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Laboratory investigation of gas leakage rate through a GM/GCL composite liner due to a circular defect in the geomembrane

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Abstract

The migration of gas through a geomembrane overlying a geosynthetic clay liner (GM/GCL composite) in a landfill cover occurs primarily through defects in the geomembrane. This paper presents the experimental results of an investigation on gas flow through a GM/GCL composite liner where the geomembrane contained a circular defect. It shows that the gas leakage rate is affected by differential gas pressure, moisture content of the GCL, contact conditions, and defect diameter. Moisture content of the GCL was found to be a significant parameter controlling the gas flow rate. This implies that the GCL in a GM/GCL composite should be kept hydrated to high moisture content in order to achieve an effective composite barrier to gas in case a defect occurs in the geomembrane. It is also shown that intimate contact between the geomembrane and the geotextile supported GCL is required to reduce gas leakage rate through a composite system.

Keywords: Defects; Gas flow; Geomembrane; GCL; Leakage

1. Introduction

Gas migration through landfill cover systems is mainly governed by the gas permeability and gas diffusion of the hydraulic barrier. With respect to hydraulic barriers such as geosynthetic clay liners (GCLs), the pores of the bentonite component must be nearly saturated to prevent gas migration during the lifetime of the cover system. This is a difficult task to fulfil since experience has shown that unsaturated flow is likely to prevail in landfill cover systems and that GCLs are likely to achieve only partial hydration conditions (Vangpaisal and Bouazza, 2004). Furthermore, recent studies indicated that dessication can occur due to seasonal changes in water content or if the GCL is subjected to prolonged heat (Henken-Mellies et al., 2002; Melchior, 2002). Although it is documented that the self healing capacity of sodium bentonite GCLs is high, experimental and field evidence shows that this capacity can be impaired if for example ion exchange takes place (Lin and Benson, 2000; Melchior, 2002). A measure frequently used is to install a geomembrane (GM) on top of the GCL to protect it from environmental distress and form in this way a composite barrier. The GM will also have another role under this configuration that is to serve as a barrier to gas migration since it is essentially impervious to gas flow when devoid of holes or defects. However, possible existence of defects in a GM needs to be considered, since it has been shown that defects in GM can occur even with carefully controlled manufacture and damages can be found even in sites where strict construction quality control (CQC) and construction quality assurance (CQA) programs have been put in place (Bouazza et al. 2002). These defects will obviously form preferential gas flow paths through the GM.

In addition to posing a safety and health risk, the migration of gases from landfills poses a potentially serious problem by creating vegetation stresses or diebacks and contamination of surface waters. Haskell and Cochrane (2001) reported on a case study where gas migration underneath a composite cover contributed to contamination

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of surface waters. The review of the cover design indicated that the low confining load acting on the GM limited the intimate contact of the GM with the underlying layer, allowing gas condensate to flow to the underside of the cover and migrate upward to the perimeter drainage ditch due to capillary forces. A forensic investigation conducted by Peggs and McLaren (2002) on vegetation diebacks observed at the surface of a landfill has shown that it was caused by gas leaks through punctures in the GM cover, as small as 2 mm, which were quite far from the location of maximum gas concentration above the cover soil. A 4 year study carried out in the UK on migration of landfill gas through mineral and GM liners has shown that despite the fact that every care has been taken in the installation of a GM, small gas leaks still occurred. It was concluded that it was unrealistic to assume that a GM will remain completely gas tight (Environment Agency, 2000).

The objectives of this paper are firstly to evaluate the migration of gas through a GM/GCL composite cover, where the GM had a circular defect and the GCL was partially hydrated and secondly to identify the main factors influencing gas leakage rate through such systems.

2. Gas transmissivity of a GM/GCL interface

The flow effectiveness of a composite barrier depends on the quality of the contact between the GM and the underlying liner. This has been highlighted in several studies on liquid flow conducted by Estornell and Daniel (1992), Rowe (1998), Rowe and Booker (2000), Touze-Foltz et al. (2001), Touze-Foltz (2002) and Cartaud et al. (2005a, b). Ideally, there is no interface flow if the GM and the underlying liner are in perfect contact. However, in the actual applications there always is some space at the interface between the two materials due to undulations occurring during the installation of the GCL, wrinkles in the GM, etc. There is a great potential for obtaining good contact between a GM and a GCL due to the fact that GCL can be placed flat on a well compact, smooth and firm foundation material (Giroud, 1997). The intimate contact can be achieved if the bentonite in the GCL is fully hydrated, swells and fills all of the pore spaces in the geotextile component. However, this depends on the geotextile type and structure and the confining stress acting on the composite liner. Furthermore, the fact that the GCL in a GM/GCL composite cover system is likely to be partially hydrated makes the so-called intimate contact condition not easy to achieve since the possible presence of a partially wet geotextile can provide potential lateral flow paths along the interface of the GM/GCL composite. Bouazza (2004) showed that geotextile gas transmissivity tended to increase as its moisture content decreased. In this respect, leakage through a defect in a GM overlying a partially saturated GCL layer depends necessarily on the contact between the GM and the underlying GCL (amongst other parameters) since it is the rational behind a composite barrier system. This makes the gas transmissivity of the GM/GCL interface an important parameter which needs to be quantified since it is dependent on the geotextile structure, the degree of intrusion of the bentonite into the voids of the geotextile of the GCL and the GM flatness. Bouazza and Vangpaisal (2004) performed recently gas transmissivity tests to evaluate the flow at the interface between the GM and the GCL of a GM/GCL composite cover. Their work has shown that the gas transmissivity of the interface between a GM and a partially hydrated GCL ranged between 2×10^{-7} and $4.5\times10^{-7}\,m^2/s$ under a 20 kPa surcharge and differential gas pressures varied up to 5 kPa. This corresponded to a reduction of approximately 40% in the gas transmissivity when the GCL moisture content increased from essentially dry to 120%. More importantly, it was also clearly observed that the hydrated bentonite had swollen and partially filled the voids of the cover geotextile but was not able to fill all of the geotextile void spaces; indicating the existence of a potentially transmissive zone for gas interface flow.

3. Materials and methods

3.1. Geosynthetic clay liners

The GCLs used in the present investigation consists of Bentofix®-x2000 and Gundseal® and are referred throughout the paper as GCL1 and GCL2, respectively. GCL1 consists of a minimum of $3.1\,kg/m^2$ of essentially dry powdered sodium bentonite sandwiched between a non-woven polypropylene geotextile cover layer and a composite carrier geotextile: a non-woven geotextile reinforced by a slit film woven geotextile in contact with bentonite. 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 and $0.38\,kg/m^2$, respectively. GCL1 initial thickness (as received from the manufacturer) averaged 8.25 mm and its average initial moisture content was 11% by dry weight. GCL2 consists of granular sodium bentonite, mixed with a water soluble non-toxic adhesive, adhered to a high density polyethylene GM 0.4 mm thick. The bentonite mat is protected by a thin layer of open weave spun-bound geotextile adhered to its surface. The typical mass per unit area of bentonite is $3.7\,kg/m^2$, GCL2 initial thickness (as received from the manufacturer) averaged 5.35 mm and its average initial moisture content was 17% by dry weight.

3.2. Sample preparation

GCL samples were prepared covering a range of moisture contents. This was achieved by immersing GCL specimens (200×200 mm) in de-ionized water for a specific time in an immersion tank, under a normal stress of 20 kPa. The immersion times were varied incrementally from 1 to 120 min to achieve a wide variation in moisture contents. Prior to immersion, the initial thickness, weight of GCL and moisture content of bentonite were determined. Once the process of immersion was completed, the GCL was stored in double resealable plastic bags for curing for a period of 7–10 days. The specimen was kept under a normal stress of 20 kPa by direct loading, to simulate the weight of a 1 m cover soil in a landfill cover system (the swelling kinetics are described in Vangpaisal and Bouazza, 2004). At the end of the curing period, the GCL was cut to a diameter of 128 mm and assembled in the gas permeability cell. The assembling procedure followed the procedures described by Bouazza and Vangpaisal (2003). A polypropylene GM, 1 mm thick, with a circular hole in the centre was placed on top of the GCL1 specimen to form a GM/GCL composite liner containing a defect in the GM, as shown in Fig. 1. The interface between the GM and the GCL was assumed to be flat and uniform. The diameters of defect in the GM varied from 3 to 8 mm.For GCL2, the defects were made directly on the GM component of the GCL.

3.3. Gas permeability cell and test procedures

The gas permeability cell was specially made to test thin shape GCL samples. The aluminium cell consisted of two separate parts: (1) a base cylinder, and (2) an upper cylinder with a piston. The two parts were held together with retaining threaded rods. A piston situated in the upper cylinder was used to transmit the applied confining stress to the GCL sample. The base cylinder had 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 was used to accommodate the GCL sample and the upper cylinder. A loading system allowed the application of a normal stress of 20 kPa on the GCL. Pressurized nitrogen gas was used as permeate gas because it is relatively inert and has very low water solubility. A pressure regulator and a pressure gauge were installed in the supply line. The gas inlet tube was connected to the base of the gas permeability cell and the gas outlet tube was connected to the piston of the cell. This allowed the gas to permeate through the GCL, before it went through the defect in the overlying GM, and flow out of the top of the cell where gas flow meters, ranging from $0–1.6 \times 10^{-7}$ to $0–2.5 \times 10^{-4}\,m^3/s$, were connected to cover the different gas flow rates. The outflow port was at atmospheric pressure. The differential gas pressure was the difference between the pressure supply and atmospheric pressure. A full description of the cell and testing procedures are given by Bouazza and Vangpaisal (2003) and Vangpaisal and Bouazza (2004).

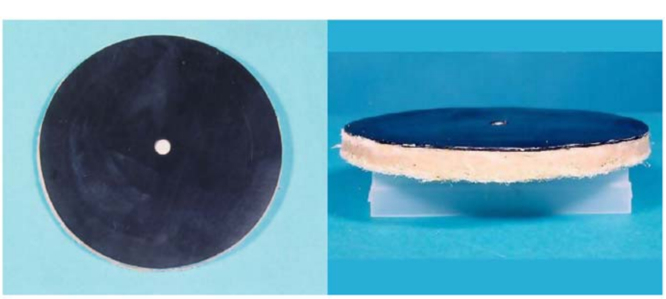

Fig. 1. Illustration of a GM/GCL1 composite containing a circular defect in the geomembrane.

4. Results and discussion

The tests of gas leakage rate through a GM/GCL composite were performed at ranges of moisture contents of GCL and defect sizes. A typical variation of gas leakage rate through a GM/GCL1 composite cap with an 8 mm circular hole in the GM is presented in Fig. 2. This figure clearly indicates that the leakage rate is governed by the moisture content of the GCL and points to the fact that the wetter the GCL, the more difficult is for the gas to migrate through the composite cap. It is also obvious that at higher moisture (>110%) the advective flow is approaching a so-called zero advective flow condition due to the reduction of pathways for gas to move through as more water is present in the air pore space available in the bentonite component of the GCL. The gas leakage rate was also found to increase as the differential gas pressure increased.

Fig. 3 shows the effect of defect size on the variation of gas leakage rate at a range of differential gas pressures over different moisture contents. It includes the case where a GM is used alone (note: the GM was sandwiched between two sand layers) and the case where a GCL at low moisture content (moisture content = 10%) is used under the GM to form a composite barrier (Fig. 3(a)). The effect of high moisture content on the leakage rate through a composite barrier is shown in Fig. 3(b).

The effect of defect size is quite clear on the GM used alone; the larger the defect, the larger the leakage rate. This suggests that the defect size is a factor controlling the gas

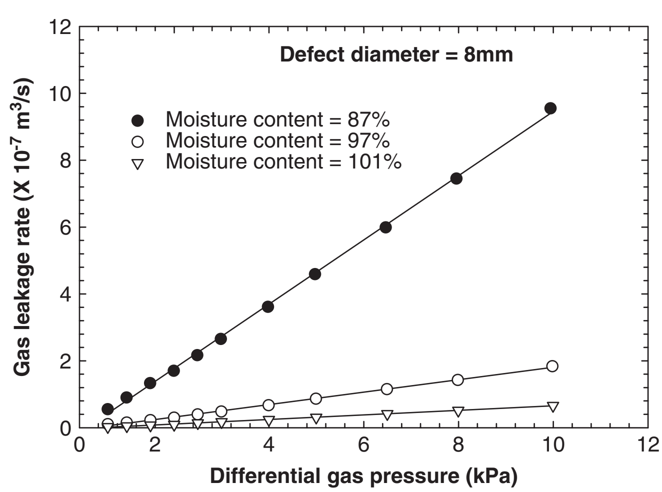

Fig. 2. Variation of gas leakage rate to differential gas pressure across the GM/GCL composite at a range of GCL moisture contents.

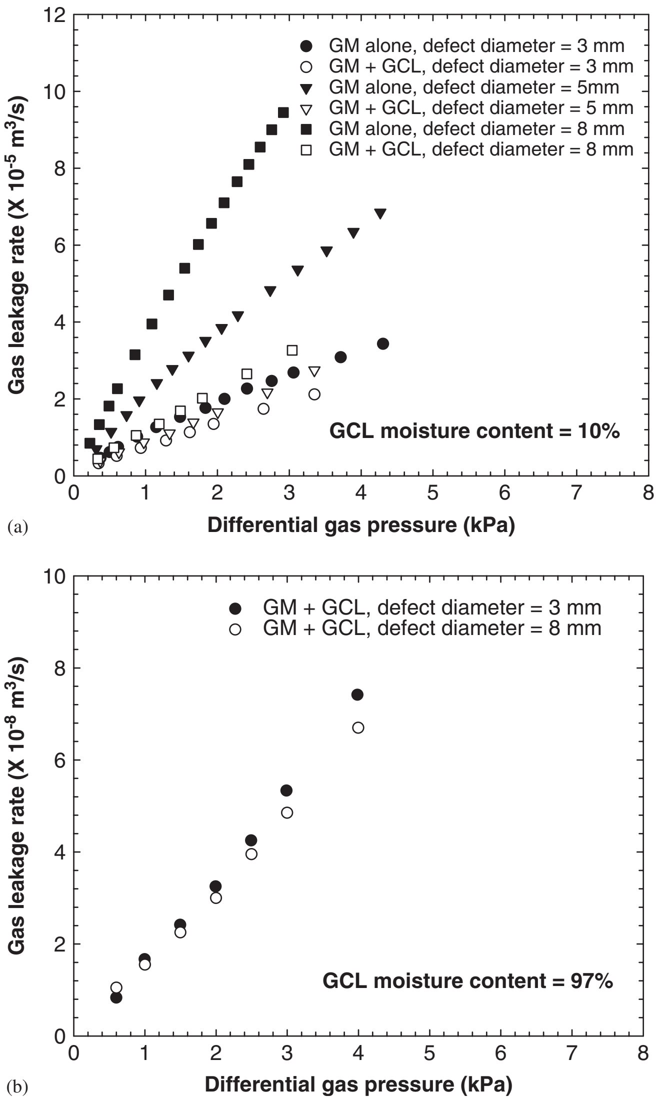

Fig. 3. Effect of defect sizes on gas leakage rates: (a) GM alone and GM-GCL with GCL at low moisture content and (b) GM-GCL with GCL at high moisture content.

leakage rate through a GM alone. The subsequent addition of a GCL, although dry, lowered the leakage rate. This indicates that the presence of a material less porous than sand, under the defect, can impact on the leakage rate. Furthermore, the results suggest that the geotextile components of the GCL might have acted as a barrier to flow. However, further investigation of this particular point is needed before a final conclusion can be made. The effect of size defects was still noticeable; mainly at differential pressures higher than 1 kPa. At pressures lower than 1 kPa, the effect of size defects was not significant. The gas leakage rate was found to be independent of defect size at higher moisture content (Fig. 3(b)). Obviously, the high moisture content of the GCL played a significant role in reducing the movement of gas. This aspect has been discussed thoroughly in Bouazza and Vangpaisal (2003) and Vangpaisal and Bouazza (2004). Interestingly, it was found that an increase in GCL moisture content from 10% (Fig. 3(a)) to 97% (Fig. 3(b)) resulted in at least 3 order of magnitude reduction in the gas leakage rate regardless of the defect sizes.

Fig. 4(a) shows typical variations of gas leakage rate at ranges of GCL moisture content at a given differential gas pressure ($\Delta P = 3\,\mathrm{kPa}$). As mentioned earlier, the gas leakage rate was found to significantly decrease as the moisture content increased. The leakage rate approached zero flow at moisture content higher than 100%. Therefore, it is important that the GCL remains hydrated and maintained at a high moisture content to ensure an effective gas barrier. It can be observed that, at a moisture content of approximately greater than 80%, the gas leakage rate is unlikely to be affected only by the defect sizes. The gas leakage rate is also controlled by the contact conditions between the GM and the GCL and probably also by the GCL properties (i.e., mass unit area of bentonite, spatial variability of moisture content through the specimens). This is evidenced in Fig. 4(b) where the gas leakage rate through a larger defect was not necessarily

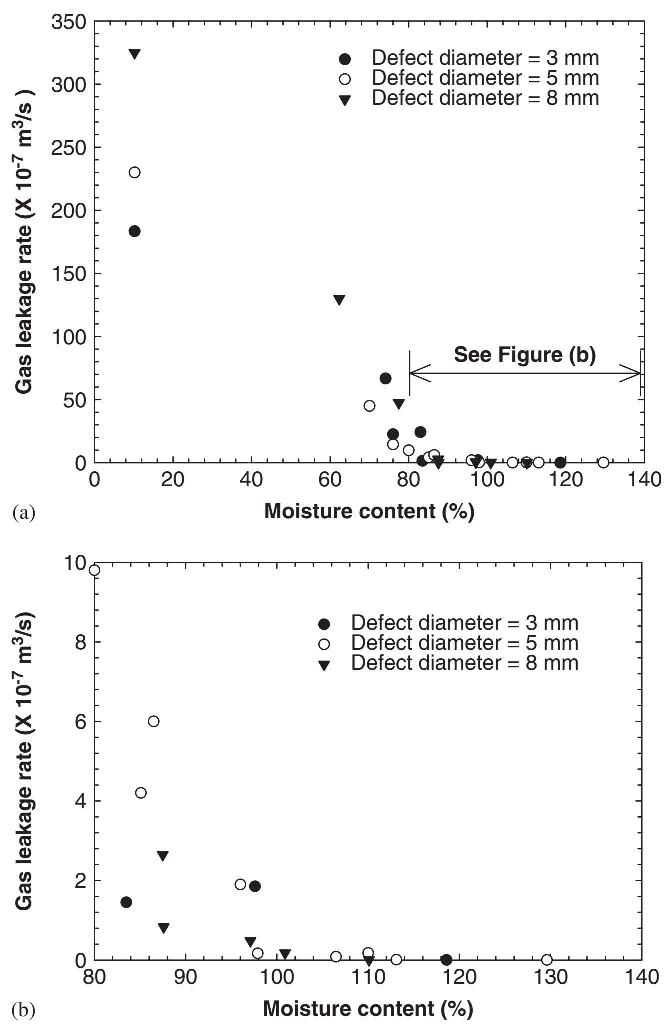

Fig. 4. Variation of gas leakage rate to a range of GCL moisture contents at a differential gas pressure of 3 kPa.

higher than that through a smaller defect. In addition, gas leakage rates tended to vary from one specimen to another, even for comparable test specimens (the same size of defect in a GM and the same moisture content of GCL); the smallest variation was achieved at moisture content higher than 120%.

In order to assess the effect of contact conditions on the gas leakage rate of a GM/GCL composite, two sets of partially hydrated GCL with different geotextile contact surfaces were tested. The first set was a GCL1 with the non-woven geotextile (NW-GT) cover in contact with a GM containing a defect. The second set was a GCL1 with the slit film woven geotextile (SW-GT) in contact with a GM. This represented a better contact between the GCL and the GM, as there are less void spaces in the slit film woven geotextile than in the non-woven geotextile. The GCL1 with the slit film woven geotextile can be obtained by removing the non-woven geotextile from the carrier layer and leaving the slit film woven to be in direct contact with the GM.

Fig. 5 shows the rate of gas leakage through a GM/GCL composite for different contact conditions. It can be seen that the gas leakage rate through the GM/GCL composite with the SW-GT contact is significantly lower than that of the NW-GT contact. This confirms that the gas leakage rate is largely dependent on the contact conditions between the GM and the GCL. An intimate contact interface, as in the case of SW-GT contact, resulted in the reduction of the effective flow paths, hence, the reduction of the total gas leakage rate.

In order to confirm the effect of contact conditions on the gas leakage rate of a GM/GCL composite, a number of tests were performed on a GM-supported GCL (GCL2). A circular defect of 5 mm in diameter was made in the GM component to simulate a defect in the GM/bentonite composite cover. The variations of gas leakage rate against moisture content for GCL1 and GCL2 are presented in Fig. 6. As expected, the gas leakage rate of GCL2 was lower than that of GCL1. At dry condition, the exceptionally high gas leakage rate of GCL2 was caused by the fact that the bentonite was in dry granular form. The granular bentonite had larger interconnected voids than that of the powdered bentonite in GCL1. Once the bentonite component started to hydrate, the interconnected voids were closed, and the gas leakage rate decreased significantly. Furthermore, it is also possible that the geotextile components of GCL1 acted as barrier to the flow and resulted on lower gas flow at low moisture contents for GCL1.

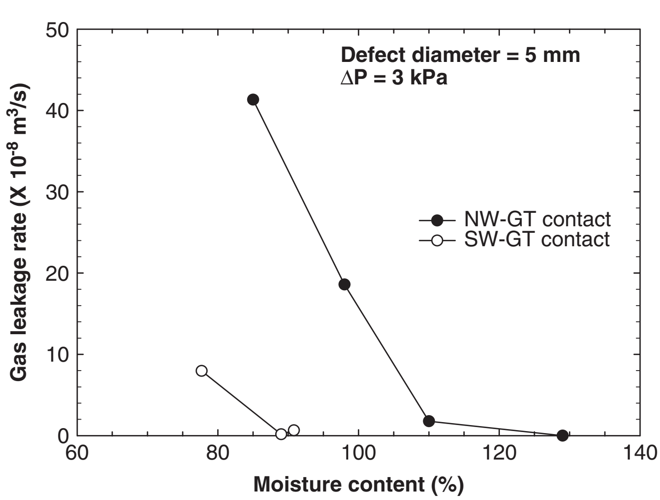

Fig. 5. Effect of the contact conditions between the geomembrane and the GCL on gas leakage rate (NW-GT = non-woven geotextile, SW-GT = slit film woven geotextile).

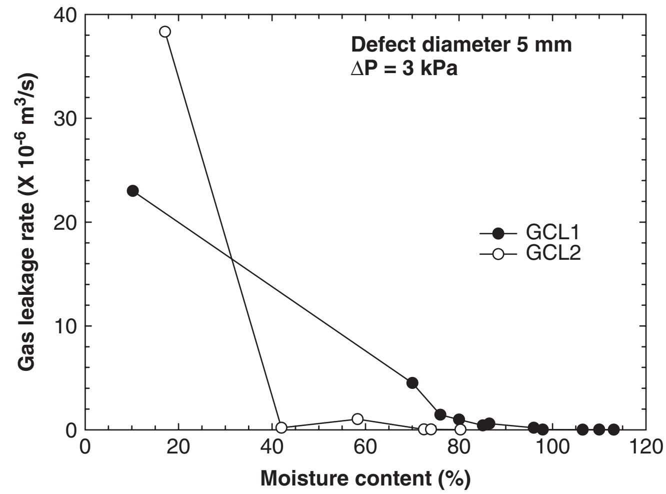

Fig. 6. Effect of the types of GCL on gas leakage rate; GCL1 is a needle punched type (NW-GT facing the geomembrane), and GCL2 is a bentonite/geomembrane composite.

It can be assumed that the intimate contact between the GM and the bentonite in GCL2 is perfect, and there is no transmissive zone in the interface. Therefore, the predominant flow component through a defect in GCL2 is the flow of gas through the bentonite directly under the defect area and the area close to the defect. It is clear that the gas leakage rate is very low compared to the GM/GCL1 composite even at moisture content as low as 40%. This is because the effective area of flow through GCL2 is considerably reduced to the approximate size of the defect. In this respect, the partially hydrated GCL2 can be considered as an effective composite cover to mitigate gas flow.

5. Conclusions

Gas leakage rate tests were performed on a GM/GCL composite, where the GCL was partially hydrated and the GM contained a circular defect. The gas leakage rate through a GM/GCL composite was affected by differential gas pressure across the GM/GCL composite, the moisture content of GCL, contact conditions, and defect diameter. It was found that gas leakage rate increased as the differential gas pressure increased, and decreased as GCL moisture content increased. At a low GCL moisture content, where very high gas flow rate was attained, the diameter of the defect was an important parameter in controlling gas flow. However, at a high GCL moisture content, where low gas flow rate was attained, the moisture content of the GCL became a significant parameter controlling the gas flow rate. This implies that the GCL in a GM/GCL composite should be kept hydrated to high moisture content in order to achieve an effective composite barrier to gas.

Apart from the moisture content of the GCL, the contact condition between the GM and the geotextile supported GCL is another important factor which needs to be considered. The experimental results confirmed that the transmissive zone at the interface between a GM and a partially hydrated GCL always existed for the GCL tested in the present investigation. Therefore, an intimate contact between the GM and the geotextile supported GCL, if achieved, can reduce further the effective flow paths in the transmissive zone. Finally, it appears that a GM supported GCL can also be an effective gas barrier because of the good intimate contact between the GM and the bentonite and the non-existence of a transmissive zone at the interface of these two materials.

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