FLOW RATE IN COMPOSITE LINERS INCLUDING GCLS AND BITUMINOUS GEOMEMBRANES

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ABSTRACT

Some studies were performed in the past years regarding the behavior of geosynthetic clay liners (GCLs) as part of a composite liner, focused on the situation where a GCL is located under a hole in a high density polyethylene (HDPE) geomembrane (GM). In this case, the contact between the geomembrane and the GCL was quantified in terms of flow rate through the composite liner and in terms of interface transmissivity. Various situations were tested in the past in order to evaluate the situation where a smooth GM is used in contact with the GCL. The situation where a textured geomembrane is used in contact with the GCL was also evaluated. More recently, the effect of the nature of the bentonite in the GCL, sodium or calcium bentonite, leading to different flow rates in the GCL was evaluated. In all cases an HDPE GM was used. This choice is linked to the fact that it is the most commonly GM used in composite liners including GCLs for chemical compatibility reasons. However one could imagine that the use of other GMs, like bituminous geomembranes (B-GMs) associated to a GCL, could be adapted for hydraulic applications. A quantification of flow rates was thus performed in laboratory tests at the decimetric scale for the case of a damaged B-GM located on top of a GCL. This corresponds to an alternative design for a canal projected in France at the moment. The effect of the side of the GM (polymeric film or sand layer for the bituminous geomembrane) in contact with a GCL containing calcium bentonite was evaluated. Results obtained are presented in this paper and compared depending on the GM side in contact with the GCL.

Keywords: Geosynthetics, composite liners, geosynthetic clay liner, bituminous geomembrane, flow rate

INTRODUCTION

Bituminous geomembranes (B-GMs) are used in many geotechnical and environmental protection applications and specifically for hydraulic, infrastructure and transportation fields such as water storage and transportation where B-GMs were used in lining drinking and navigation water canals (Domange 1983, Duquennoi et al. 1995, Etienne et al. 1995, Breul and Herment 1998, Potié 1999, Fagon et al. 1999, Flaquet-Lacoux et al. 2005), lining, reinforcement and protection of dams and reservoirs (Tisserand 1983, Alonso et al. 1990, Girard et al. 1996, Poulain el al. 1997, Breul and Herment 1997, Breul et al. 1998, Breul and Eldrige 2009) and also for retention ponds (Breul et al. 2006) and aquifer protection from environmental impact of roads (Coppinger et al. 2002). Apart from environmental applications, B-GM were also used as components of the liner in cover systems in landfills (Ossena et al. 1997, Potié et al. 1997, Faure and Itty 1999, Peggs 2008, Marchiol et al. 2006) mining (Breul et al. 2008), tunnels (Benchet et al. 2011), ditches (Imbert and Carcenac 1997), railways (Imbert et al. 1997), and road foundations (Breul and Herment 1995, 1997)

As presented by Breul et al. (2008), the structure of a B-GM is generally composed by (Fig. 1): (i) a non-woven polyester geotextile whose mass per unit area is 200 to 400 g/m², (ii) a glass fleece reinforcement which provides stability during fabrication and contributes to the strength of the GM, (iii) a bituminous mastic consisting of a blown 100/40 pen bitumen, and filler. This mastic impregnates the whole structure and gives the waterproofing of the product and ensures the longevity and the high resistance of the product, (iv) a Terphane film bonded to the underside when the membrane is hot, which prevents penetration of the geomembrane by plant roots, and (v) a coating of fine sand on the upper surface to provide a greater traction on slopes, giving greater operator safety and security, and to give protection from the degrading effects of UV radiation (Breul et al. 2008).

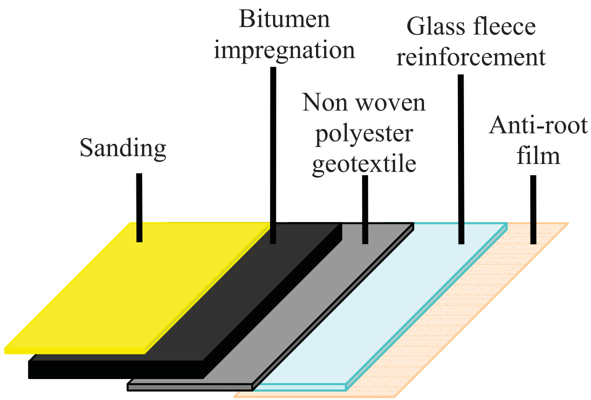

Fig. 1 Typical cross-section of a BGM (adapted from Breul et al. 2008)

On another hand, design engineers working on projects requiring the use of a GM in a composite liner with a geosynthetic clay liner (GCL) often limit their consideration of options to a high density polyethylene (HDPE) GM, perhaps on the basis of their experience with landfill design. Research performed on HDPE GMs and GCLs as parts of a composite liner focused on the situation where the GM is presenting a hole, aims to quantify the flow rate and the interface transmissivity between the GM and the upper geotextile of the GCL. The objective of this paper is to provide design engineers with elements to consider a broader range of GMs in their designs and to use a rational approach for GM selection for hydraulic applications.

In this paper, first, previous results on interface transmissivity measurements in composite liners composed by a HDPE GM and a GCL are presented. Second, materials tested and interface transmissivity measurement procedure is presented. Finally flow rates and interface transmissivity test results obtained on a composite liner made with a B-GM-GCL containing calcium bentonite are presented and discussed.

FLOW RATES AND INTERFACE TRANSMISSIVITY IN COMPOSITE LINERS WITH A GCL, INCLUDING A DAMAGED GM

The work performed in the past years regarding the behaviour of a composite liner containing a GCL and a punctured HDPE GM was focused on obtaining flow rates and interface transmissivities. The flow through a defect in the GM depends, as indicated by Brown et al. (1987), on the contact between the GM and the underlying soil liner. According to these authors, if the contact is not perfect, once fluid has migrated through the defect, it spreads laterally through the gap existing between the GM and the underlying soil, called interface. This interface flow covers an area called wetted area. Finally, the liquid migrates into and through the soil liner. The contact between the GM and the GCL was quantified in terms of flow rate through the composite liner and in terms of interface transmissivity.

Analytical Solution for Calculating Interface Transmissivity in a Composite Liner

To calculate the GM–GCL interface transmissivity θ, an analytical solution developed by Touze-Foltz et al. (1999) for the case of a circular defect in the GM was used. This analytical solution assumes that: (i) the interface transmissivity is uniform; (ii) the liquid flow in the transmissive layer is radial; (iii) the flow occurs under steady-state conditions; (iv) the compacted clay liner (CCL), the GCL and the GM–GCL interface are saturated; and (v) the additional flow through the passive barrier (CCL + GCL) is one-dimensional and vertical. The final flow rates (steady-state conditions) measured in the transmissivity tests were used in the calculations. It should be pointed out that the interface transmissivity calculated based on the analytical solution described above should be viewed as an apparent transmissivity, due to the fact that preferential flow paths occurred in the tests, as discussed above, which were not considered in the development of the analytical solution employed.

In a composite liner, a great fraction of the liquid that passes through the GM puncture flows along the GM–GCL interface, moving laterally to a certain distance from the GM puncture before infiltrating into the GCL and underlying layers. The contour of the region reached by the fluid defines the wetted area. Under the conditions of the tests performed in this work, the radius of the wetted area is the internal radius of the cell. Eqs 1 to 5 below apply to the boundary condition where the hydraulic head is equal to zero at a certain radius in the specimen, which in the present case is the cell radius:

$$Q = \pi r_0^2 k_s \frac{h_w + d_s}{H_s} - 2\pi r_0 \theta \alpha \left[A I_1(\alpha r_0) - B K_1(\alpha r_0) \right] \quad (1)$$

Where: Q is the flow rate under steady-state conditions; r_0 is the circular defect radius; k_s is the hydraulic conductivity of the liner GCL + (CCL); h_w is the hydraulic head; d_s is the thickness of the liner (GCL + CCL); H_s is the thickness of the soil component of the composite liner (GCL + CCL); θ is the interface transmissivity; I_1 and K_1 are modified Bessel functions of the first order; and α, A and B are parameters given by Eqs 2 to 5, as follows

$$\alpha = \sqrt{\frac{k_s}{\theta d_s}} \quad (2)$$

$$A = -\frac{h_w K_0(\alpha R) + H_s\left(K_0(\alpha R) - K_0(\alpha r_0)\right)}{K_0(\alpha r_0) I_0(\alpha R) - K_0(\alpha R) I_0(\alpha r_0)} \quad (3)$$

$$B = \frac{h_w K_0(\alpha R) + H_s(I_0(\alpha R) - I_0(\alpha r_0))}{K_0(\alpha r_0) I_0(\alpha R) - K_0(\alpha R) I_0(\alpha r_0)} \quad (4)$$

$$A I_1(\alpha R) + B K_1(\alpha R) - H_s = 0 \quad (5)$$

where K_0 and I_0 are modified Bessel functions of zero order and R is the radius of the wetted area.

It should be pointed out that the interface transmissivity calculated based on the analytical solution should be viewed as an apparent transmissivity, due to the fact that preferential flow paths can occur in the tests due to the application of the load through a granular layer having points of contact with the GM. The type of contact between the GM and the GCL, were not considered in the development of the analytical solution employed.

Previous Interface Transmissivity Studies Carried Out on Composite Liners Made with GCLs

Various situations were tested in the past in order to evaluate the effect of a smooth GM in contact with the GCL (Harpur et al. 1993, Barroso et al. 2006, 2010). Harpur et al. (1993) verified that under steady-state conditions, the most significant fraction of the flow takes place along the interface between the GM and the cover geotextile of the GCL, through the cover geotextile, and along gaps between the cover geotextile of the GCL and the bentonite. A less important amount of fluid percolates through the bentonite and below the GCL. Barroso et al. (2006, 2010) examined the influence of the hydraulic head, pre-hydration of the GCL and confining stress on the GM-GCL interface transmissivity. The results obtained by those authors showed that it is difficult to establish general trends expressing the influence of pre-hydration, confining stress and hydraulic head on the interface transmissivity. Nevertheless, it seems that, regarding the flow rate, it is important to take into account both the initial water content of the specimen and the confining stress (Barroso et al. 2006). The confining stress affects differently the flow rate, depending on the initial water content of the specimen. In fact, the flow rate in pre-hydrated GCLs is about one order of magnitude larger in tests under a confining stress of 50 kPa than in tests under 200 kPa. On the other hand, for non-pre-hydrated specimens, the flow rates are similar for the two confining stresses under steady-state flow conditions (Barroso et al. 2006).

The situation where a textured HDPE GM was used in contact with the GCL was also evaluated (Barroso et al. 2008). Results showed that tests were reproducible and that the texture had a small impact on flow rates obtained at steady-state, although, at the beginning of the tests, larger flow rates were obtained with smooth GMs than with textured ones. This suggests that, at the early phases of the tests, the water flows more easily at the interface when smooth GMs are used. The texture seems to reduce the space available at the interface for the water flow. However, with time, the sodium bentonite in the GCL swelled resulting in a better contact between the GM and the GCL.

More recently, the effect of the nature of the bentonite in the GCL, sodium or calcium bentonite, leading to different flow rates in the GCL was evaluated (Mendes et al. 2010). Those authors concluded that the nature of the bentonite and the manufacturing process of the GCLs studied did not affect the GM-GCL interface transmissivity when steady-state flow conditions were reached. They did also notice that for hole diameters in the range 4 to 10 mm the diameter of the hole in the GM did not significantly influence the flow rate through the GM-GCL composite liner: the expansion of the sodium bentonite was effective in blocking the puncture in the GM, yielding to a significant reduction on the flow rate. The results suggest that GCLs containing sodium bentonite, whose hydraulic conductivity increases due to cation exchange, can still maintain a good performance in a composite liner in terms of GM-GCL interface transmissivity and flow rate through the composite liner.

EXPERIMENTS

Materials Tested

A stitch bonded GCL containing calcium bentonite is tested in this study in contact with a B-GM. Both geotextile on the two faces of the GCL were woven. The mass per unit are of dry calcium bentonite in the GCL is 8.10 kg/m². The B-GM, according to the fabric presentation made in Table 1 exhibit two sides with different aspects: a polymeric film is located on one surface whereas a sand layer is encountered at the surface of the second side. These layers are different in terms of their roughness as the polymeric film face (Fig. 2) is smoother than the other one made with a sand impregnation (Fig. 3).

Table 1 Properties of B-GM

Composition			
Designation	Functionality	Unit	Values
Glass-mat	Reinforcement	g/m²	50
Non-woven geotextile	Reinforcement	g/m²	400
Oxidized bitumen	Binder	g/m²	7310
Sand	Surface finish	g/m²	217
Polyester antiriot film	Under surface finish	g/m²	15
Thickness (on finished product) EN 1849-1		mm	5.6

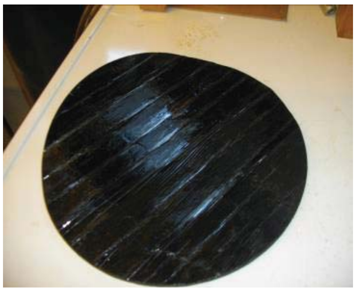

Fig. 2 Polymeric film side of B-GM

Fig. 3 Sand layer side of B-GM

Apparatus Description and Set Up

Transmissivity tests are carried out in an apparatus specially designed to measure the flow rate in a composite liner, as shown in Fig. 4. As previously described by Touze-Foltz (2002), Touze-Foltz et al. (2002), Cartaud and Touze-Foltz (2004) and Barroso et al. (2006), Barroso et al. (2008), Barroso et al. (2010), Mendes et al. (2010) it consists of a Plexiglas cell basically composed by four parts: (i) a bottom plate which supports the soil and applies the confining stress; (ii) a 200 mm inside diameter base cylinder, 80 mm high, to accommodate the CCL and the GCL specimen; (iii) a top coarse granular drainage layer; and (iv) an upper cylinder that accommodates the granular layer.

In the experimental setup, the B-GM, exhibiting a circular hole, is located on the GCL. To assemble the test, initially the base soil, simulating a CCL, is compacted in the bottom cylinder of the equipment with the upper side contacting a rigid metallic plate in order to ensure a smooth CCL surface underneath the GCL. The final thickness of the CCL is about 6 cm. The internal walls of the bottom cylinder are lubricated before soil compaction, in order to minimise friction between the CCL and these walls during the tests. Once the test cell is closed, the B-GM is ensuring the watertightness of the upper part of the cell. When the flow rate is important, it is noticed at the downstream side of the cell but when flow rate is not visible to the trained eye, readings are made at the upstream side of the cell.

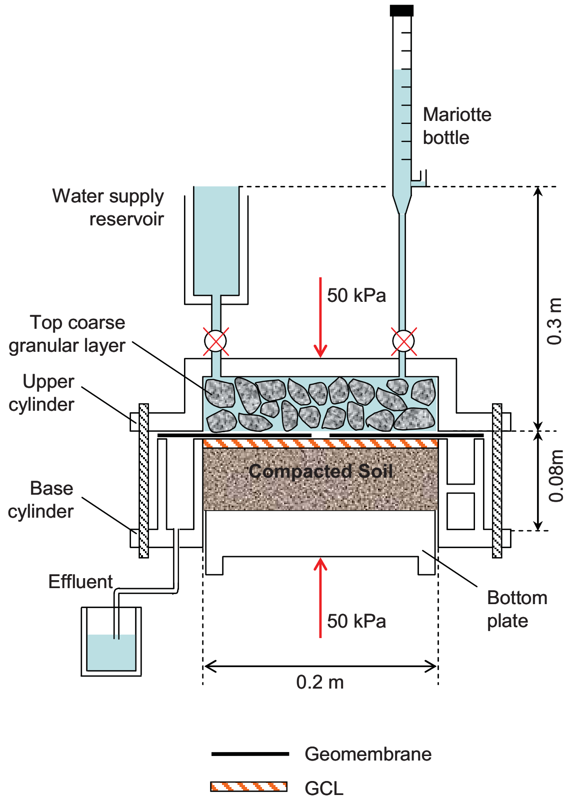

Fig. 4 Interface transmissivity test apparatus (Mendes et al., 2010)

In order to get comparable results between the various testing configurations presented in the literature and tests performed in this study, a 4mm diameter hole in the geomembrane is used, and a 50kPa load and a 0.3m hydraulic head applied. The CCL layer used is similar to the one from previous studied performed by Barroso et al. (2006, 2008) and Mendes et al. (2010) (see Table. 2).

Table 2 Properties of the base soil used (adapted from Barroso et al. 2006)

Percent fines (%)	Percent clay (%)	Atterberg limits ASTM D 4318		Proctor modified ASTM D 1557		K_{CCL} (m/s)
		ω_L (%)	ω_P (%)	ω_{OPT} (%)	γ_{dmax} (KN/m3)	
73.6	40.5	54.2	23.7	13.6	19.1	8 x 10^{-11}

K_{CCL}, hydraulic conductivity of the soil composing the CCL; PI, plasticity index; ω_L, liquid limit; ω_{OPT}, optimum moisture content; ω_P; plastic limit; γ_{dmax}, maximum dry density.

RESULTS

As can be noted, flow rate along the B-GM-GCL interface decreases gradually versus time during 300 hours for the two cases (rough face and smooth face in contact with the GCL) (Fig. 5). Afterwards the flow rate does no longer evolve. This corresponds to steady state.

Table 3 shows flow rates, hydraulic conductivities and interface transmissivities results obtained at steady-state. Hydraulic conductivities are obtained using results of previous tests carried out in oedopermeameter cells using NF P 84-705. Apparent interface transmissivities are calculated using the analytical solution proposed by Touze-Foltz et al. (1999) (Equation 1).
We conduct a comparison of flow rates obtained in composite liners according to the side in contact with the GCL. Results show that the smoother side in contact with the GCL gives rise to lower flow rates than for the rougher side in transient state (Fig. 5).

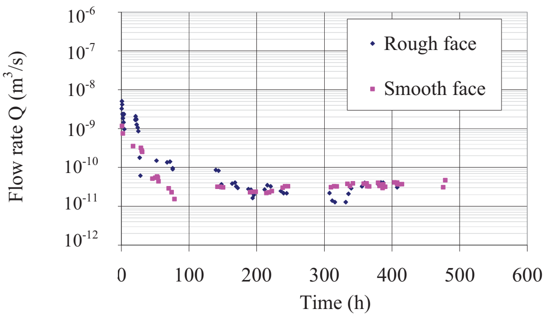

Fig. 5 Comparison between interface transmissivity results of the two faces of the B-GM

This could be explained by the fact that the rough side allows the storage of a larger quantity of water at the interface with the GCL, than the smooth side of the B-GM. B-GM-GCL contact may also present interface irregularities so water could have preferential flow paths between the B-GM and the GCL. Once pores are filled and the bentonite is swollen, results were not affected. So in the end of the test, flow rates are similar for both configurations at steady state. As shown, in Table 2, flow rate obtained are equal to 2.69×10^{-11} m^3 / s for the case of the rough side of the B-GM (sand impregnation) and 3.14×10^{-11} m^3 / s for the case of the smooth side of the B-GM (film side). It is thought that these minor differences can be associated to the difference on the contact quality between the two configurations at steady state, as water flows more easily at the interface when smoother GMs are used. This steady state results agrees with the one of tests carried out by Barroso et al. (2010) on smooth and textured GMs when flow rates values were about 1.1×10^{-11} m^3 / s when a smooth GM is used and between 7.6×10^{-12} m^3 / s and about 1.9×10^{-11} m^3 / s at steady state.

Table 3 Values of final interface transmissivity calculated by the analytical solution given by Eq. 1

Test	Q (m^3/s)	K_{GCL} (m/s)	R (m)	θ (m^2/s)
Rough side (sand side)	2.69 x 10^{-11}	6.9 x 10^{-10}	0.1	5.03 x 10^{-11}
Smooth side (film side)	3.14 x 10^{-11}	6.9 x 10^{-10}	0.1	5.96 x 10^{-11}

Q, flow rate; K_s, hydraulic conductivity at steady-state; R_c, radius of the wetted area; θ, interface transmissivity calculated by the analytical solution.

Figure 6 gives a synthesis of the various interface transmissivity data obtained from the literature and from this study. All data corresponding to the two configurations (rough side or smooth side of the B-GM in contact with the GCL) are located under the GM-GCL contact condition defined by Barroso and Touze-Foltz (2006) linking the interface transmissivity θ to the hydraulic conductivity k_{GCL} of the GCL according to Equation 6:

$$\log\theta = -2.2322 + 0.7155\log k_{GCL} \qquad (6)$$

This result shows the efficiency of this B-GM-GCL composite liner to reduce interface transmissivity and flow rates along the interface at level that are comparable to the ones obtained in the case of the use of a HDPE GM in composite liner.

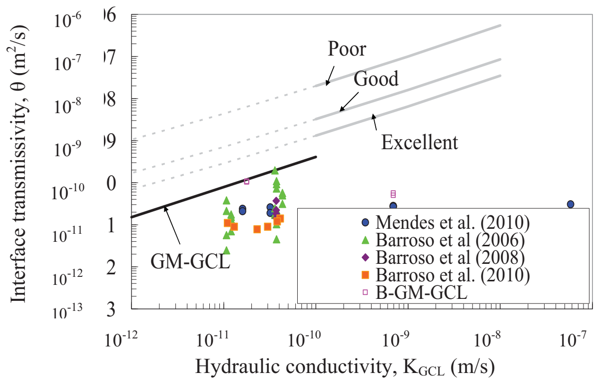

Fig. 6 Synthesis of transmissivity data obtained in the literature for GCLs in contact with HDPE GMs with introduction of results obtained with B-GM

CONCLUSIONS

The work performed in this study aims to quantify flow rate measurements throw composite liners defined by a defective B-GM presenting two sides (a rough side defined by a sanding and a smooth side made with a film) and a GCL. Tests are performed under a 50 kPa confining pressure and a 0.3m constant hydraulic head in an interface transmissivity test cell. The B-GM-GCL composite liner has shown a performance in term of flow rates and interface transmissivity comparable to the one obtained for HDPE GM-GCL composite liners. For the two cases, data are located under the GM-GCL contact condition. This provides information on the possibility from a hydraulic point of view to use B-GM in association with a GCL for hydraulic applications, where there is no question regarding chemical compatibility between the GM and the liquid to contain.

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