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Gas permeability of a needle punched geosynthetic clay liner subjected to wetting and drying

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ABSTRACT: Gas permeability tests of partially saturated needle punched GCL showed that the intrinsic gas permeability was very sensitive to the change of gravimetric moisture content and volumetric water content. For the conditions examined, it was found that the desiccated GCL tended to have higher intrinsic gas permeability than the hydrated GCL at a comparable gravimetric moisture content, as desiccation leads to shrinkage and the formation of desiccation cracks of the bentonite component. The results imply that hydrated GCL in cover system must be properly protected from desiccation, as there is strong possibility for gas to escape if the GCL starts to desiccate. Furthermore, the tests showed that the presence of overburden pressure during hydration could reduce intrinsic gas permeability of hydrated GCL indicating that the GCL should be subjected to confinement at time of installation or hydration.

1 INTRODUCTION

In recent years, there has been a growing interest in the use of geosynthetic clay liners (GCLs) as an alternative to soil barriers as part of waste containment cover systems. This application stems from the fact that GCLs were found to be very effective as hydraulic barriers, easy to install, and could withstand distortion and distress while maintaining their low hydraulic conductivity (Bouazza et al. 1996, LaGatta et al. 1997). Over the past decade GCLs, have been investigated intensively, especially in regard to their hydraulic and diffusion characteristics, chemical compatibility, and mechanical behaviour (Boardman & Daniel, 1996, Fox et al. 1998, Lake & Rowe 2000, Lin & Benson 2000, Mazzieri & Pasqualini 2000, Petrov et al. 1997, Shackelford et al. 2000). Although GCLs are usually installed to limit advection of fluids (e.g. water through a cover system) they may also serve another important role in covers as a gas barrier. With GCLs being increasingly used as part of the capping, their gas performance has come under a growing scrutiny. The recent work has shown that the manufacturing process and the form of bentonite (powdered or granular) have a significant effect on their gas permeability (Didier et al. 2000, Bouazza & Vangpaisal 2000, Vangpaisal & Bouazza 2001).

The ability of GCL to minimise gas flux is important particularly in landfill covers where it is likely to be partially saturated and, in some cases, be subjected to desiccation. This paper presents a series of gas permeability tests performed on needle punched geosynthetic clay liners (GCLs) subjected to partial hydration and drying.

2 MECHANISM OF GAS TRANSPORT

Gas migration through landfill cover may be driven by 1) a build up of gas pressure within the landfill; 2) a drop of atmospheric pressure below the pressure in the landfill; and 3) gas diffusion due to a difference of partial pressure of the gas of interest. This paper will consider the movement of gases in response to pressure gradient, or advective flow. Flow measurement performed by Alzaydi & Moore (1978) showed that Darcy's law can provide a fair approximation of gas flow in a low permeability material. Brusseau (1991) indicated that for low pressure differences (similar to the one encountered in landfills), gas compressibility can be neglected and therefore the incompressibility assumption is valid.

Based on Darcy's law, the one-dimensional mass flow (Q) of gas in porous media in [L^3T^{-1}] is given as follows:

$$Q = -\frac{k}{\mu} A \frac{dP}{dx} \tag{1}$$

where k is the intrinsic permeability of the porous material in [L^2], μ is the dynamic viscosity of the fluid in [$ML^{-1}T^{-1}$]. A is the cross sectional area of the porous material [L^2], and dP/dx is the pressure gradient ($ML^{-1}T^{-2}L^{-1}$). It is assumed that the intrinsic permeability is a function only of the properties of the porous material, not the permeating fluid or gas.

Considering the compressibility of gases, the rate of flow changes from one point to another point as the pressure decreases. However, it may be assumed that landfill gases behave like ideal gases and the continuity equation of ideal gas can be written as follows:

$$\frac{\rho_0 T_0}{P_0} = \frac{\rho T}{P} \tag{2}$$

where ρ_0 is the gas density at standard pressure P_0 and standard temperature T_0, and ρ is the gas density at pressure P and temperature T. Assuming that the rate of mass flow is constant, ρQ = constant, and the law of mass conservation is applied. In an isothermal condition, a steady state flow ($dM/dt = 0$) of gas in an isotropic homogeneous porous medium can be considered. The mass flow of gas through a porous media of length L, is obtained by integrating equation (1) subjected to the boundary conditions, $P = P_1$ at $x = 0$ and $P = P_2$ at $x = L$:

$$Q_2 = -\left(\frac{k}{\mu}\right) A \frac{(P_2^2 - P_1^2)}{2LP_2} \tag{3}$$

It is known that the application of Darcy's law is only valid in a restricted domain, i.e. when the flow is laminar. The Reynolds number (Re), a dimensionless number expressing the ratio of inertial to viscous forces, is generally used as a criterion to distinguish between laminar flow occurring at low velocities and turbulent flow. The flow rate at which the flow begins to deviate from Darcy's law behaviour is observed when the Reynolds number exceeds some value between 1 and 10 (Bear 1972). For flow through porous media the Reynolds number is defined as:

$$\mathrm{Re} = \frac{vd}{\nu} \tag{4}$$

where v is the Darcy velocity in[LT^{-1}], d designates an average grain diameter of the porous matrix in [L], and ν denotes the kinematic viscosity of the fluid in [L^2T^{-1}].

3 MATERIALS AND METHODS

3.1 *GCLs*

The basic characteristics of the GCL investigated in this study are presented in Table 1. The GCL consists of essentially dry powdered sodium bentonite sandwiched between non-woven polypropylene geotextile layers. The geotextiles are held together as a composite material by needle-punching. The cover and carriers geotextiles have reference mass per unit area of 0.27 kg/m^2 and 0.38 kg/m^2, respectively. M_{bent} is determined from the difference between mass per unit area of GCL and mass per unit area of geotextiles ($M_{bent} = M_{GCL} - M_{geo}$). H_{GCLdry} represents the thickness of the GCL at a dry state or as received conditions.

Table 1. Characteristics of GCL used in the present study.

GCL types	M_{GCL} (kg/m^2)	Mbent (kg/m^2)	H_{GCL}dry (mm)
Bentofix-X2000	3.8-4.5	3.1-3.8	7.8-8.7

Bentonite retrieved from the GCL was tested for basic properties (Table 2), which included swell index test, moisture adsorption test, and Atterberg limit tests. The bentonite swell index tests and the Atterberg limit tests were performed according to ASTM D 5890 and ASTM D 4318, respectively. The moisture absorption tests is based on the Enslin-Neff test as defined in DIN18132 Standard, which measures the weight of water absorbed by dry bentonite after 24 hours.

Table 2. Properties of bentonite component.

Parameters	Values
Swell index (mL/2g)	24
Moisture adsorption (%)	715
Liquid limit (%)	404
Plasticity index	355

3.2 *Sample preparation*

Two sets of GCL samples were prepared covering a range of moisture contents. The first set is to simulate the partial hydration or wetting of the GCL and the second set is to simulate the drying of the GCL. For the wetting condition, each GCL specimen (200 mm × 200 mm) was immersed in de-ionized water in an immersion tank. Once the process of immersion was completed, the GCL was stored in double resealable plastic bags for curing. A curing period of 7 to 10 days was considered sufficient to homogenize the moisture content of the bentonite. The specimen was cured following two methods. In the first method, the GCL was kept under a normal stress of 20 kPa by direct loading, to simulate the weight of 1 m cover soil in a landfill cover system. In the second method, the GCL was allowed to swell under zero confinement. This could represent the case when GCL is hydrated before the placement of a soil cover. After curing, the GCL specimen was carefully cut by a sharp knife and was installed in the permeability cell for testing.

For the drying condition, each GCL specimen was hydrated with de-ionized water in an immersion tank in a set up illustrated in Figure 1. The GCL was placed between two flat perforated steel plates supported with galvanized steel meshes, and subjected to a normal stress of 20 kPa. The perforated steel plates, supported by the galvanized steel meshes, provide the open area for moisture to evaporate from the GCL sample during desiccation. According to preliminary tests, the moisture content of the GCL should be in the range of 150-170% after 18 hours of immersion time in the water. After that the excess water was drained out, and the excess water on the GCL surfaces and the supporting plates was dried. The GCL samples were then left to desiccate in room temperature of 21±1°C with humidity ranging from 36% to 50%. Silicone sealant was applied along the periphery of the GCL specimens to prevent the loss of bentonite and to reduce desiccation along the periphery. The GCLs were kept under a normal stress of 20 kPa at all times. Each GCL sample was cut and tested at different final moisture content depending on the desiccation times, which ranged from 1 day up to 9 days.

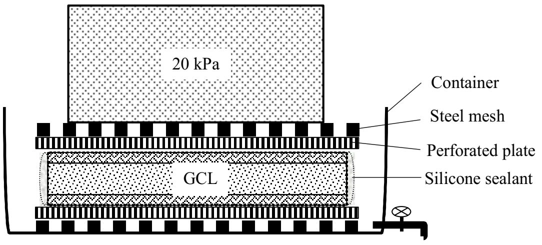


Figure 1. Set up for GCL desiccation.

3.3 *Gas permeability cell and test procedures*

The gas permeability cell (Fig. 2) consists of two separate parts: 1) a base cylinder, and 2) an upper cylinder with a piston. The two parts are held together with retaining threaded rods. A piston situated in the upper cylinder is used to transmit the applied confining stress to the GCL sample. The base cylinder has two different inside diameters, a diameter of 130 mm at the upper part and a diameter of 100 mm at the lower part, creating a shoulder on its wall, which is used to accommodate the GCL sample and the upper cylinder. A loading system allows the application of a normal stress of 20 kPa on the GCL.

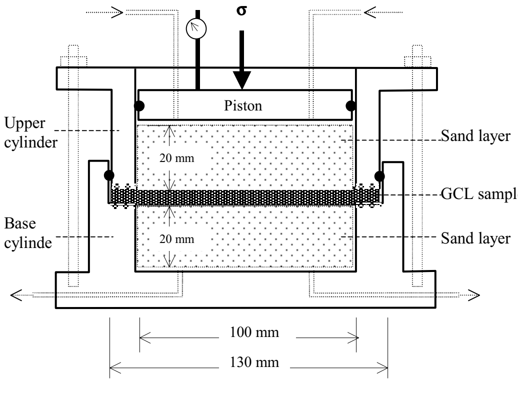


Figure 2. Cross section of gas permeability cell.

Pressurized nitrogen gas was used as permeate gas because it is relatively inert and has very low water solubility. This choice represents a conservative assumption for actual landfill conditions. A pressure regulator and a pressure gauge were installed in the supply line. Influent gas from the top of the cell permeated through the GCL specimen and outflowed at the base of the cell where gas flow meters, ranging from 0-10 mL/min up to 0-15

L/min, were connected to measure the different gas flow rates. This port was kept at the atmospheric pressure. The differential gas pressure was the difference between pressure supply and atmospheric pressure. A full description of the cell and testing procedures are given by (Bouazza & Vangpaisal 2002).

4 RESULTS AND DISCUSSION

GCL samples were tested covering ranges of moisture contents. The tests were conducted in a temperature-controlled room (21±1°C) where density and viscosity of gas are considered constant. Based on Equation 3, the intrinsic gas permeability of the GCL can be found from the following equation.

$$k = \frac{2Q_2 \mu L P_2}{A(P_1^2 - P_2^2)} \qquad (5)$$

The application of Darcy's equation to the case of gas flow through porous media shows that the flow rate is proportional to the square of differential gas pressure ($P^2_1 - P^2_2$). In the present case, the flow through the GCL sample is measured at the outlet port which is at an atmospheric pressure, therefore $P_2 = P_{atm}$. The linear relationship between gas flow rate and the square of differential gas pressure was used to calculate for the intrinsic gas permeability. The Reynolds number was also calculated for all flow measurement to ascertain the validity of Darcy's equation.

In most tests, the differential gas pressure during the test was designated to the range of 0.5 to 10 kPa. This is because the build up of gas pressure under the cover system in landfill sites is unlikely to be higher than 10 kPa depending on the features of landfill sites (Mcbean et al. 1995). However, some GCLs were tested at differential gas pressure as high as 40 kPa above the atmospheric pressure depending on the level of moisture content of the GCL to verify further the validity of Darcy's law.

The variations of intrinsic gas permeability versus volumetric water content for the tested GCL are presented in Figure 3. The results show that the decrease of intrinsic gas permeability is associated with the increase of volumetric water content. For the ranges of volumetric water content studied, a decrease of up to 6 orders of magnitude in the intrinsic permeability was obtained. It is also shown that the GCLs exposed to a surcharge during hydration tend to have lower intrinsic permeability than the GCLs hydrated under zero confinement, particularly at the medium to high volumetric water content (>50%). This can be attributed to the fact that the application of a confining stress limits the swelling of hydrated bentonite and induces a more uniform distribution of moisture content through the samples. As a result, pore size and the interconnected void in the bentonite component is likely to reduce, therefore, the lower intrinsic gas permeability. This implies that the GCL should be subjected to confinement at time of installation or hydration.

The variation of intrinsic gas permeability to gravimetric water content for the GCLs tested after hydration (wetting) and after desiccation (drying) is presented in Figure 4. The plain square symbol represents GCL samples hydrated to achieve a specific gravimetric moisture content, while open circle symbol represents GCL samples hydrated to a gravimetric moisture content of around 160% (i.e. a degree of saturation more than 80%) and then allowed to dry to given gravimetric moisture content. The results show that the intrinsic gas permeability decreases as the gravimetric moisture content increases. However, at the same level of gravimetric moisture content, the GCLs subjected to drying conditions have an intrinsic gas permeability of up to 2 orders of magnitude higher than the GCLs subjected to wetting.

Due to a very large moisture adsorption and swelling capacity of bentonite, the hydrated GCLs tend to have lower intrinsic gas permeability as more water is adsorbed and the interconnected pore spaces in the hydrated bentonite component are decreased. On the contrary, if the GCLs start to desiccate and lose the adsorbed water, the hydrated bentonite in the GCL starts to shrink, which leads to a formation of interconnected gas flow paths across the bentonite layer. As a result, the desiccated GCLs tend to have higher intrinsic gas permeability.

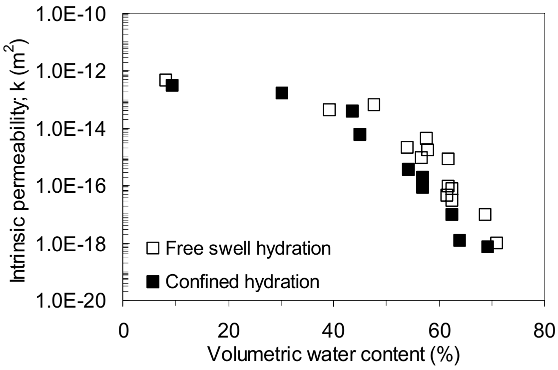


Figure 3. Variation of intrinsic gas permeability versus volumetric water content.

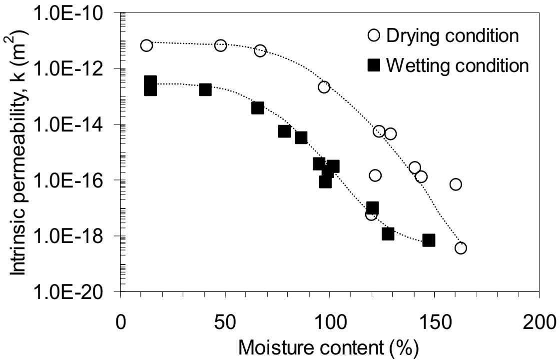
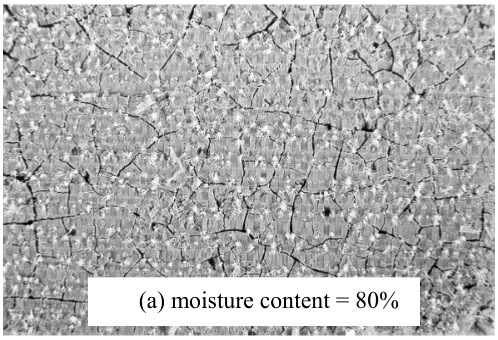


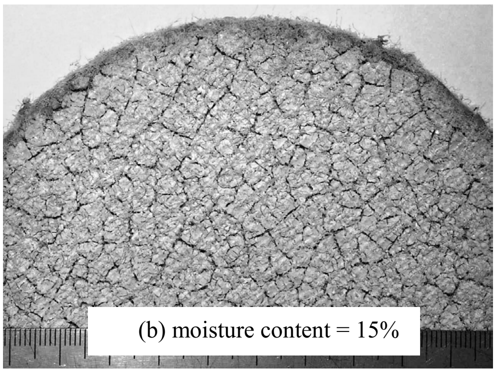
Figure 4. Variation of intrinsic gas permeability of GCLs under wetting and drying conditions.

As the desiccation continues (lowering in gravimetric moisture content), the desiccation cracks of the hydrated bentonite component may be formed as micro cracks, which leads to very high gas permeability. Visible desiccation cracks in the bentonite are observed at a gravimetric moisture content of around 80% (Fig. 5a). At the completely dry state, the intrinsic gas permeability of desiccated GCLs is around one and half orders of magnitude higher than the original GCL. This is because the nature of bentonite component after desiccation is clearly different from the original form (Fig. 5b). The desiccated bentonite is in large portions surrounded with cracks. The larger interconnected pore spaces provide very high gas permeability compared with the finer interconnected pore spaces in the dry powdered bentonite. The rate of increase in the intrinsic gas permeability is very low at gravimetric moisture contents lower than 80%, as the desiccation cracks are large enough to accommodate very high gas flow rate, rendering the increase in crack size insignificant.

It is also shown from Figure 5 that the desiccation cracks are distributed uniformly across the bentonite layer The presence of needle punched fibres, perhaps, helped the development of uniform desiccation cracks by providing restraints against shrinkage of bentonite as it dried out. In any case, it is possible that these desiccated cracks will close during rehydration. However, although it is established that the self healing capacity of sodium bentonite GCLs is high, experimental evidence published recently show this capacity can be impeded if the self healing process is coupled with ion exchange (Lin & Benson 2000, Mazzieri & Pasqualini 2000). This warrants further investigation in the context of gas permeability.



(a) moisture content = 80%



(b) moisture content = 15%

Figure 5. Desiccation cracks of GCLs at different moisture contents.

5 CONCLUSIONS

Gas permeability tests were performed on partially saturated needle punched GCL. The results showed that the intrinsic gas permeability was very sensitive to the change of moisture content and volumetric water content. The intrinsic gas permeability decreased as the moisture content and volumetric water content increased. Therefore, gas migration through GCLs by advective flow mechanism is unlikely to happen at a high degree of hydration.

For the conditions examined and at comparable gravimetric moisture contents, it was found that the desiccated GCL tended to have higher intrinsic gas permeability than the hydrated GCL. This is because desiccation leads to the shrinkage of bentonite component and possibly to the formation of desiccation cracks, which provide preferential gas flow paths. The results imply that the hydrated GCL in cover system must be properly protected from desiccation, as there is strong possibility for gas to escape if the GCL starts to desiccate.

Furthermore, the presence of the overburden pressure during hydration also contributes to the lowering of the intrinsic gas permeability of the hydrated GCL. This implies that the GCL should be subjected to a confinement pressure at the time of installation or hydration.

6 ACKNOWLEDGEMENT

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