\[ J = -D_p \frac{\partial C_g}{\partial z} \]  

(1)

Where $J$ is the mass diffusive flux of the gas (gm$^{-2}$s$^{-1}$), $C_g$ is the concentration difference in the gaseous phase (gm$^{-3}$), $D_p$ is the diffusion coefficient of the gas (m$^2$s$^{-1}$), $z$ is a distance (thickness,
height, etc.) (m), and $\partial C_g / \partial z$ is the concentration gradient (gm$^{-4}$). The minus sign in equation (1) indicates that mass transfer over time occurs in the direction of decreasing concentration.

The transient one-dimensional diffusion of a nonreactive gas can be derived from continuity equation and Fick’s first law and is described by Fick’s second law as given below:

$$\frac{\partial C_g}{\partial t} = D_p \left( \frac{\partial^2 C_g}{\partial x^2} \right) \tag{2}$$

where $\varepsilon$ is the air-filled porosity (m$^3$ m$^{-3}$), and $t$ is the time (s). Assuming that the sample porous medium is uniform with respect to diffusion coefficient and $\varepsilon$ is constant in space and time, equation (2) can be solved subject to the boundary and initial conditions for the diffusion chamber method (Currie 1960; Rolston and Moldrup 2002). Hence, equation (2) can be used for the calculation of the diffusion coefficient, which is dependent on the pores and fluid characteristics such as total porosity, tortuosity, degree of saturation, and molecular weight.

### 2.2. Advection

Advection is a process of gas flow in which the gas moves in response to a gradient in total pressure (Troeh et al. 1982; Bouazza and Vangpaisal 2003; Vangpaisal and Bouazza 2004; Barral et al. 2010). A mass of gas travels from a region of higher pressure to a lower pressure until pressure equilibrium is reached. In the context of landfills, the primary driving force for gas migration, especially through cover systems, is a pressure differential due to natural fluctuations in atmospheric pressure (Vangpaisal and Bouazza 2004). Other factors that can also contribute to the pressure differential are changes in the leachate/water table or temperature (Lundgren 2001; Vangpaisal and Bouazza 2004). Other major mechanisms driving gas migration include elevated internal gas pressure resulting from gas generation caused by bacterial decomposition, volatilization and chemical reactions (McBean et al. 1995) and gas density driven transport (Thomas et al. 2010).

Several past studies have shown that Darcy’s law could provide a fair approximation of advective gas flow in a low permeability material (Alzaydi et al. 1978; Bouazza and Vangpaisal
2003; Vangpaisal and Bouazza 2004). Furthermore, Massmann (1989) indicated that a groundwater flow model provides a good approximation for gas advection up to a differential pressure of 50 kPa.

The one-dimensional volumetric flow rate \( Q \) (\( m^3 \cdot s^{-1} \)) of gas in porous media can be described by Darcy’s law as shown below:

\[
Q = -\frac{k}{\mu} A \frac{dP}{dz} \tag{3}
\]

Where \( k \) is the intrinsic permeability of the porous material (\( m^2 \)); \( A \) is cross section of the porous material (\( m^2 \)); \( dP/dz \) is pressure gradient; and \( \mu \) is dynamic viscosity of gas (\( N \cdot s \cdot m^{-2} \)).

Generally, intrinsic permeability is considered a property of porous material which is independent of permeating gas/fluid.

The gas permeability, \( K \) (\( m \cdot s^{-1} \)) of any porous media can be estimated from the equation given below:

\[
K = \frac{\rho g}{\mu} k \tag{4}
\]

where \( \rho \) is density of the gas (\( kg \cdot m^{-3} \)) and \( g \) is gravitational acceleration (\( m \cdot s^{-2} \)).

Applying the continuity equation and assuming that landfill gas behaves as an ideal gas, equation (3) can be expressed as:

\[
PQ \frac{dz}{P} = -\frac{k}{\mu} AP dP \tag{5}
\]

For a specimen of length \( L \) (m), equation (5) may be integrated subjected to boundary conditions, \( P = P_1 \) at \( z = 0 \) and \( P = P_2 \) at \( z = L \), where \( P_2 \) is the atmospheric pressure, to give the mass flow rate entering the atmosphere (\( Q_2 \)), in terms of boundary pressure, viz:

\[
Q_2 = \frac{k}{\mu} A \frac{P_1^2 - P_2^2}{2P_2L} \tag{6}
\]

By combining equation (4) and equation (6), gas permeability can be expressed as:
3. MATERIALS AND METHODS

3.1 Geosynthetic clay liner

The commercially available GCL examined in the present investigation was composed of powdered sodium bentonite sandwiched between a nonwoven geotextile (NW) cover layer and a woven geotextile (W) carrier layer 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 \( (M_{\text{bent}}) \) was calculated from the difference between the mass per unit area of the GCL \( (M_{\text{GCL}}) \) and the mass per unit area of the geotextiles \( (M_{\text{GT}}) \). \( M_{\text{GCL}} \) and \( M_{\text{GT}} \) were obtained following the procedures outlined in ASTM D5993 and ASTM D5261, respectively. The GCL physical characteristics are shown in Table 1.

3.2 Specimen preparation

GCL specimens were prepared and hydrated to cover various conditions (i.e., gravimetric water contents and hydration processes). Firstly, 135 mm diameter GCL specimens were cut, from an A-3 sized GCL sheet (previously cut from a GCL roll), using a sharp knife and a plastic disc as a cutting base. One specimen from each A-3 sized GCL sheet was used to measure initial thickness, mass and gravimetric water content respectively. The initial thickness and mass of each GCL specimen was also recorded to facilitate further analysis. The GCL specimens were selected in such a way that the mass per unit area of the GCL specimens fell within the representative range of mass per unit area histogram shown in Figure 2. The histogram is not normally distributed due to the lack of uniformity in mass per unit area at different locations of the roll. Thus there is potential for a substantial variation in the mass per unit area if the specimens are cut without referring to the representative mass per unit area histogram. This in turn can have a significant impact on gas migration as indicated by Bouazza and Rahman (2007).

\[
K = \frac{2Q_s P_s L_{fg}}{A \left( P_1^2 - P_2^2 \right)} \tag{7}
\]
The specimens were conditioned by placing them on a saturated porous plate to uptake moisture for different specified time periods (bottom-up hydration process). Once the target time was reached the specimens were removed from the moisture uptake set up and stored in a double re-sealable plastic bag for hydration/moisture equilibration. The moisture equilibration of the specimen took place gradually until all available water was absorbed by the bentonite as dry bentonite has a very high negative water potential. For this reason, the equilibration of GCL after moisture uptake was essential. The specimens were hydrated/equilibrated following two different methods. In the first method, the GCL was kept under a normal stress of 20 kPa by direct loading, to simulate the weight of a 1-m thick soil layer typically used in a cover system at least in humid climates (Hosney and Rowe, 2013). However, it is important to point out that Meer and Benson (2007) indicated that 1 m cover soil might not be sufficient to minimize changes in hydraulic conductivity of GCLs caused by dehydration/desiccation and cation exchange. In the second method, the GCL was placed under 2 kPa vertical confinement to provide a minimum stress to ensure uniform distribution of moisture content in the specimen. An equilibration period of 10-14 days was used to ensure a uniform distribution of moisture in the GCL specimens (see also section 3.3.2.4) prior to sequential measurement of gas diffusion and gas permeability.

### 3.3 Apparatus and Test Procedures

#### 3.3.1 The gas flow unified measurement system (UMS-G)

The gas flow unified measurement system (UMS-G) for measuring GCL gas diffusion and permeability (Figure 1) was developed by integrating and improving a diffusion chamber method (Currie 1960; Rolston and Moldrup 2002), a gas permeability apparatus (Bouazza and Vangpaisal 2003), and a recently developed soil unified measurement system (UMS_SC) for gas transport parameters with suction control (Rouf et al. 2012). The UMS-G comprises three major parts, all made of acrylic: a bottom cylindrical diffusion chamber (100 mm in inner diameter and 95 mm in height), a middle cylinder to accommodate a GCL specimen and a cylindrical top/upper chamber (100 mm in inner diameter and 70 mm in height) with a moveable steel piston. The three parts are held together with four threaded retaining rods. The diffusion chamber was equipped with two measurement ports/valves, an \( O_2 \) electrode (KE-25, Figaro Engineering
Inc., Japan), and a pressure transducer (MBR20, range: 0-1bar G, precision: 0.25%, MeasureX Pty Ltd., Melbourne, Australia). The $O_2$ electrode was used to measure the $O_2$ concentration variations inside the diffusion chamber. The function of the pressure transducer was to monitor the pressure variations inside the diffusion chamber. The middle cylinder has two different diameters for the upper and lower part. The upper part has a diameter of 140 mm and the lower part has a diameter of 100 mm, creating a shoulder on the wall. This shoulder was used to accommodate the GCL specimen and the upper cylinder. A groove was made at the top surface of the bottom cylinder and at the bottom surface of the middle cylinder to accommodate a sheet-metal sliding separator (130 mm× 400 mm) containing a 100 mm diameter hole. The purpose of the fitted sheet-metal sliding separator in between the diffusion chamber and the middle cylinder is to control the movement of gas by opening or closing the hole. Since the hole diameter in the sheet metal sliding separator was 100 mm, the effective gas flow area of the UMS-G was $7.85 \times 10^{-3} \text{ m}^2$. O-rings were provided both in the grooves of the middle cylinder and the bottom cylinder for sealing as well as to ensure a smooth movement of the sheet-metal sliding separator. The upper cylinder consisted of 6 ports (10 mm diameter; connected to atmosphere) located on the top cap with stoppers and a moveable steel rod (piston) inserted through its centre. The 6 ports can be unstoppered during the subsequent gas diffusion measurements. During gas permeability measurement only one port was kept open. A set of five interchangeable gas flowmeters (GFM17 Mass Flow Meters, Aalborg, Denmark; accuracy: 1.5% of full range at 20°C and atmospheric pressure) was attached to this port to record gas outflow ranging from 0-10 cm$^3$/min to 0-15,000 cm$^3$/min. The purpose of the moveable steel rod situated in the upper cylinder was to transmit the target applied stress to the GCL specimen through the perforated steel mesh (100 mm diameter) attached at the bottom of the rod. A steel plate was also attached to the top portion of the moveable steel rod to allow load application during the test. In addition, a displacement gauge (LP-20F, Midori Precisions, ADM Instruments Engineering, Australia) was installed on top of the steel plate to record the change in thickness of the GCL specimen during the test. The connections of the upper cylinder with the middle cylinder wall and with the moveable steel rod were sealed using O-rings. A 5 mm thick and 140 mm diameter (but 100 mm inner diameter perforated) steel plate was placed on the shoulder of the middle cylinder to avoid a possible sagging of the GCL due to the applied load as there was no subgrade material below the GCL in the set-up system. O-rings were provided both at the shoulder of the middle cylinder
and above the perforated steel plate to avoid gas leakage in lateral direction through the interface. The $O_2$ electrodes, pressure transducer and displacement gauge were connected to a data logger (DT 505, Data Taker Pty Ltd., Melbourne, Australia) and a computer for monitoring and storage of the data. Nitrogen ($N_2$) gas ($\mu = 1.76 \times 10^{-5}$ N s m$^{-2}$, $\rho = 1.165$ kg m$^{-3}$ at 20°C at atmospheric pressure) was used as permeating fluid in this investigation because it is relatively inert and has very low water solubility.

3.3.2 Testing procedure

3.3.2.1 Specimen assembling process

The GCL specimen assembling process involved several steps. First, a sheet-metal sliding separator with a 100 mm diameter hole was fitted with the groove present in the top surface of the diffusion chamber. Next, the middle cylinder was placed above the sheet-metal sliding separator so that its groove fitted well with the sliding separator and groove of the bottom cylinder. Then, a 135 mm diameter hydrated GCL specimen was placed on the 5 mm thick (>40% area) perforated steel plate above the shoulder of the middle cylinder. As more than 40% area of the 5 mm thick steel plate was perforated it was assumed that the resistance from the steel plate for gas flow was negligible. Additionally, the gas flow loss test check showed that the perforated steel plate had no resistance to gas flow. Tests were also conducted with and without a steel mesh and no noticeable difference in $O_2$ concentration was observed that could change the gas diffusion coefficient. After completing the GCL specimen placement, four retaining rods were tied to fit and secure the upper cylinder to the middle cylinder and diffusion chamber. Care was taken not to over tighten the retaining rods to avoid squeezing of bentonite from the perimeter under excessive compression. Then, the moveable steel rod was placed above the GCL specimen to allow the application of the target vertical stress (2 or 20 kPa) before the start of the test.

3.3.2.2 Measurement and calculation of gas diffusion coefficient

The diffusion test consisted of introducing $N_2$ gas into the diffusion chamber (receptor) to displace the $O_2$ present in the chamber. Both the ports/valves of the diffusion chamber were shut off. The 100 mm diameter hole of the sheet-metal sliding separator was kept open and the 6
Draft

stoppers at the top cap of the upper cylinder (O$_2$ source chamber) were opened. This allowed air to diffuse through the specimen to the diffusion chamber thereby increasing the O$_2$ concentration in the diffusion (receptor) chamber. After opening the sheet-metal sliding separator, sufficient time (5 minutes) was given to mix the gas inside the diffusion chamber and gas in the space between GCL specimen and the sheet-metal sliding separator. Then the O$_2$ concentration in the diffusion chamber was recorded by the O$_2$ electrode at 1 minute intervals.

The calculation of the diffusion coefficient of GCL was conducted according to Fick’s second law (equation (2)). The solution (Carslaw and Jaeger 1959) for the relative concentration ($C_r$) in the chamber can be given as:

$$C_r = \frac{C(L, t) - C_0}{C_i - C_0} = \sum_{n=1}^{\infty} \frac{2h.\exp\left(-D_p\alpha_n^2 t / \varepsilon\right)}{L \left(\alpha_n^2 + h^2\right) + h}$$

(8)

Equation (8) can be expressed in a linear form by considering the terms for $n \geq 2$ are negligible with respect to the first term, as shown below:

$$\ln(C_r) = \ln\left(\frac{C(L, t) - C_0}{C_i - C_0}\right) = \frac{D_p\alpha_1^2}{\varepsilon} t + \ln\left(\frac{2h}{L(\alpha_1^2 + h^2) + h}\right)$$

(9)

where $L$ is the height/thickness of sample (m), $C(L, t)$ is the gas concentration in the diffusion chamber at time $t > 0$ (g $m^{-3}$), at $z > L$; $C_0$ is the gas concentration in the atmosphere (source) (g $m^{-3}$), at $z < 0$; $C_i$ is the gas concentration in the diffusion chamber at $t = 0$ (g $m^{-3}$), at $z > L$; $h = \varepsilon L_a (m^{-1})$, where $L_a$ is the height of the diffusion chamber + length of the free space below the GCL specimen (m).

Using equation (9) the GCL gas diffusion coefficient, $D_p$ can be derived from the slope ($-\frac{D_p\alpha_1^2}{\varepsilon}$) of the plot $\ln(C_r)$ versus time, $t$ which becomes linear for sufficiently large time as shown in Figure 3a and 3b at high and low gravimetric water content and stress, respectively. Here, $\alpha_1$ is the first positive root of $hL = \alpha_n L_a \tan(\alpha_n L_a)$ (n =1,2,…………). From the slope ($-\frac{D_p\alpha_1^2}{\varepsilon}$) of $\ln(C_r)$ versus time plot the gas diffusion coefficient can be calculated from estimated values of $\varepsilon$ and $\alpha_1$ for each gas diffusion test. In the case of a specimen having a high
gravimetric water content, a long testing time was required to measure gas diffusion coefficient accurately. However, the short-time data can be used to estimate the gas diffusion coefficient by considering several terms (up to sixth terms were used in this investigation) of equation (8) when \( n > 1 \) as documented by Rolston and Moldrup (2002). For several terms of equation (8) several positive roots of \( \alpha \) can be calculated as explained above (in case of first positive root) from the known value of \( \alpha_n L_n \) given by Carslaw and Jaeger (1959). Up to the sixth root of \( \alpha \) were used in this study to calculate gas diffusion coefficient at high gravimetric water contents (\( w > 70\% \)).

The boundary conditions for the UMS-G were similar to those for the conventional diffusion chamber method described by Currie (1960) and Rolston and Moldrup (2002). The bottom of the diffusion chamber (Figure 1) can be assumed to be the zero-gas flux condition and the gas diffusion between the atmosphere and the diffusion chamber occurs through the upper cylinder and 6 valves (10 mm in diameter) of the upper cylinder wall.

3.3.2.3. Measurement and calculation of gas permeability

To measure gas permeability \( (K) \), pressurized \( N_2 \) gas from a gas cylinder was injected into the diffusion chamber through a port. The differential pressure range of 0-10 kPa was used as the build-up of gas pressure under a landfill cover system is unlikely to be higher than 10 kPa (McBean et al. 1995). The injected gas passed through the GCL specimen and flowed out through only one outflow port where a flow meter was attached. The inlet pressure was observed by a pressure transducer installed in the diffusion chamber and the gas outflow was monitored by one of the five flow meters used to cover a range of gas flow rates. The extended Darcy’s law (equation (7)) was used to calculate the gas permeability of the GCL specimen.

3.3.2.4 Moisture content verification

After completing the sequential measurement of gas diffusion and permeability, the specimen was removed from the UMS-G for visual inspection of possible leakage spot (if any) (i.e. identification of dry spots) Final thickness, weight and gravimetric water content of the GCL specimen was also recorded for post-test analysis. Furthermore, the uniformity of gravimetric water content across the GCL specimens was verified on selected sacrificial specimens by
measuring gravimetric water content from at least four different locations and the average gravimetric water content was reported. The gravimetric water contents of all specimens (on at least four locations for each specimen) were measured on completion of the gas diffusion and permeability tests. A maximum variation of gravimetric water content of ±5% (from the average value) was deemed acceptable. Specimens having greater gravimetric water content variation were rejected from further analyses. A similar technique was used by Bouazza and Vangpaisal (2003) to verify the moisture distribution of their GCL specimens. It is also worth mentioning that GCL moisture losses were insignificant (<1%) during the tests, this was confirmed by conducting mass measurement of the GCL specimens before and after the tests. All the measurements were performed in a temperature-controlled laboratory (20±1°C) where density and viscosity of gas are considered to be constant.

3.3.2.5 Change in thickness

The displacement gauge installed above the top plate of the moveable steel rod (piston) measured the variation of GCL thickness during the sequential measurement of gas diffusion and permeability. The variation of GCL thickness with time under 2 and 20 kPa stress conditions is shown in Figure 4. It can be observed that the change in thickness under both stress conditions is negligible. This is probably due to the fact that the GCL specimens have previously been conditioned at the same stress levels during the hydration process. A specimen subjected to a low stress (2 kPa) was thicker than the specimen subjected to a higher stress (20 kPa) due to the ability of the GCL specimen to swell more under a low stress.

3.3.2.6 UMS-G Leakage and inflow-outflow check

Before starting the experiment, possible gas leakage from the diffusion chamber was checked by injecting \( N_2 \) gas to bring the \( O_2 \) concentration of the chamber to near zero. The increase of \( O_2 \) concentration in the closed diffusion chamber filled with 100% of \( N_2 \) gas was found to be less than 0.005% over a 24 hours period and thus was deemed to be leak free. The whole system was checked following the same process and less than 0.008% \( O_2 \) concentration increase was observed over 24 hours which indicates that top and middle cylinders were also leak free.
The gas inflow and outflow test of the empty UMS-G is essential to confirm that it will give reliable gas diffusion and permeability without any flow losses. The N\textsubscript{2} gas was injected in the diffusion chamber over a differential pressure ranging from 1 to 10 kPa and measured outflow at UMS-G outflow port was found to be practically the same (with negligible loss <0.1%) which indicated that almost no resistance to gas flow occurred in the equipment.

4. RESULTS AND DISCUSSION

4.1 Gas diffusion coefficient

The variation of O\textsubscript{2} concentration against elapsed time is shown in Figure 5a and 5b for two different gravimetric water contents (8% and 61%) and two different stress conditions (2 and 20 kPa), respectively. Figure 5a shows that O\textsubscript{2} concentration increased with time increase due to the flow of atmospheric O\textsubscript{2} from the upper cylinder to the diffusion chamber through the GCL specimen. It was also observed that O\textsubscript{2} concentration increased by more than 12% with the reduction of gravimetric water content from 61% \((D_{p}=7.0\times10^{-8} \text{ m}^{2}/\text{s})\) to 8% \((D_{p}=5.5\times10^{-7} \text{ m}^{2}/\text{s})\) under the same stress (20 kPa) condition. This increase of O\textsubscript{2} concentration at low gravimetric water content compared to higher gravimetric water content might be due to the fact that specimens at higher gravimetric water content (61%) have more interconnected pore spaces filled with water which allowed less O\textsubscript{2} to diffuse through the GCL. Figure 5b shows that O\textsubscript{2} concentration increased with time under both 2 kPa and 20 kPa stresses for similar gravimetric water content (~60%). The increase in O\textsubscript{2} concentration for the specimen under 2 kPa \((D_{p}=1.7\times10^{-7} \text{ m}^{2}/\text{s})\) was higher than for that under 20 kPa \((D_{p}=7.0\times10^{-8} \text{ m}^{2}/\text{s})\) due to the reduction of pore spaces and disruption of pore network at higher stress compared to lower stress.

Numerical simulations were also performed to validate the calculation schemes for determining the gas diffusion coefficient using the UMS-G. Transient diffusive O\textsubscript{2} gas transport was simulated based on the boundary conditions given for the UMS-G. The governing equation for diffusive gas transport (equation 2) was solved numerically by a finite element method using COMSOL Multiphysics version 4.3. The domain was divided into fine meshes with a total of 968 triangular elements (62 elements for the GCL and 906 elements for the diffusion
In addition, the Millington and Quirk (1961) tortuosity model was used to solve $O_2$ concentration numerically with time. $O_2$ concentration within the diffusion chamber at $t=0$ and the atmospheric $O_2$ concentration were used as the initial conditions for the diffusion chamber and the GCL specimen, respectively. The gas diffusion coefficient in air ($1.8 \times 10^{-5}$ m$^2$/s for $O_2$ at 20°C) was used as a gas diffusion coefficient in the diffusion chamber and gas diffusion coefficient calculated using equation (8) or (9) was used as gas diffusion coefficient in GCL specimen. The simulation was done with the same air filled porosity and thickness of GCL specimen used in the experiments. The air filled (effective) porosity was calculated based on the concept proposed by Petrov and Rowe (1997) and Rouf et al. (2014) which takes into account GCL thickness, mass per unit area of GCL and geotextiles, specific gravity of bentonite and geotextiles, and initial water content of GCL. The simulated $O_2$ concentration was found to be in good agreement with the experimental $O_2$ concentration as shown in Figures 5a and 5b. Therefore, calculation of gas diffusion coefficient using equation (9) or (10) was deemed to be valid.

The calculated (using equation 8 and 9) GCL gas diffusion coefficient ($D_p$) was plotted against GCL gravimetric water content in Figure 6 for 2 and 20 kPa applied stress. $D_p$ decreased with an increase in gravimetric water content under both stresses. At 2 kPa stress, the $D_p$ values decreased by four orders of magnitude when the gravimetric water content increased by about 140%. At 20 kPa stress, about 130% increase in gravimetric water content caused about four orders of magnitude reduction in gas diffusion coefficient. Up to 40% gravimetric water content, no marked difference in gas diffusion coefficient was observed for the conditions considered in this study. This is likely due to the fact that in this range (i.e., 8 to 40% gravimetric water content) there was insufficient moisture to reduce/block the air filled pore network of the specimen and hence to reduce gas diffusion. However, at higher gravimetric water contents (>40%) a notable reduction in gas diffusion values was observed. Up to 60% gravimetric water content, the difference in gas diffusion values under 2 and 20 kPa applied stress was small, indicating negligible effect of stress in this range. Norrish (1954) indicated that at gravimetric water content <60%, the swelling of bentonite is negligible. Due to insignificant bentonite swelling behaviour the change in pore structure of GCL specimens investigated under 2 and 20 kPa stresses is negligible as a result gas diffusion was not affected by stress. Beyond this range,
the reduction in gas diffusion coefficient with gravimetric moisture content was greater under 20 kPa than 2 kPa stress. This reduction is considered to be due to a much greater reduction of pore space and disruption of the air filled pore networks caused by the higher 20 kPa stress compared to a lower 2 kPa stress condition. Thus, for this GCL, the effect of stress is insignificant up to 60% gravimetric water content (i.e., for a low degree of saturation as discussed below) but beyond this range gas diffusion coefficient was slightly affected by the increase in vertical stress.

Bouazza and Rahman (2007) gas diffusion coefficient data for GCL-1 under free swell condition (0 kPa) were also included in Figure 6 for comparative purposes. GCL-1 is similar to the GCL used in the present investigation but had a much lower bentonite mass unit area (3.1 to 3.8 kg/m²) compared to the current GCL (4.0-5.4 kg/m²). The variation of the diffusion coefficient versus gravimetric water content is similar for both GCLs. However GCL-1 has slightly higher diffusion coefficient due to its lower bentonite mass unit area. From Figure 6 it can also be observed that the gas diffusion coefficient variation between 2 and 20 kPa stress conditions is less than 12% at high GCL gravimetric water content (>60%) conditions and negligible below it. Thus, one can deem that the variation of gas diffusion coefficient under 2 kPa and 0 kPa vertical stresses for similar material would be negligible.

Calculation of volumetric water content or degree of saturation for GCL is a challenging task because of the composite nature of GCLs. Previously, an approach was developed by Petrov and Rowe (1997) to calculate bulk void ratio of GCLs. Lake and Rowe (2000) extended that approach to estimate the total porosity of bentonite. They took into account the measurement of GCL thickness, mass per unit area of GCL and geotextiles, specific gravity of bentonite and geotextiles and initial gravimetric water content of GCL. However, the thickness of GCL is difficult to measure accurately due to the presence of geotextiles overlapping the bentonite. Didier et al. (2000) also made an attempt to calculate the porosity of a GCL based on the assumption that all the pores within the geotextile were filled by bentonite, which may not be the actual case for GCLs under unsaturated conditions, even though the bentonite component of GCL can swell and partially fill the geotextile voids during hydration (Bannour et al. 2014). Presence of bentonite in geotextiles can also impact the calculation of bulk void ratio and porosity of GCL. Therefore, calculation of the volumetric water content or actual degree of saturation for GCL is a challenging task.
saturation for a GCL material is a subject for discussion. Due to the above mentioned difficulties, Rayhani et al. (2011), Anderson et al. (2012), Rouf et al. (2013), Singh and Bouazza (2013) and Rouf et al. (2014) used another approach to measure the degree of saturation of GCL specimens having similar mass per unit area based on the concept of apparent degree of saturation instead of the GCL degree of saturation. The apparent degree of saturation can give fairly good indication of GCL pore property variation for different water content. Limitation of this method is that if the mass per unit area of GCL varies substantially, the resulting variation of apparent degree of saturation may become unreliable. The apparent degree of saturation \( S_\text{r}^* = \frac{w}{w_{\text{ref}}} \) is defined as the gravimetric water content \( w \) of a GCL at a given time divided by the maximum gravimetric water content \( w_{\text{ref}} \) that the same GCL reached during hydration under the same applied stress conditions. The \( w_{\text{ref}} \) for the GCL under 2 kPa and 20 kPa stressed specimens were 234% and 203%, respectively (Figure 7a). Whereas, the \( w_{\text{ref}} \) of Bouazza and Rahman’s (2007) GCL-1 was 166% (from Vangpaisal, 2002, Figure 7b) which was not in true equilibrium indicating that the actual \( w_{\text{ref}} \) can be higher than what was reported. Figure 8 shows the variation in GCL gas diffusion coefficient \( D_p \) against the apparent degree of saturation for 2 and 20 kPa applied stress, as well as Bouazza and Rahman’s (2007) GCL-1 gas diffusion coefficient data under zero stress.

Figure 8 shows that \( D_p \) of the GCL used in the present study generally decreases with the increase of the apparent degree of saturation under 2 and 20 kPa stress. The gas diffusion coefficient did not decrease in the range up to 20% apparent degree of saturation (i.e. relatively dry conditions). Above this range, \( D_p \) reduced by four orders of magnitude when the apparent degree of saturation increased from 20% to 62% and 20% to 65% respectively for 2 and 20 kPa stress conditions. However, at a given apparent degree of saturation there was very little difference in the values of the diffusion coefficient under the two applied stresses (although the water content required for a given apparent degree of saturation is lower for the 20 kPa stress than the 2 kPa stress). Thus it appears that the apparent degree of saturation tend to affect the diffusion coefficient in this range of stresses as it is function of the reference water content \( w_{\text{ref}} \) at the given target vertical stress as shown above. Bouazza and Rahman’s (2007) GCL-1 gas diffusion coefficients under free swell conditions were higher compared to the current data at 2 kPa stress. There are a number of possible explanations for this difference. The presence of lower mass per
unit area of bentonite in Bouazza and Rahman’s (2007) GCL-1 can increase the gas diffusion due to presence of higher interconnected pores in bentonite compared to present study but such large deviation cannot be explained by material difference only. The observed difference in gas diffusion is most likely due to the use of a reference gravimetric water content ($w_{ref}$) in Bouazza and Rahman (2007) investigation which was not based on true equilibrium gravimetric water content as shown in Figure 7b. Consequently, the apparent degree of saturation for Bouazza and Rahman’s (2007) GCL-1 is much higher. Not surprisingly, Bouazza and Rahman’s (2007) GCL-1 under free swell condition showed higher gas diffusion compared to the present study at 2 kPa vertical stress. It can be inferred from this discussion that the variation of gas diffusion can be comparable if the equilibrium reference gravimetric water content for Bouazza and Rahman’s (2007) GCL-1 can be quantified. More importantly, the present work indicates that the newly developed gas measurement device (UMS-G) is capable of measuring gas diffusion reliably.

The GCL gas diffusion coefficient was also plotted against the bentonite degree of saturation ($S_r$) as shown in Figure 9 which included the Bouazza and Rahman (2007) gas diffusion data. Vangpaisal (2002) has shown that at moisture content range ≤ 100%, the degree of saturation of the bentonite component tended to be higher than that of the GCL as a composite material. At a higher range of moisture content (i.e ≥ 140%) the difference in the degree of saturation of the two materials tended to be lower and in some cases higher $S_r$ values recorded for GCLs were higher than for bentonite due to more water being present in the geotextile components.

Figure 9 shows that $D_p$ decreased by four orders of magnitude when the bentonite degree of saturation increased up to about 98% for both stress conditions considered in this investigation. Very little difference in gas diffusion coefficient values was observed between the two stress conditions. Furthermore, the data shown in Figure 9 compare well with the data reported by Bouazza and Rahman (2007). Additionally, two widely used predictive models [Collin (1987) and Rowe (2001)] for gas diffusion in soils were used in the present investigation (Figure 9).

Collin (1987) model accounts for gas diffusion in both the air and the liquid phase. The model is expressed by:
\[ D_p = \varepsilon D_a \left( \frac{\varepsilon^{2x+1}}{n^2} \right) + H \theta D_w \left( \frac{\theta^{2y+1}}{n^2} \right) \]

(10)

where \( D_a \) and \( D_w \) are the diffusion coefficients corresponding to air and water phases respectively, \( \theta \) is the volumetric water content, \( H \) is the Henry’s law constant and \( n \) is the total porosity of the bentonite. The values of \( x \) and \( y \) are obtained by solving the following two equations (Collin and Rasmusson 1988):

\[ \varepsilon^{2x} + (1-\varepsilon)^x = 1 \quad (11) \]

\[ \theta^{2y} + (1-\theta)^y = 1 \quad (12) \]

Typical values of \( x \) and \( y \) are within the range of 0.6 to 0.75 (Aubertin et al., 2000).

Rowe (2001) developed an empirical gas diffusion model for soils with respect to degree of saturation \( (S_r) \) and is expressed as follow:

\[ D_p = D_a \exp \left[ -A \exp \left( BS_r \right)^c \right] \]

(13)

where \( A, B \) and \( c \) are empirical parameters which can be obtained from the best fit relationship of gas diffusion coefficient and bentonite degree of saturation.

Both models are plotted in Figure 9 and were found to correlate well with the experimental data over the range of degree of saturation investigated in the present study. In case of Collin (1987) model \( x \) and \( y \) values were in the range of 0.6 to 0.75 similar to the range reported by Aubertin et al. (2000) and also Aachib et al. (2004). Rowe (2001) model parameters \( A, B \) and \( c \) were 1.85, 0.0165 and 1.1, respectively, which were similar to Bouazza and Rahman (2007) reported values (2.00, 0.016 and 1.1, respectively) for similar type of bentonite. Both models can be used to obtain an estimate of the gas diffusion coefficient through bentonite. Furthermore, the predictive models further validate the gas diffusion coefficient measured by the UMS-G.

4.2. Gas permeability

According to the Darcy’s law shown in equation (6), flow rate is not proportional to differential pressure \( \Delta P \) across the specimen but rather to the pressure squared \( (P_1^2 - P_2^2) \) in the context of gas
flow through porous media. In Figure 10, the variation of gas flow rate was plotted with respect to $P_1^2 - P_2^2$ at different gravimetric water contents and two different stress (2 and 20 kPa) conditions. The gas flow rate varied linearly with $P_1^2 - P_2^2$ for water contents and stress conditions showed herein. The estimated Reynolds number (Table 2) for both wet and dry, and at different stress conditions (2 and 20 kPa) gave values within the range given by Bear (1972) for laminar flow in porous media. Therefore, it was assumed that Darcy’s law is applicable as reported by Bouazza and Vangpaisal (2003) and Rouf et al. (2013). It was also observed from Figure 10 that higher gravimetric water content (61%) specimen gave about one to two orders of magnitude less gas flow rate compared to low gravimetric water content (8%) specimen at the same applied stress (20 kPa) condition due to the reduction of pore spaces at high gravimetric water content condition. Additionally, it was also observed that the specimen under 20 kPa gave about one order of magnitude less gas flow rate compared to the specimen under 2 kPa at similar gravimetric water content (~60%) condition. This reduction of flow rate at higher stress condition might be due to the decrease of pore voids and reduction of pore network by compression caused by the higher stress.

The gas permeability measured by the UMS-G against GCL gravimetric water content under 2 kPa and 20 kPa stress conditions is reported in Fig. 11a and 11b, respectively. Additionally, gas permeability measured using the conventional set-up described in Bouazza and Vangpaisal (2003) is included in both figures for comparative purpose.

Figure 11a shows that gas permeability decreased with the increase of gravimetric water content for 2 kPa stress condition. It can also be observed that UMS-G gas permeability remained constant up to about 60% gravimetric water content and then decreased by six orders of magnitude due to gravimetric water content increase of about 85% (from 60% to 145%). It can also be observed from Fig. 11a that the UMS-G measurements agree well with the data obtained with the conventional measurement device used by Bouazza and Vangpaisal (2003). The gas permeability under 20 kPa stress condition against gravimetric water content (Fig. 11b) also showed similar decreasing behaviour. Under 20 kPa stress condition, UMS-G measured gas permeability remained practically the same up to 60% of gravimetric water content and then reduced from $1.17 \times 10^{-7}$ m/s to $8.00 \times 10^{-13}$ m/s when gravimetric water content increased from
60% to 134%. It can be concluded that the UMS-G measured gas permeability compares well with the conventionally measured gas permeability under 20 kPa stress condition (Fig. 11b).

The measured gas permeability was plotted against GCL gravimetric water content (Fig. 12a) and GCL apparent degree of saturation (Fig. 12b) for both 2 kPa and 20 kPa stresses. Figure 12a shows that there is no marked difference in the gas permeability under two different (2 and 20 kPa) stress conditions for gravimetric water content \( \leq 60\% \) indicating that the stress effect is negligible at least in the range of stresses investigated in this study. This is probably due to the insufficient swelling of the bentonite component experienced in this range of gravimetric moisture content. Consequently, this condition resulted in its inability to reduce the pore network at higher (20 kPa) stress compared to lower (2 kPa) stress investigated in this study. However, at higher gravimetric water content (>60%), a noticeable difference in gas permeability values was observed. The gas permeability reduced from 1.17×10\(^{-7}\) to 8×10\(^{-13}\) m/s when water content increased from 60% to 145% at 2 kPa and 60% to 134% at 20 kPa stress, respectively, indicating one to three orders of magnitude reduction in gas permeability for specimens hydrated and tested under 20 kPa compared to specimens under 2 kPa (Fig. 12a). This reduction is considered to be due to a much greater reduction of pore space and disruption of the air filled pore networks at higher stress compared to low stress specimens. These results, for the stress levels considered in this investigation, imply that for this GCL the effect of stress is insignificant up to 60% gravimetric water content; beyond this range gas permeability was affected by stresses. However, gas permeability in terms of apparent degree of saturation did not show much difference under two stress conditions (Fig. 12b) considered in this study similar to gas diffusion coefficient (Fig. 8).

5. CONCLUSION
A gas flow unified measurement system (UMS-G) was developed to measure sequentially gas diffusion and gas permeability of the same GCL specimen under applied stress conditions. The measurements made with the UMS-G were found to compare very well with measurements made with conventional gas permeability and gas diffusion results reported from literature on similar GCLs. The UMS-G removes the need to rely on two separate systems and increases further the reliability of the gas properties measurements.
The gas diffusion and gas permeability remained constant up to 40% and 60% gravimetric water content (20% and 25% apparent degree of saturation) respectively under both stress (2 and 20 kPa) conditions. Beyond this range, both the gas diffusion coefficient and gas permeability reduced greatly with the increase of both gravimetric water content and apparent degree of saturation. Additionally, it was found that up to 60% of gravimetric water content the effect of stress on both gas diffusion and gas permeability was insignificant due to insufficient swelling of bentonite while above this range, both parameters were greatly affected by applied stress considered in this investigation. These findings suggest that at a nominal overburden stress of 20 kPa, this GCL needs to be hydrated to 134% gravimetric water content (65% apparent degree of saturation) before gas diffusion and the gas permeability dropped to $5.5 \times 10^{-11}$ m$^2$/s and $8.0 \times 10^{-13}$ m/s respectively and to an even higher gravimetric water content (apparent degree of saturation) at lower stress. The results highlight the need for the adjacent layers to have a sufficiently high gravimetric water content to hydrate GCL to at least these levels before coming in contact with gas either in landfill or mine tailings application and that there is enough cover above the GCL to prevent it from subsequently drying to lower this level of hydration.

ACKNOWLEDGEMENT

This study was supported under the Australian Research Council’s Discovery funding scheme (project number DP110104078). Our sincere appreciation is extended to the council. The anonymous reviewers made many constructive comments and valuable suggestions. These comments and efforts associated with the review are greatly appreciated by the authors.

REFERENCES


List of Tables and Figures

Tables

Table 1. Characteristics of GCL used in this study

Table 2. Estimated Reynolds number for used GCL
Figures

Figure 1. Schematic design of the experimental setup for the gas flow unified measurement system (UMS-G)
Figure 2. Histogram of GCL mass per unit area

Figure 3. Variation of logarithm of relative oxygen concentration versus elapsed time for (a) two different gravimetric water contents (8% and 61%) and (b) two different (2 and 20 kPa) stress conditions

Figure 4. GCL thickness against time

Figure 5. Oxygen concentration versus elapsed time as percentage of air saturation for (a) two different gravimetric water contents (8% and 61%) and (b) two different (2 and 20 kPa) stress conditions

Figure 6. Variation of gas diffusion coefficient against gravimetric water content under 2 and 20 kPa stress condition

Figure 7. Reference gravimetric water content for (a) this study GCL at 2 kPa and 20 kPa stress, (b) Bouazza and Rahman (2007) investigation [collected from Vangpaisal (2002)] at 0 kPa stress

Figure 8. Gas diffusion coefficient with respect to GCL apparent degree of saturation

Figure 9. Gas diffusion coefficient versus bentonite degree of saturation

Figure 10. Variation of gas flow rate against $P_1 - P_2^2$ under 2 and 20 kPa stress conditions

Figure 11. UMS-G and conventionally measured gas permeability with respect to gravimetric water content under (a) 2 kPa stress and (b) 20 kPa stress condition

Figure 12. Gas permeability against (a) gravimetric water content and (b) apparent degree of saturation under 2 and 20 kPa stresses
Figure 1. Schematic of the experimental setup for the gas flow unified measurement system (UMS-G)
Figure 2. Histogram of GCL mass per unit area variation
Figure 3. Variation of logarithm of relative oxygen concentration versus elapsed time for (a) two different gravimetric water contents (8% and 61%) and (b) two different (2 and 20 kPa) stress conditions
Figure 4. GCL thickness against time
Figure 5. Oxygen concentration versus elapsed time as percentage of air saturation for (a) two different gravimetric water contents (8% and 61%) and (b) two different (2 and 20 kPa) stress conditions.
Figure 6. Variation of gas diffusion coefficient against gravimetric water content under 2 and 20 kPa stress condition
Figure 7. Reference gravimetric water content for (a) this study GCL at 2 kPa and 20 kPa stress, (b) Bouazza and Rahman (2007) investigation [collected from Vangpaisal (2002)] at 0 kPa stress
Figure 8. Gas diffusion coefficient with respect to apparent degree of saturation
Figure 9. Gas diffusion coefficient versus bentonite degree of saturation
Figure 10. Variation of gas flow rate against $P_1^2-P_2^2$ under 2 and 20 kPa stress conditions
Figure 11. UMS-G and conventionally measured gas permeability with respect to gravimetric water content under (a) 2 kPa stress and (b) 20 kPa stress condition.
Figure 12. Gas permeability against (a) gravimetric water content and (b) apparent degree of saturation under 2 and 20 kPa stresses.
Table 1. Characteristics of GCL used in this study

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite Type</td>
<td>Sodium/powdered</td>
</tr>
<tr>
<td>Bonding</td>
<td>Needle Punched and thermally treated</td>
</tr>
<tr>
<td>Upper Geotextile</td>
<td>Nonwoven</td>
</tr>
<tr>
<td>Lower Geotextile</td>
<td>Woven</td>
</tr>
<tr>
<td>GCL mass per unit area, $M_{GCL}$ (kg/m$^2$)</td>
<td>4.5-5.9</td>
</tr>
<tr>
<td>Bentonite mass per unit area, $M_{bent}$ (kg/m$^2$)</td>
<td>4.0-5.4</td>
</tr>
<tr>
<td>Upper geotextile mass per unit area, $M_{UG}$ (kg/m$^2$)</td>
<td>0.30</td>
</tr>
<tr>
<td>Lower geotextile mass per unit area, $M_{LG}$ (kg/m$^2$)</td>
<td>0.15</td>
</tr>
<tr>
<td>Thickness of upper geotextile, $H_{UG}$ (mm)</td>
<td>2.30-2.68</td>
</tr>
<tr>
<td>Thickness of lower geotextile, $H_{LG}$ (mm)</td>
<td>0.49-0.58</td>
</tr>
<tr>
<td>Thickness of as received GCL, $H_{GCL}$ (mm)</td>
<td>6.18-6.86</td>
</tr>
</tbody>
</table>

Table 2. Estimated Reynolds number

<table>
<thead>
<tr>
<th>GCL gravimetric water content (%)</th>
<th>Hydration &amp; Test stress (kPa)</th>
<th>Average grain size (m)</th>
<th>Gas flow rate ($m^3/s$)</th>
<th>Flow velocity (m/s)</th>
<th>Reynolds number</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>20</td>
<td>$5.09 \times 10^{-6}$</td>
<td>$1.12 \times 10^{-4}$</td>
<td>$1.43 \times 10^{-2}$</td>
<td>$4.82 \times 10^{-3}$</td>
</tr>
<tr>
<td>58</td>
<td>2</td>
<td>$5.09 \times 10^{-6}$</td>
<td>$7.10 \times 10^{-5}$</td>
<td>$9.04 \times 10^{-3}$</td>
<td>$3.01 \times 10^{-3}$</td>
</tr>
<tr>
<td>61</td>
<td>20</td>
<td>$5.09 \times 10^{-6}$</td>
<td>$1.73 \times 10^{-5}$</td>
<td>$2.20 \times 10^{-3}$</td>
<td>$7.32 \times 10^{-4}$</td>
</tr>
</tbody>
</table>