Geomembranes over GCLS: The optimal combination for barriers against contaminant transport

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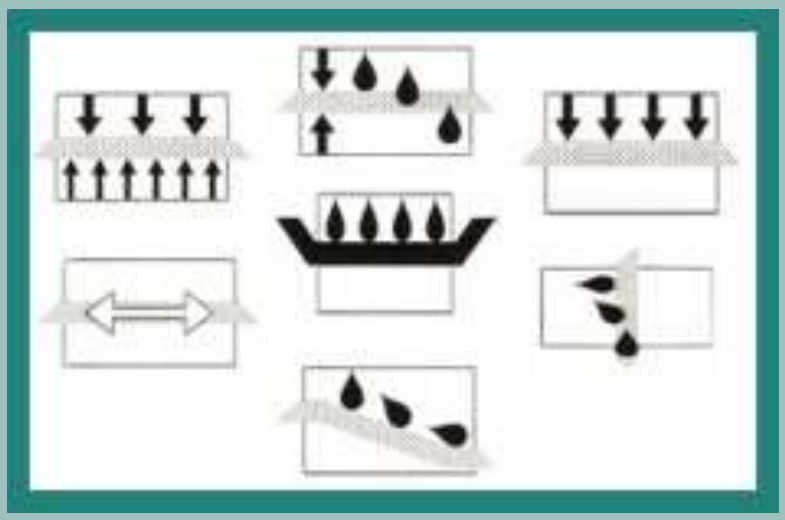

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GEOMEMBRANES OVER GCLS: THE OPTIMAL COMBINATION FOR BARRIERS AGAINST CONTAMINANT TRANSPORT

Nathalie TOUZE[1] **Hajer BANNOUR[2]**

ABSTRACT

The equivalence of composite liners involving a geomembrane (GMB) and a geosynthetic clay liner (GCL) to regulatory composite liners with a GMB and a compacted clay liner (CCL) can offer greater environmental protection to the underlying aquifer. It is suggested that GCLs and GMBs can play a very beneficial role in providing environmental protection even though GCLs are altered by their environment due to cation exchange and wet-dry cycles or there are defects in the GMB. The performance of GMB-GCL composite liners is accessed in terms of diffusion of contaminants and in terms of advective transfer due to the presence of defects in GMBs. Experimental, numerical and empirical quantification of advective transfers are examined through single GMBs and GCLs and are compared to GMB-CCL composite liners included in the case of aged GCLs.

1. INTRODUCTION

Regulatory agencies around the world have introduced geosynthetics in the design solution in certain applications, like in the waste management sector. Europe, South Africa, Australia and the United States to name a few provide exemplary cases for the incorporation of geosynthetics into environmental regulations to prevent or reduce as much as possible any negative impact from landfilling on surface water, groundwater, soil, air or human health. This is achieved by introducing stringent technical requirements. In Europe the Landfill Directive requires that the protection of soil, groundwater and surface water, be achieved by the combination of a compacted clay liner (CCL) of given thickness and hydraulic conductivity and a geomembrane. In France, in addition to the regulatory barrier prescribed by the European Directive, the CCL should be overlying an attenuation layer. as seen in Fig. 1a. In case no clay is available, some regulations allow the use of geosynthetic clay liners (GCLs) over a more or less permeable soil liner, provided that equivalence towards advective and diffusive transfers is demonstrated. In France, GCLs are used as a reinforcement of the CCL which thickness and performance cannot be reduced, in case the attenuation layer does not fulfil the requirements (Fig. 1b). GCLs have gained widespead acceptance thanks to their low permeability and better hydraulic performance than CCL in association with a GMB. Following, in the European context, GCLs are always associated to CCLs under the GMB of landfill bottom liners.

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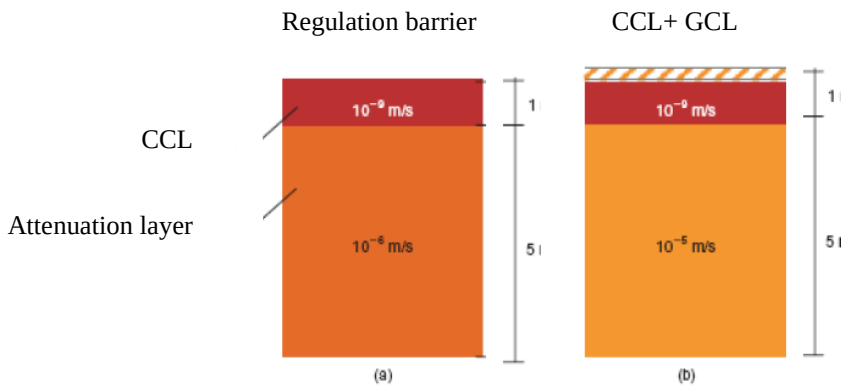


Figure 1. French recommendations for the use of GCLs in passive barrier (MEEDDAT, 2009)

In case no GCL is used, installers sometimes use a geotextile (GTX) at the CCL surface in order to prevent the GMB from puncturing by the CCL and to make the seaming process easier. The question then arises of the hydraulic performance of the different types of composite liners. Advective transfers take place in case the GMB is damaged (Cartaud et al., 2005; Barroso et al., 2006; Rowe &Abdellaty, 2012) and diffusive transfers take place through intact areas of the geomembrane (Rowe, 2007; Touze-Foltz et al. 2016; Rosin-Paumier et al. 2011; Mendes et al. 2013, 2014b).

The focus of this paper is to evidence the complementarity of GMBs and GCLs in composite lining systems based on recent findings. Thus, after briefly defining the materials, this paper adresses the hydraulic performance of GMBs, GCLs and GMB-GCLs composite liners. The important role of geotextiles and the structure of the GCL for limiting contaminant transport through these barriers againt advective and diffusive transport is discussed. The impact of the ageing of the GCL is also highlighted and an empirical equation for predicting advective flow rates through GMB-GCL composite liners taking into account the alteration by the environment of the GCL is also presented in the last section of this paper.

2. GEOMEMBRANES AND GEOSYNTHETIC CLAY LINERS

2.1 Barriers

The barrier function consists of preventing or limiting the migration of fluids. Geosynthetic barriers (GBRs) are geosynthetic materials that fulfill this function. A geosynthetic barrier is defined in EN ISO 10318 (AFNORa) as a low-permeability geosynthetic material used in geotechnical and civil engineering applications with the purpose of reducing or preventing the flow of fluid through the construction. GBRs fall into three categories according to the material that fulfills the barrier function: (i) clay geosynthetic barriers (GBR-C) whereby the barrier function is implemented by clays, (ii) bituminous geosynthetic barriers (GBR-B) whereby the barrier function is implemented by bitumen, and (iii) polymeric geosynthetic barriers (GBR-P) whereby the barrier function is implemented by a polymer.

2.2. Geomembranes

Other terminologies exist. The word "geomembrane" is often used to refer to GBR-Bs and GBR-Ps. A geomembrane is defined in the Recommended Descriptions of Geosynthetics Functions, Geosynthetics Terminology, Mathematical and Graphical Symbols of the IGS as a planar, relatively impermeable, polymeric sheet used in civil engineering applications. Various polymers are used to manufacture GMBs: high-density polyethylene (HDPE), flexible polypropylene (PP), linear low density polyethylene (LLDPE), plasticized polyvinyl chloride (PVC-P), ethylene propylene dieneterpolymer (EPDM), and even bitumen (Touze-Foltz, 2010). In addition, a number of additives (i.e., chemical compounds) are used in the manufacturing process to ensure the durability of the polymeric materials. The chemical and mechanical characteristics of Geosynthetics depend strongly on the type of polymer used, the additive formulation, the morphology, and the application of the geosynthetic (Hsuan et al. 2008).

2.3. Geosynthetic Clay Liners

The terminology geosynthetic clay liner (GCL) is used in parallel to the wording GBR-C. GCLs are defined in the IGS terminology as an assembled structure of geosynthetic materials and low hydraulic conductivity earth material (clay) in the form of a manufactured sheet used in civil engineering applications. Multicomponent GCLs are also available on the market. A multicomponent GCL is a GCL onto which is attached a film, coating, or membrane that decreases the hydraulic conductivity, protects the clay core, or both (von Maubeuge et al. 2011). Herein, the term geomembrane and the designation GCL are used.

2.4 Watertightness

Because the unique function of a GMB or a GCL is to act as a barrier, the only property to test should be the flow rate. The EN 14150 standard (AFNORb) is used in CE marking to quantify the flow rates of virgin GMBs during the manufacturing process. The principle of the test consists in applying a 100kPa water head difference between both sides of a flat GMB. Recently, the device from EN 14150 was also used to quantify the flow rates of exposed GMBs (up to 40 years after installation) of high density polyethylene (HDPE), ethylene-dieneterpolymer (EPDM), polyvinyl chloride (PVC) and bituminous geomembranes. Results obtained showed that most GMBs used are still exhibiting flow rates close to the one of virgin GMBs, so close to 10^{-6} $m^3/m^2/d$. An adaptation performed to quantify the flow rate through multicomponent GCLs has been also developed (Touze-Foltz, 2015).

To measure the flow rate through GCLs, a rigid-wall permeameter from NF P84-705 (AFNORc) is used in France. The value of the hydraulic conductivity, *k*, can be calculated using Darcy's law. Alternatively the Standard Test Method for Measurement of index flux through saturated GCLs specimens using a flexible wall permeameter (ASTM D5887 / D5887M) can also be used on saturated GCLs.

Table 1 gives the level of performance in terms of flow rates of various mineral and geosynthetic materials. In fact, GMBs are nonporous media so Darcy's law does not apply to them. The same rationale applies to multicomponent GCLs. Assigning a hydraulic conductivity to GMBs or multi-component GCLs is thus nonsense. The data presented in

Table 1 show that GMBs are significantly more impervious than other barrier materials. Multicomponent GCLs and GCLs also offer greater hydraulic performance than mineral materials.

Table 1. Properties and flow rates through various lining materials including GCLs and GMBs for an applied hydraulic head of 1 m for porous materials. The difference in pressure applied between both faces of the GMBs and multicomponent GCLs is 100 kPa (Touze-Foltz, 2018).

Material	Testing conditions	Hydraulic conductivity (ms^{-1})	Thickness (m)	Flow rate ($m^3\,m^{-2}\,d^{-1}$)
Cement concrete	In the field[a]	10^{-10} [a]	0.1	9.5×10^{-5}
Roller compacted concrete		10^{-8} [a]	0.5	2.6×10^{-3}
Asphaltic concrete	In the field with excellent construction and quality control[a]	10^{-9} [a]	0.1	9.5×10^{-4}
Asphaltic concrete	In the field with ordinary construction and quality control[a]	10^{-8} [a]	0.1	9.5×10^{-3}
Compacted clay liner	With excellent construction and quality control[a]	10^{-9} [a]	1	1.7×10^{-4}
Compacted clay liner	With ordinary construction andquality control[a]	10^{-8} [a]	1	1.7×10^{-3}
Geosynthetic clay liners	As manufactured, confined and hy- drated with low cation concentration so- lutions	10^{-11} [a]	0.01	8.7×10^{-5}
Multicomponent GCLs	As manufactured	Meaningless	0.01	$<2\times10^{-5}$ [b]
Geomembranes	As manufactured	Meaningless	0.001	$<10^{-6}$ [b]

[a] Giroud and Plusquellec 2017, [b] Touze-Foltz et al. 2016.

However, the benefits of using geosynthetic liners as part of a barrier system may not be fully realized if the GMB is physically damaged: GMBs form excellent barriers to fluids only if there are no holes in the GMB (Rowe 2017). GMBs may develop holes during installation, although most holes can be prevented by good quality control (Touze-Foltz et al. 2008, Rowe 2017). The objective of the following sections is to illustrate how GMB overlying a GCL are complementary materials against infiltration. This paper discusses the experimental quantification in the laboratory, using numerical modeling or using empirical calculations. The elementary transfer modes focused on herein are diffusion, which is the transfer of fluid due to different concentrations of a given contaminant on the two sides of a liner material, and advection, which is the transport of fluid due to a difference in hydraulic head between the two sides of a liner material. No attempt is made here to evaluate the combined effect of advection and diffusion.

2.5 Diffusion Properties

Diffusion is a process whereby contaminants (leachate in this case) migrate from locations of high concentration (e.g. a landfill, lagoon or contaminated groundwater) to a region of lower concentration (e.g. clean groundwater). It can occur in air, water, soil or even through solids such as GMBs or GCLs. In landfills, metals and metalloids are still recognized as priority pollutants as in contrast with most organic pollutants they do not degrade in landfills (Pinel-Raffaitin et al., 2006). Landfills also contain micropollutants with toxic effects (acute toxicity, genotoxicity, reproductive toxicity, etc.) (Sisinno et al.,2000; Takigami et al., 2002). The presence of organic contaminants in leachate from municipal solid-waste landfills has been clearly demonstrated in several countries (Oman and Hynning,1993; Ahel and Tepic, 2000; Robinson et al., 2001; Hiroshi et al.,2002).

2.5.1 Theory of diffusive transfer through geosynthetic clay liners

Rowe and Booker (1987) developed a model for predicting the one-dimensional transport of contaminants through soils of finite thickness which can be used to predict the one-dimensional transport of contaminants through a saturated GCL for a single reactive solute without degradation (Lake and Rowe, 2004; Rowe et al., 2005; Rosin-Paumier et al., 2011; Mendes et al., 2013, 2014a). The parameters accounted for in the model are the concentration, the total porosity of the GCL, the effective diffusion coefficient, the dry density, and the sorption coefficient. Sorption can be quantified on the basis of batch sorption tests for the various components of a GCL (geotextiles, geotextile fibers in the bentonite, bentonite).

2.5.2 Theory of diffusive transfer through GMBs

Although the basic mechanism causing molecular diffusion is the same as for a porous medium (e.g. GCL, CCL or underlying subsoil), the details of how diffusion occurs through a “solid” GMB are somewhat different. In the case of the saturated porous medium the diffusion occurs in the pore water between the solids (be they soil particles or geotextile fibres) and sorption onto the soil particles or geotextile fibres serves to remove contaminant from the pores and hence from impact on an underlying receptor. In the case of a solid GMB, sorption (partitioning) onto the polymer is an essential first step that attaches the contaminant to the polymer and provides an initial concentration for diffusion through the GMB. It needs to be remembered that while a GMB is a solid, at the molecular level it is made up of chains of polymers that are vibrating (with the amount of vibration being a function of temperature) and there is space between these polymer chains which, although not visible to us, may be significant with respect to the size of contaminant atoms or molecules. Thus the diffusion of contaminants through an intact GMB is a molecule activated process that can be envisioned to occur by steps or jumps over a series of potential barriers, following the path of least resistance. The mechanism of diffusion in geomembranes and the related equations can be found in Sangam and Rowe (2001) and Rowe et al. (2004). It can thus be seen, by the examination of the diffusive transfer mechanisms both in GCLs and in GMBs that these two materials have complementary behaviors. This will be further confirmed by the examination of data regarding the diffusion of inorganic species through GMBs. The diffusion or organic species will not be discussed in this paper.

2.5.3 Diffusion through geosynthetic clay liners

An important parameter controlling the diffusion of inorganic species in GCLs is the bulk void ratio. The bulk-GCL void ratio was defined by Petrov et al. (1997) as:

$$e_b = \frac{H_{GCL} - H_s}{H_s} \tag{1}$$

Where H_{GCL} is the GCL height; and H_s is the height of solids in the GCL. The height H_s is defined by:

$$H_s = \frac{M_{bent}}{\rho_s(1+\omega_0)} + \frac{M_{geo}}{\rho_{sg}} \tag{2}$$

Where M_{bent} is the mass of bentonite per unit area in the GCL, M_{geo} is the mass of geosynthetics per unit area in the GCL, ρ_s is the density of bentonite solids, ρ_{sg} is the density of polypropylene geotextile solids; and ω_0 is the initial water content of the bentonite.

The diffusion coefficients of sodium and chloride inferred from GCL diffusion measurements done with 3-5 g/L solutions decrease linearly with decreasing final bulk-GCL void ratio (Lake and Rowe, 2000). The diffusion coefficient was shown to depend on the source solution and, upon significantly increasing the NaCl concentration, the diffusion coefficient inferred also increased. The diffusion coefficients were estimated to range from $1x10^{-10}$ to $2x\ 10^{-10}$ m^2/s.

Lange et al. (2009) further studied the diffusion of various metals for the following four cases where a GCL might serve as an effective barrier against metals and metalloids: acidic rock drainage, gold-mine tailings, lime-treated mine effluent, and municipal solid waste. The averaged diffusion coefficients for Cu, Cd, Zn, Fe, and Ni covered a narrow range from $6.7x10^{-11}$ to $8.9\ x10^{-11}$ m^2/s. The diffusion coefficients for As, Al, Mg, Mn, and Sr range from $8.0\ x\ 10^{-11}$ to$1.6\ x10^{-10}$ m^2/s. The diffusion coefficients of the individual metals did not change significantly upon changing the composition of the solution, which suggests that, although the composition of the solution has some effect on the diffusion coefficient of the metal, sorption onto the GCL is the dominant factor controlling the metal mobility.

2.5.4 Sorption of inorganic species on the bentonite

Lange et al. (2004) examined the migration of various metals (Al, Fe, Mn, Ni, Pb, Cd, Cu, Zn) through GCLs exposed to a synthetic municipal solid-waste leachate. The GCLs are found to retard the migration of the metals, although only under specific pH conditions. Mn is the least attenuated. Al, Fe, and Cu are strongly retarded, so these metals are retained within the clay. Ni, Zn, and Cd are moderately attenuated. In addition, Ca may have been responsible for the lack of metal retention of the leachate species. Due to the higher retention at higher pH and the release of metals at lower pH, adsorption of hydrolyzed species in addition to cation exchange are hypothesized to be the mechanisms that contribute the most to metal retention.

2.5.5 Diffusive transfer of inorganic compounds through GMBs

Rowe (2005) presented the results of a measurement of the diffusion of chloride through a GMB that, at the time of publication, had run for 12 years. The receptor concentration in this measurement remained below about 0.02% of the source concentration, lying within the range of analytical uncertainty for the chemical analysis. Rowe (2005) also cites a study by August and Tatsky (1984) that concludes that negligible diffusion of heavy metal salts from a 0.5 M acid solution occurs through a HDPE GMB over a four year measurement period. Based on these results, Rowe (2012) concluded that an intact GMB is an excellent barrier against advective and diffusive migration of inorganic contaminants from a leachate.

It thus logically follows from those results that GMBs and GCL act as complementary barriers also from the point of view of inorganic contaminant transport as geomembranes represent perfect barriers to inorganic contaminants as long as they are not damaged. If damaged, they will allow the transfer of inorganic contaminants that can be sorbed on the components of the GCL.

3. EXPERIMENTAL QUANTIFICATION OF ADVECTIVE TRANSFERS IN COMPOSITE LINERS

3.1. Phenomenology of Advective Transfers Through Composite Liners

The work done over the past years regarding the features of GCLs that are part of a composite liner mainly focused on the situation where the GCL (which contains sodium bentonite) is located under a hole in an HDPE GMB. As indicated by Brown et al. (1987), the flow through a defect in the GMB depends on the contact between the GMB and the underlying medium. According to these authors, if the contact is not perfect, fluid that has migrated through the defect spreads laterally within the gap (i.e., the interface) between the GMB and the underlying medium. The area covered by this interface flow is called the "wetted area." Finally, the liquid migrates into and through the underlying medium (Figure 2).

Various situations were tested to evaluate the flow through a GMB in contact with a 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 occurs along the interface between the GMB 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 significant amount of fluid percolates through the bentonite and below the GCL. As a consequence, the amount of leakage depends mainly on the interface quality contact between the GMB and the GCL. Contact between the GMB and the GCL was quantified in terms of the flow rate through the composite liner and in terms of interface transmissivity. The interface transmissivity is a measure of the resistance to lateral flow due to a hydraulic head in the transmissive zone i.e the interface that may be envisioned between the GMB and the GCL. Interface transmissivity, θ, is obtained using the integration of Navier-Stokes equation between two parallel plans (Brown et al., 1987; Giroud and Bonaparte, 1989). Its value can be obtained using Equation 3:

$$\theta = \frac{\rho g s^2}{12\eta} \tag{3}$$

With: g, the acceleration due to gravity (m.s^{-2}); s, the thickness of the interface (m); η the liquid viscosity (kg.m^{-1}.s^{-1}).

Two types of scale test measurements were used to evaluate the amount of leakage and the interface transmissivity through the interface between the GMB and the GCL, i.e. small scale (decimeter) and large scale (meter scale) tests.

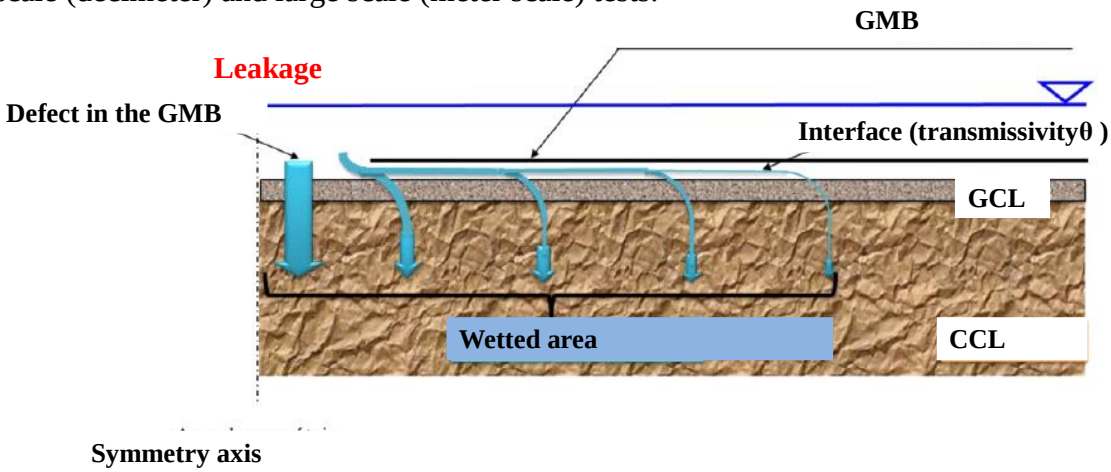


Figure 2. Flow rate through GMB-GCL composite liners

3.2. Small Scale Apparatus and Set Up and Measurements

3.2.1 Description

Small scale tests were carried out using two different apparatus in order to measure axisymmetric flow rate through composite liners. The first apparatus, shown in Figure 3 was used by Barroso et al. (2006, 2008, 2010), Bannour et al. (2013a, b), Mendes et al. (2010) and Touze-Foltz (2002). Flow rates were experimentally measured from which interface transmissivity have been calculated using the analytical solution for axisymmetric defect developed by Touze Foltz et al. (1999). In fact the final flow rate, Q, (steady state conditions) were used in Equation 4:

$$Q = \pi r_0^2 k_s \frac{h_w + H_s}{H_s} - 2\pi r_0 \theta \alpha \left[A I_1(\alpha r_0) - B K_1(\alpha r_0) \right] \tag{4}$$

Where: r_0 is the circular defect radius (m); k_s is the hydraulic conductivity of the liner (GCL + CCL) (m.s^{-1}); h_w is the hydraulic head (m); H_s is the thickness of the soil component of the composite liner (GCL + CCL) (m); θ is the interface transmissivity (m^2.s^{-1}); I_1 and K_1 are modified Bessel functions of the first order; and α, A and B are parameters given by Equations 5 to 8:

$$\alpha = \sqrt{\frac{k_s}{\theta d_s}} \tag{5}$$

$$A = -\frac{h_w K_0(\alpha R) + H_s \left(K_0(\alpha R) - K_0(\alpha r_0) \right)}{K_0(\alpha r_0) I_0(\alpha R) - K_0(\alpha R) I_0(\alpha r_0)} \tag{6}$$

$$B = \frac{h_w K_0(\alpha R) + H_s \left(I_0(\alpha R) - I_0(\alpha r_0) \right)}{K_0(\alpha r_0) I_0(\alpha R) - K_0(\alpha R) I_0(\alpha r_0)} \tag{7}$$

As $AI_1(\alpha R) + BK_1(\alpha R) - H_s = 0$ (8)

Where K_0 and I_0 are modified Bessel functions of zero order and R is the radius of the wetted area at the interface between the GMB and the GCL. The interface transmissivity, θ, and the radius of the wetted area, R, were calculated using a parametric study assuming that there is no flow at R ($Q(R)=0$). They correspond to interpretations as the assumption that the geometry is axisymmetric is made.

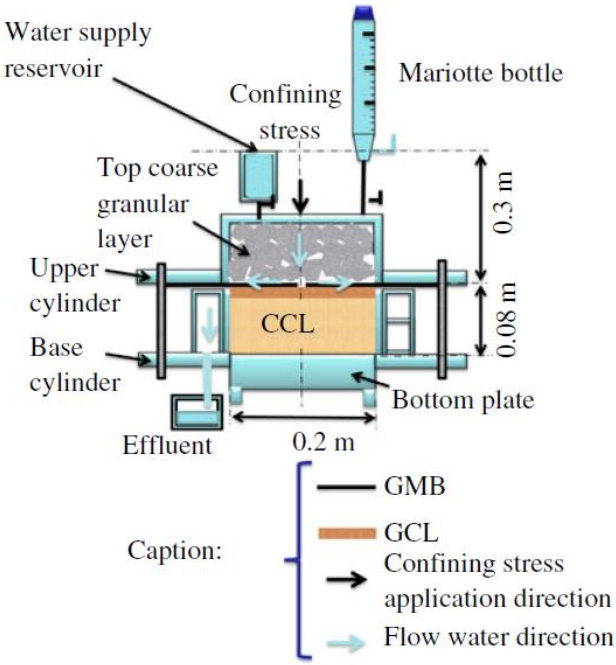


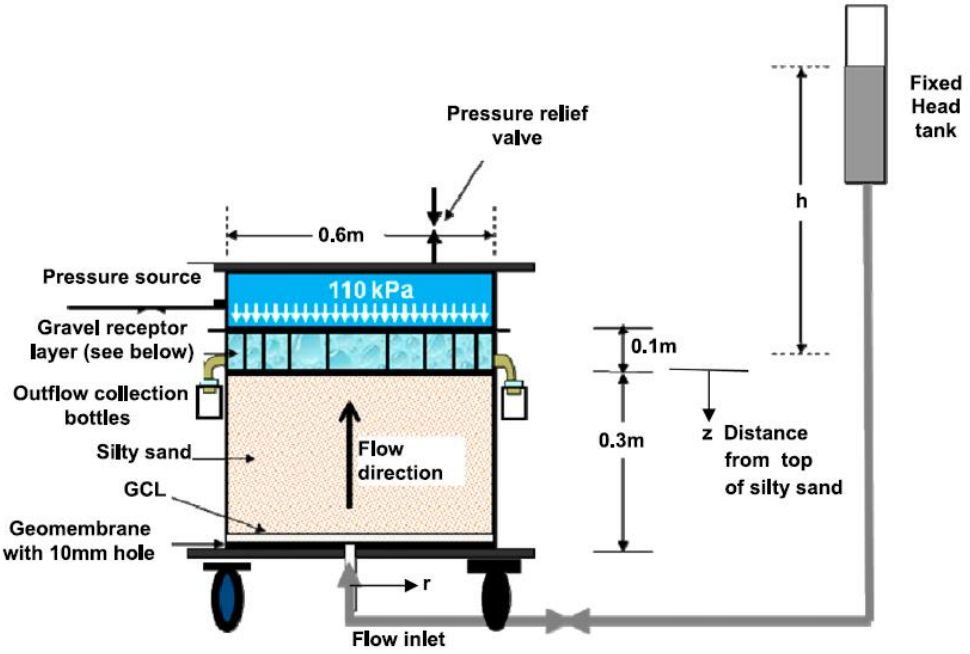
Figure 3. Small scale test apparatus for measuring interface transmissivity between the GMB and the GCL (adapted from Barroso et al., 2006)

Furthermore, Rowe and Abdellaty (2013) and Abderrazak and Rowe (2019) used the small scale apparatus shown in Figure 4. According to these authors, it was convenient to invert the configuration compared to the typical field condition in order to mitigate the problem of trapped air in such tests. The inflow interface transmissivity, θ_{inflow}, was calculated by monitoring the change of water volume in the influent burette over a prescribed time period (as in a falling head test), whereas the outflow interface transmissivity, θ_{outflow}, was calculated by monitoring the volume collected in an effluent bottle over a similar time period (as in a constant head test). Inflow and outflow interface transmissivity values were monitored until steady state was reached. Equations 9 and 10 were used to estimate the interface transmissivity at any time:

$$\theta_{\inf low} = a.\frac{\ln\left(\frac{R_2}{R_1}\right) \times \ln\left(\frac{h_2}{h_1}\right)}{2\pi t} \tag{9}$$

$$\theta_{outflow} = \frac{Q}{t}.\frac{\ln\left(\frac{R_2}{R_1}\right)}{2\pi havg} \tag{10}$$

Where: R_2 is the outer radius of specimen(m); R_1 is the hole radius (m); a is the cross sectional area of falling head burette (m^2); h_2 is the head at the end of monitoring interval (m); h_1 is the head at start of monitoring interval (m); h_{avg} is the average head over a specific time interval (m); Q is the collected volume (m^3); and t is the monitoring time interval (s).



(a)

Figure 4.Small scale laboratory apparatus for measuring interface transmissivity between GMB and GCL (Abderrazak and Rowe, 2019)

3.2.2 Case of virgin GCLs or multicomponent GCLs containing sodium bentonite

Various situations were tested to evaluate the flow through a smooth GMB in contact with virgin GCLs containing sodium bentonite. Harpur et al. (1993) studied the effect of the geotextile and the bentonite granularity on the value of θ between GCL and GMB by testing five different GCLs under 7 or 70 kPa normal stresses. The multicomponent GCL made of bentonite directly glued to a geofilm exhibited the smallest transmissivity (Table 2). At a 7 kPa confining stress, no effect of the cover geotextile fabric was noticed, whereas at a 70 kPa confining stress, θ for the GCL with woven cover GTX was one order of magnitude lower than that for the GCL with nonwoven cover GTX. They obtained a lower interface transmissivity (by about one order of magnitude) for a GCL with powdered bentonite than for one with granular bentonite.

Barroso et al. (2006; 2010) examined how hydraulic head, pre-hydration of the GCL, nature of the bentonite (granular or powder) and confining stress affects the GMB-GCL interface transmissivity. According to authors, it was difficult to identify general trends for the influence of hydraulic head, prehydration, and confining stress on the interface transmissivity. However both the initial water content of the specimen and the confining stress appears to affect the flow rate value (Barroso et al., 2006b). In fact, the flow rate in pre-hydrated GCLs was about one order of magnitude larger for a confining stress of 50 kPa than for a confining stress of 200 kPa. For non-pre-hydrated specimens, the flow rates

for both confining stresses were similar under steady state-flow conditions (Barroso et al., 2006). Results suggested that the nature of bentonite (granular or powdered) had little influence on the final flow rate in the interface.

In addition, Mendes et al. (2010) noticed that, for holes in the GMB with diameters ranging from 4 to 10 mm, the diameter has no significant influence on the flow rate through the GMB-GCL composite liner (Table 2). The expansion of the sodium bentonite was effective in blocking the puncture in the geomembrane, leading to a significant reduction in the flow rate.

Rowe and Abdelatty (2013) examined the effect of permeation with a 0.14-M NaCl solution on transport through a GMB-GCL composite liner. They concluded that there was only about a 3% increase in the flow (leakage) compared with permeation with water despite almost a one order of magnitude increase in sodium bentonite GCL hydraulic conductivity near the hole.

3.2.3 Case of virgin GCLs containing calcium bentonite or aged GCLs

The relationship between the composition of the initial bentonite in the GCL (i.e., sodium or calcium bentonite) and flow rates in the GCL was determined by Mendes et al. (2010), who concluded that the type of bentonite, which influences markedly the hydraulic conductivity of the GCLs, has no impact on the transmissivity at the interface between the GMB and the GCL in a composite liner.

More recently, Abdelrazek and Rowe (2019) reported a laboratory investigation of the interface transmissivity for five different geosynthetic clay liners (GCLs) and a range of different GMBs for a range of stresses from 10 to 150 kPa under a hydraulic head of 0.1 and 1.2 m. The GCLs were prehydrated under normal stress before permeation. The GCLs examined comprised three multicomponent and two conventional GCLs. GCL prehydration and permeation with highly saline solutions and a synthetic leachate leads to higher interface transmissivity, up to one order of magnitude higher under low hydraulic head, compared to RO water.

How does an evolution with time of this composition affects the interface transmissivity? It is well know that cation exchange, whereby sodium cations, which initially are between the bentonite platelets, are replaced by multivalent cations (calcium) that originate from contact with leachate or soil liner takes place in bentonite. Cation exchange leads to a decrease in GCL swelling capacity (Lin and Benson, 2000; Barral et al., 2012) and water absorption (Melchior, 2002) and to an order-of-magnitude increase in hydraulic conductivity compared with virgin GCLs (Egloffstein, 2001; Benson, 2013). As pointed out by Egloffstein (2001), complete cation exchange occurs after one to two years when the GCL is used in unsaturated conditions. To simulate this situation, Rowe and Abdelatty (2012, 2013) made measurements that show that the steady-state flow rate in GMB-GCL composite liners remains similar to that of virgin GCLs containing sodium bentonite despite an increase in the hydraulic conductivity of the GCL of the composite liner due to permeation by a highly concentrated NaCl solution that results in cation exchange. These results suggest that GCLs initially containing sodium bentonite, whose hydraulic conductivity increases due to cation exchange, can maintain low transmissivity at the GMB-GCL interface and low flow rate through the composite liner when used in a composite liner.

In addition to cation exchange, the GCL can also be subjected to wet-dry cycles due to moisture or temperature gradients generated across the whole barrier by climatic conditions, especially in landfill covers and dams. The effect of cation exchange combined to wet-dry cycles on the hydraulic performance of GCLs has been studied previously and is highly documented, especially as regards landfill covers (Lin and Benson, 2000; Egloffstein, 2002; Melchior, 2002; Southen and Rowe, 2005; Benson et al., 2007; Bouazza et al., 2007; Meer and Benson, 2007; Zanzinger and Touze-Foltz, 2009; Touze-Foltz et al., 2010b; Barral et al., 2012; Benson, 2013). This effect represents the primary mode of degradation for bentonite in GCLs. In fact, the combination of cation exchange and wet-dry cycles more strongly affects the swelling capacity of the bentonite and causes a greater increase in the hydraulic conductivity of the GCL than does cation exchange alone, to the point that the GCL no longer acts as a hydraulic barrier (Melchior, 2002; Meer and Benson, 2007; Benson et al., 2007). In fact, after a number of wet-dry cycles, shrinkage cracks, which occur after desiccation, may not fully heal when the bentonite hydrates. Cation exchange combined with wet-dry cycles occurring over the service life of GCLs lead to a significant increase (four to five orders of magnitude) in the hydraulic conductivity of the GCL. This raises the question of how the increase in hydraulic conductivity affects the hydraulic characteristics of a GMB-GCL composite liner when the GMB covering the GCL has a hole. Bannour et al. (2015) used laboratory measurements to address the question of how cation exchange combined with wet-dry cycles affects the flow rate and interface transmissivity of a GMB-GCL composite liner. Three of the GCLs tested were exhumed from a dam and a fourth GCL was exhumed from a landfill. These exhumed GCLs had endured cation exchange combined with wet-dry cycles, which had led to an increase in their hydraulic conductivity and a decrease in their swell index. The flow rates of composite liners including these exhumed GCLs were compared with that of a composite liner containing virgin GCLs: although the increase in hydraulic conductivity of the GCL renders it permeable as a single liner, steady state flow rates and interface transmissivities for composite liners containing GCLs that were pre-exposed to cation exchange and wet-dry cycles are of the same order of magnitude as for composite liners containing virgin GCLs. Thus, the flow rate through composite liners containing GCLs that were subjected to cation exchange and wet-dry cycles is not linked to hydraulic conductivity, even if the hydraulic conductivity of GCLs exhumed from field sites has increased by four to five orders of magnitude with respect to virgin GCLs. Thus, ageing of GCLs is not a concern when they are used in a composite liner. This indicates that GMB and GCLs have a symbiotic relationship.

3.2.4 Summary of the results in terms of interface transmissivity and perspectives

Fig. 5 gives an overview of the various interface transmissivity data obtained from the studies discussed above. All data are located below the curve representing the conditions of GMB-GCL contact defined by Barroso (2005) that relates the interface transmissivity to the hydraulic conductivity k_{GCL} of the GCL as follows:

$$\log \theta = -2.2322 + 0.7155 \log k_{GCL} \tag{11}$$

Recently, Bannour et al. (2015) defined the additional contact condition given by Equation 12 (see Figure 5) for composite liners containing GCLs whose hydraulic conductivity exceeds 10^{-10}m/s. This contact condition is valid for GCLs pre-exposed to cation exchange and wet-dry cycles and can also be extended to GCLs containing calcium bentonite.

Therefore, the GMB-GCL contact condition initially given by Barroso (2005) for effective GCLs (i.e., k_{GCL} less than10^{-10} m/s) is enhanced and readjusted for all GCLs, whatever their composition or field history:

$$\log\theta = -8.5965 + 0.1476\log k_{GCL} \tag{12}$$

As the various studies investigating leakage quantification through composite liners have been undertaken at the decimetric scale, the question arises of edge effects on flow rate and interface transmissivity measurements. Barroso et al. (2006) highlighted that small-scale tests overestimate the flow as compared to large-scale tests and thus flow rates obtained in small-scale tests represent an upper bound of flow rates that would be obtained in field conditions. Working at the meter scale is much more appropriate because the area studied is close to that encountered by GMB/GCL composite liners in real situations of barriers in landfill areas, where edge effects are negligible (Touze-Foltz et al., 2006). Table 2 gives a summary of results from small scale tests with various nature and contact at the interface for the various studies performed at the small scale apparatus.

3.3 Meter Scale Apparatus and Setup

The experimental setup developed and used in Irstea consists of a 1-m-diameter cell as previously described by Cartaud et al. (2005a) Barroso et al. (2006) and Touze Foltz et al. (2006).
Four different kinds of composite liners were studied:
• GMB/CCL composite liners,
• GMB/GTX/CCL composite liners,
•GMB/GCL/CCL composite liners, and
•GMB/GTX/GCL/CCL composite liners.

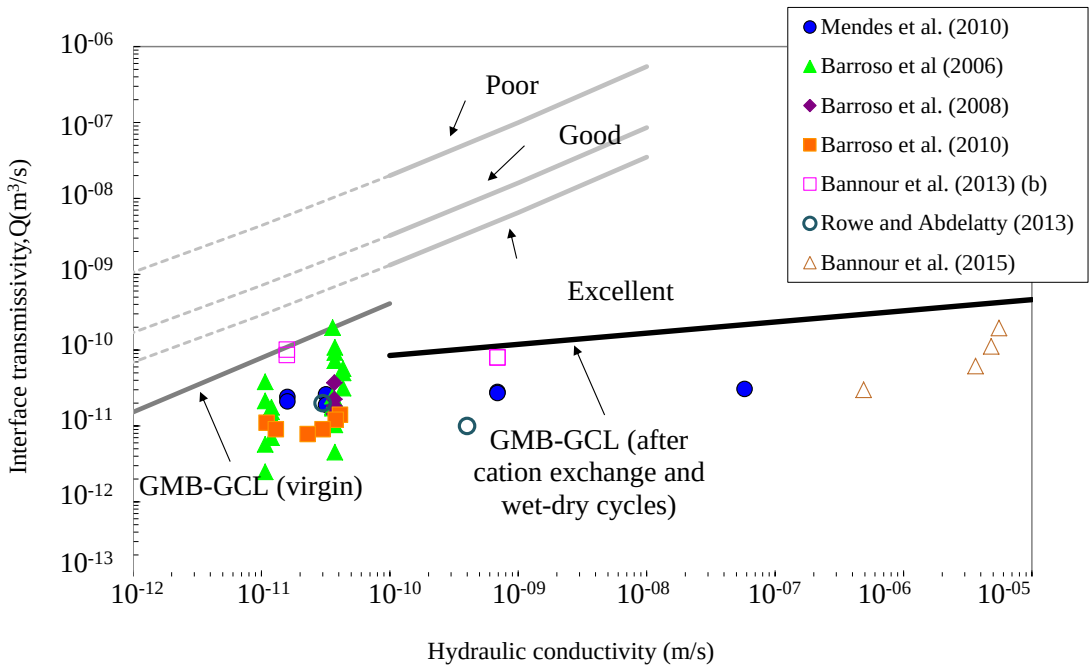


Figure 5. Synopsis of transmissivity taken from the literature for GCLs in contact with GMBs and for GCLs after cation exchange and wet-dry cycles.

Table 2. Summary of interface transmissivity tests performed at the small scale apparatus

Reference	Contact nature at the interface	K_{GCL} (m.s^{-1})	Liquid	Hydraulic head (m)	Confining stress (kPa)	R_0 (mm)	Q(m^3.s^{-1})	θ (m^2.s^{-1}
Harpur et al. (1993)	GMB-glued-G B_{np}	-	TW	0-0.3	7-70	7.6	-	3×10^{-12}
	GMB-W-B_{np}	-	TW	0-0.3	7	7.6	-	3×10^{-11}
	GMB- -W-B_{np}	-	TW	0-0.3	70	7.6	-	6×10^{-12}
	GMB-NW-B_{np}	-	TW	0-0.3	7	7.6	-	9×10^{-11}
	GMB-NW-B_{np}	-	TW	0-0.3	70	7.6	-	8×10^{-12}
Barroso et al. (2006)	GMB-NW-B_{np}	$<5 \times 10^{-11}$	TW	0.3	50	4	1.0×10^{-11}	2.3×10^{-11}
	GMB-W-B_{np}	$<5 \times 10^{-11}$	TW	0.3	50	4	5.6×10^{-12}	1.3×10^{-11}
	GMB-NW-B_{np}	$<5 \times 10^{-11}$	TW	0.3	25-200	4	2.7×10^{-12}-5×10^{-11}	1.3×10^{-11}-1.1×10^{-10}
	GMB-NW-B_{np}	$<5 \times 10^{-11}$	TW	0.3-1.2	50	4	2.7×10^{-12}-3.6×10^{-10}	7×10^{-12}-2×10^{-10}
Mendes et al. (2010)	GMB-W-B_{np}	1.6×10^{-11}-5.8×10^{-08}	TW	0.3	50	4-10	1.2×10^{-11}-1.8×10^{-11}	$.1.9\times 10^{-11}$-3×10^{-11}
Rowe and Abdellaty (2013)	GMB-NW-B_p	4.6×10^{-11}	NaCl	0.3-1	100	10	1.5×10^{-11}-5.2×10^{-11}	1.0×10^{-11}-2.4×10^{-11}
Bannour et al. (2013a)	GMB-L/C-W:NW-B_{np}		TW	0.3	50	4	1.3×10^{-11}-2.2×10^{-11}	$.2.6\times 10^{-11}$-2.8×10^{-11}
	L/C-W/NW-B_{np}		TW	0.3	50	4	1.7×10^{-11}-2.2×10^{-10}	3.5×10^{-11}-5.5×10^{-10}
Bannour et al. (2015)	GMB-W/NW-B_p	1.5×10^{-11}-5.5×10^{-06}	TW	0.3	50	4	1.2×10^{-11}-1.5×10^{-10}	2.4×10^{-11}-1.1×10^{-10}
Abdelrazek and Rowe (2019)	GMB/W/B			1.2	150	4		1.6×10^{-11}-2.2×10^{-11}
	GMB-L/C-W-B_p		RO	0.1-1.2	50-150			1.7×10^{-11}-7.2×10^{-10}
	GMB-L/C-W-B_p		SL	0.1-1.2	50-150			1.4×10^{-10}-6.7×10^{-08}
	GMB-L/C-W-B_p		SS	0.1-1.2	50-150			1.8×10^{-10}-4.1×10^{-10}

B= bentonite; G= granular; np= non prehydrated; p= prehydrated; W= woven; NW= non woven; TP= tap water; L= lamination; C= coating; RO=reverse osmosis; SS= Saline solution; SL= synthetic landfill leachate

Three different soils were used in this study. The first one called S1 was a mix of fine sand and clayey loam, 50% in dry mass each, which hydraulic conductivity was close to 10^{-9} m/s. The second one called S2 was a clayey soil coming from a Portuguese landfill (Barroso 2005) with a hydraulic conductivity measured to be 3×10^{-10} m/s. S1 and S2 were used in combination with GCL1 and GCL2 respectively. S3 was a dark clayey soil from a French municipal solid waste with a hydraulic conductivity equal to 2×10^{-10} m/s. A smooth 2 mm thick HDPE geomembrane was used in all composite liners.

The two GCLs used were natural sodium bentonite core sandwiched between a slit-film polypropylene woven geotextile and a polypropylene staple fiber nonwoven geotextile. Bentonite was granular in GCL1 and powdered in GCL2. Dry bentonite mass per unit area were 5.3 kg/m^2 and 4.67 kg/m^2 respectively for GCL1 and GCL2 with an initial water content equal to 9% and 9.5% with respect to dry weight respectively for GCL1 and GCL2. They were supplied by different manufacturers.

Three different geotextiles were used based on an enquiry reported by Cartaud et al. (2005a) on the geotextile types used at the GMB/CCL interface. The first one (GA) was the most frequently cited in the enquiry, with a mass per unit area equal to 300 g.m^{-2}. GB was also a nonwoven needlepunched geotextile, 330 g.m^{-2} supplied by a different manufacturer. Finally, GC was a thin non-woven thermal-bonded geotextile, 130 g.m^{-2} (Table 3).

Table 3. Synthesis of tests performed.

Test number	CCL	GCL or Geotextile	Liquid	Load (kPa)	Flow rate (m^3/s)
1	S1	GCL1	PF+ RL	50	1×10^{-12}
2	S1	$GCL1_{PH}$	PF+ RL	50	6×10^{-12}
3	S2	GCL2	DW	50	2.7×10^{-12}
4	S3	–	DW	6	7×10^{-6}
5	S3	–	DW	64	5×10^{-12}
6	S3	GA	DW	64	1×10^{-9}
7	S3	^{GA}PH	DW	64	5×10^{-8}
8	S3	GB	DW	64	4×10^{-8}
9	S3	GB_{PH}	DW	64	4×10^{-8}
10	S3	GC	DW	64	1×10^{-9}
11	S3	GC_{PH}	DW	64	1×10^{-9}
12	S3	GA	DW	134	9×10^{-10}
13	S3	GA_{PH}	DW	134	2×10^{-7}
14	S3	GB	DW	134	2×10^{-8}
15	S3	^{GB}PH	DW	134	2×10^{-8}
16	S3	GC	DW	134	1×10^{-9}
17	S3	GC_{PH}	DW	134	1×10^{-9}

PH: pre-hydrated; PF: pre-hydration fluid; RL: real leachate; DW: deionized water

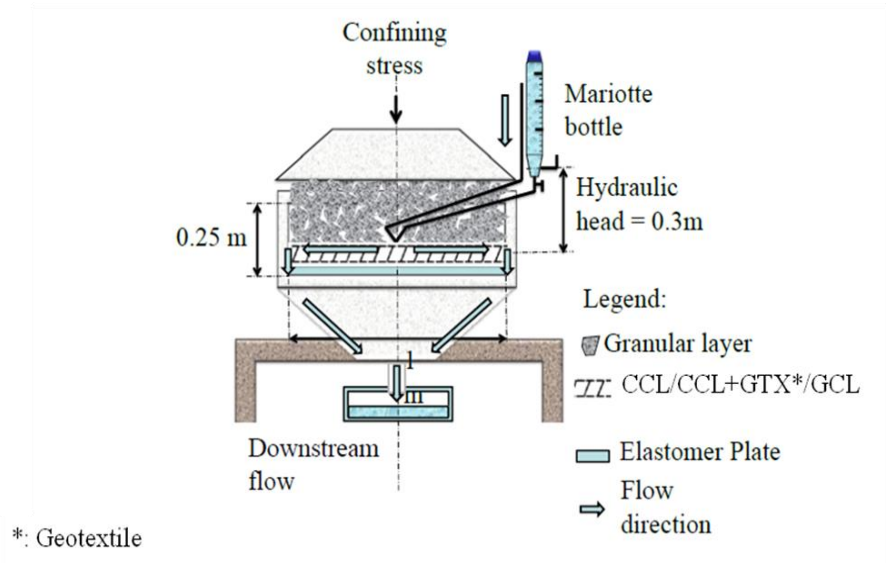
3.3.1 GMB/CCL composite liners

Tests 4 and 5 were performed using S2 compacted according to the experimental protocol described by Cartaud et al. (2005a). Under 64 kPa, steady-state flow stabilized at a rate close to 5×10^{-12} m^3.s^{-1} after a 4 months period. Another flow feature observed during the experiments was the time at which the liquid appeared at the periphery of the interface. Under 64 kPa, no flow was observed at the cell outlet within the 4 months of the test. These results show that even for the case of a CCL surface representative of in situ conditions, very low flow rate can be obtained, similar to those obtained when a GCL is included in the composite liner.

3.3.2. GMB/GTX/CCL composite liners

According to GMBs installers and to landfill owners, the installation of a nonwoven needlepunched geotextile beneath the GMB is assumed to: (i) avoid rutting of the compacted clay liner (CCL) during GMB installation; (ii) improve seam quality by ensuring that the lower surface of the GMB remains clean; and (iii) prevent damage of the geomembrane by hard puncturing elements sometimes present at the CCLsurface. The following question then arises: can the presence of such a geotextile according to its structure (woven, nonwoven, thermal bonded) and its thickness increase or decrease the flow rate? To answer this question, various studies have been undertaken in order to investigate the effect of different geotextiles in contact with a CCL and a GMB . Fukuoka (1986) constructed a 1.5m diameter large-scale testing equipment to measure advective flow rates through composite liners. Tests conducted with a nonwoven geotextile at the interface resulted in lower flow rates than tests conducted without. According to Fukuoka (1986), this phenomenon was linked to the presence of gravel in the soil liner, resulting in a surface that was not smooth despite a careful lower-tank filling process.

Cartaud et al. (2005a) also focused on the hydraulic impact of the presence of a geotextile at the interface between the GMB and the CCL surface of a landfill bottom liner under two confining stresses (64 and 134 kPa). The results show that the flow rate is increased in the presence of a geotextile at the interface. The comparison of flow rates obtained under 64 and 134 kPa normal stresses shown in Fig. 7 tends to show that the increase of the normal stress did not significantly decrease the flow rates. This fact tends to prove that the geotextile thickness, supposed to decrease under mechanical stress, is not the only parameter of influence on flow rates in composite liners in the presence of a geotextile. The lowest leakage rates with geotextile at interface were obtained by using the thinnest geotextile product, composed of thermal-bonded fibers (GC in Fig. 7), and more surprisingly, by using a dry needlepunched and thick geotextile. As a consequence, the thickness does not seem to be the only parameter that needs to be taken into account. The unsaturated hydraulic properties of the three geotextiles under study were quantified in order to assess their ability to transport fluid and, more precisely, to assess the decrease in their hydraulic conductivity K when their degree of saturation S decreases. While desaturated, the geotextile acts as a resistant medium to fluid flow under unsaturated conditions on the drying path. The results of this study also underline the fact that geotextiles apparently similar in features can exhibit different behaviors. The geotextile has a great influence on the flow rate in the interface through two intrinsic parameters, namely its thickness and its unsaturated behavior.

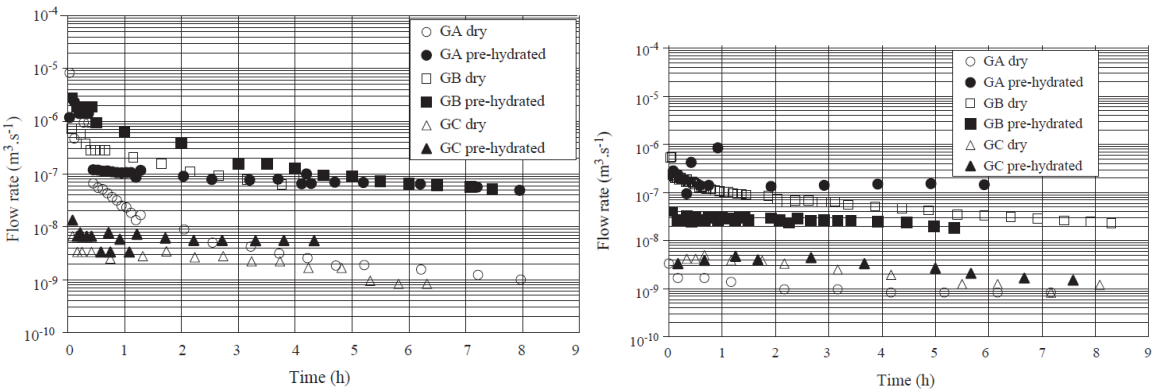


(a)

(b)

Figure 6. (a) Principle of meter scale apparatus in the case of a CCL/GCL/ GMB composite liner and (b) picture of the device (Based on Touze-Foltz et al., 2006)

Different behaviors were thus observed for composite liners incorporating either a single geotextile or a geotextile as part of a GCL. Indeed in the case of a single geotextile, steady-state was achieved in about eight hours in all cases, and the lowest flow rates measured with needlepunched GT were 10^{-9} m^3/s (see Fig. 7). On the contrary for all composite liners incorporating GCLs, 4 months were necessary to reach steady-state. Furthermore, flow rates obtained at steady-state ranged between 1×10^{-12} and $6 \times 10^{-12} m^3/s$ making it clear that geotextile behave in a different way whether used alone or as part of a GCL (see Fig. 8).



(a) (b)

Figure 7. Flow rate in composite liner function of the geotextile used at interface under (a) 64 kPa and (b) 134 normal stress (From Cartaud et al. 2005) (GA, GB: Non woven geotextiles; GC non woven thermal bonded)

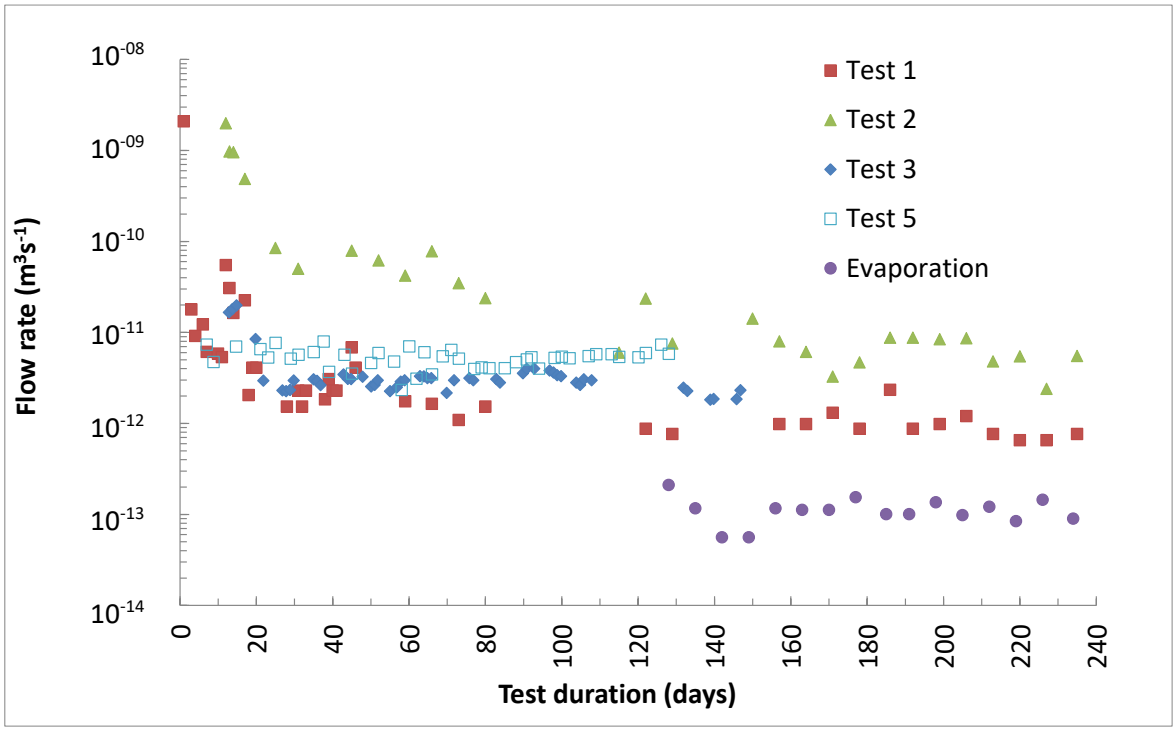


Figure 8. Temporal evolution of flow rates measured for tests 1, 2, 3 and 5 as compared to evaporation.

4.NUMERICAL MODELING OF ADVECTIVE TRANSFERS IN COMPOSITE LINERS

4.1 Advective Transfers By Taking Into Account GCLs As Homogenous Materials

For composite liners involving GCLs, Foose et al. (2001), Cartaud et al. (2005b), and Saidi et al. (2006) used a three-dimensional finite-difference model (MODFLOW For Foose et al. (2001) and METIS for Cartaud et al (2005b), Saidi et al. (2006)) to simulate leakage through circular and longitudinal holes in a flat GMB. Rowe and Abdelatty (2012) and

Siemens et al. (2012) used SEEP/w to simulate steady-state flow and transient hydration of GCLs.

Saidi et al. (2006) performed a numerical study in order to investigate the influence on the flow rate of the presence of defects in the GMB (circular defects and defects of infinite length) of a composite liner involving GCLs (Figure 10). These studies successes in reproducing the reduction in flow rate measurements with time wıthout considering confining stresses. Flow rates calculated are in the range of flow rates experimentally measured (Figure 11).

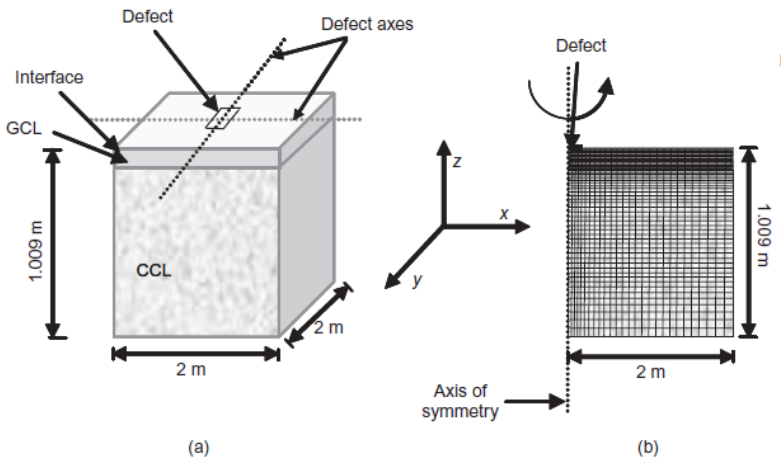


Figure 10. Composition of the composite liner studied and principle of the mesh adopted for modeling (from Saidi et al., 2006)

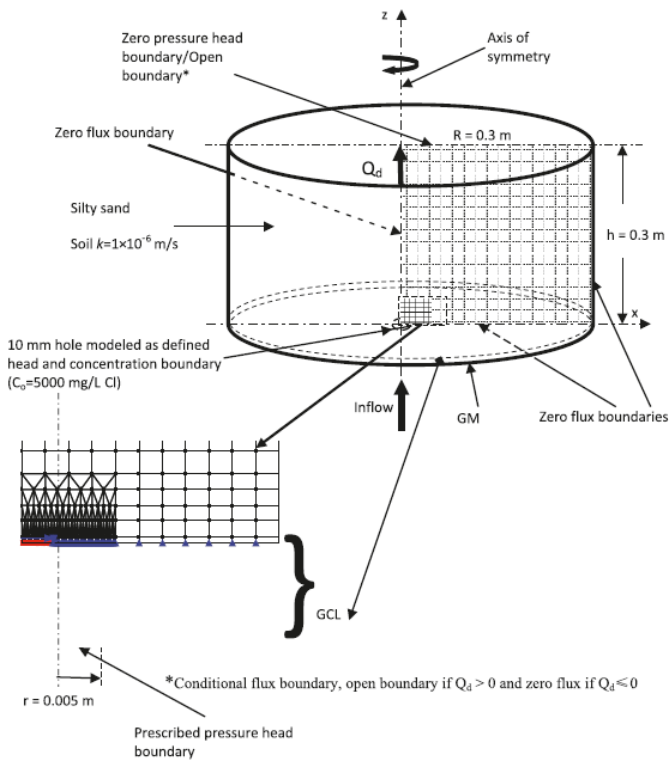


Figure 11. Schematic of axisymmetric composite liner model showing boundary conditions (from Rowe and Abdellaty, 2012)

Rowe and Abdellaty (2012) succeeded in reproducing numerically flow rate measurements at steady state compared to experimental results under a 100 kPa confining stress. They concluded that after 2.5 years of permeation with a 0.14 mol/L NaCl solution, the inferred interface transmissivity between the GMB and GCL had decreased to 1.1×10^{-11} m^2/s for both the 0.3 and 1 m heads. Thus permeation with this salt solution improved (reduced) the interface transmissivity despite an approximately order of magnitude increase in GCL hydraulic conductivity. This explains the negligible increase (3%) in leakage that was observed in the experiments reported by Rowe and Abdelatty (2013).

The results for steady-state flow rate and interface transmissivity obtained by these simulations (Cartaud et al., 2005b; Saidi et al., 2006; Rowe and Abdelatty, 2012) agree well with experiments and the analytical solution proposed by Rowe (1998) and Touze-Foltz et al. (1999).

However, all these studies considered GCLs as homogeneous materials. But GCLs actually consist of a special layered composite structure that combines two types of materials, geotextiles and bentonite, which are connected together by various processes. One could imagine that, when the GCLs hydrates, the difference in hydraulic properties of the unsaturated geotextile and the bentonite affect the hydraulic behaviour of the composite liner as evidenced by Abuel-Naga and Bouazza (2010). The next section will investigate this question.

4.2 Advective Transfers By Taking Into Account GCLs As Heterogonous Materials

Bannour et al. (2015) investigated the advective flow through a composite liner involving a GCL and a GMB. The GCL was represented in all its components thus as an heteregeneous material composed by geotextiles and bentonite. Calculations were performed in transient and steady state conditions. The objective was to evaluate how the hydraulic properties of the unsaturated geotextile and bentonite influence the temporal evolution of advective flow through composite liners. Measured water-retention curves of geotextiles and bentonite were used as parameters for the calculations. Results indicate that the reproduced flow rate is influenced by the desaturation of the geotextile that occurs as the bentonite hydrates. The reduction in flow rate is thus governed by the hydraulic conductivities of the geotextile and the bentonite, both of which vary with the degree of saturation. Consequently, the presence of a non conductive geotextile while unsaturated contributes to reduce significantly the flow rate through GMB-GCL composite liners. So in addition to experimental results, numerical simulations has also revealed the important contribution of the geotextile as part of the GCL in reducing the flow rate in GMB-GCL composite liner under low confining stress and without considering swelling of the bentonite.

5. EMPIRICAL EQUATIONS TO PREDICT ADVECTIVE TRANSFERS IN COMPOSITE LINERS

Despite the fact that there are different methods (experimental, analytical and numerical) for estimating the rate of leakage occuring through GMB-GCL composite liners, at present, the flow through composite linerswhen the GMB is presenting a hole is usually calculated using empirical equations established by curve fitting families of solutions from analytical equations. The detailed methodology of establishing empirical equation used to calculate the flow rate through composite liners is presented below in addition to the

qualitative and quantitative descripition of contact condition and empirical equation existing in the litterature. Finally, a comparative study is undertaken in order to highlignt the effect of different contact configuration on calculated flow rates based on empirical equations.

5.1 Methodology of Establishing Empirical Equation

To develop empirical equations for calculating the flowrate, Q, in the case of a circular defect in the GMB component of a composite liner, Giroud et al. (1989) and Fukuoka (1986) used an interpolation method combining theoretical and experimental results. Empirical equations for predicting the flow rate through defects in GMBs underlained by CCL and GCLs have been developed based on contact conditions (poor, good, excellent for GMB-CCL & GMB-GCL contact condition and have been successively updated (Barroso 2005, Foose et al. 2001, Touze-Foltz & Barroso 2006, Touze-Foltz & Giroud 2003) in order to consider a wide range of parameters (hydraulic head, shapes and dimensions of defects, etc.). The mathematical expression of flow rate, *Q*, through an axysymetric defect in the GMB is presented in Equation 13:

$$Q = C_c\, h_w^{\chi}\, a^{\xi}\, k_s^{\kappa}\left[1+\lambda\left(\frac{h_w}{H_s}\right)^{\mu}\right] \tag{13}$$

Where: C_c is the contact condition factor; h_w is the hydraulic head on top of the GMB; a is the circular defect area; k_s is the equivalent hydraulic conductivity of the soil liner (GCL+ Compacted clay liner "CCL"); λ is a factor; H_s is the equivalent thickness of the soil liner (GCL+CCL); and χ, ξ, κ and μ are exponents. Equation 1 can only be used with the SI units as follows: Q (m^3s^{-1}), h_w (m), a (m^2), k_s ($m.s^{-1}$), and H_s (m); dimension of C_c is variable; χ, ξ, κ, λ and μ are dimensionless. In this equation, the term in brackets is the average hydraulic gradient, i_s, in the soil liner (GCL+CCL).

The general methodology consists in determining the values of the unknown exponents and factors of Equation 13 i.e. χ, ξ, κ, μ, λ and C_c. This was done by comparing the values of Q calculated using the empirical Equation 13 with the values of Q calculated using the analytical solution expressed by Rowe (1999) and Touze-Foltz et al. (1999) and adjusting the values of the unknown parameters to obtain an acceptable approximation.

5.2. Presentation of Contact Condition

In the case where there is an interface, the transmissivity is introduced to quantitatively describe the contact characteristic between the GMB and the CCL or GGL. Contact conditions express the characteristics of the interface between the GMB and the CCL or GCL. They correspond to the value of interface transmissivity used to quantify the contact conditions as a function of the GCL hydraulic conductivity values. The contact conditions characteristics are based on experiments of flow rate measurements through GMB-GCL composite liners. Four types of contact conditions are usually considered: poor contact, good contact, excellent contact and GMB-GCL contact. Good and poor contact conditions have been introduced qualitatively by Giroud and Bonaparte (1989) in order to take into account CCL surface condition and the possible existence of wrinkles in the GMB. According to them Poor contact condition corresponds to a GMB installed with wrinkles and placed on a non compacted CCL with a rough surface. Good contact condition corresponds to a GMB installed with minimum wrinkles and a smooth CCL surface perfectly compacted. Rowe (1998) suggested that Equations 14 and 15 could be used to

represent the evolution of the interface transmissivity with the hydraulic conductivity of the soil located below the geomembrane:

$$\log_{10}\theta = -0.5618 + 0.7155\log_{10} k_f \quad \text{for poor contact} \tag{14}$$

$$\log_{10}\theta = -1.3564 + 0.7155\log_{10} k_f \quad \text{for good contact} \tag{15}$$

Excellent contact condition developed by Touze Foltz and Giroud (2003) assume a GMB without wrinkles on top of a soil component of a composite liner. It consists of a GCL installed on top of, and in close contact with, a low-hydraulic conductivity CCL (adequately compacted and presenting a very smooth surface). Furthermore, it is assumed that there is sufficient compressive stress to maintain the GMB in contact with the GCL. Equation 16 can be used for excellent contact:

$$\log_{10}\theta = -1.7476 + 0.7155\log_{10} k_s \quad \text{for excellent contact} \tag{16}$$

In addition to that, Touze-Foltz & Barroso (2006) presented contact condition expression especially for the GCL-GMB contact condition with a hydraulic conductivity of GCLs lower than 10^{-10} m.s^{-1} as follows:

$$\log_{10}\theta = -2.2322 + 0.7155\log_{10} k_L \quad \text{for GMB-GCL contact} \tag{17}$$

As presented in Section 3, Bannour et al. (2015) defined the additional contact condition given by Equation (12) for composite liners containing GCLs whose hydraulic exceeds 10^{-10} m.s^{-1}. This contact condition is valid for GCLs pre-exposed to cation exchange and wet-dry cycles and can also be extended to GCLs containing calcium bentonite.

5.3. Presentation of Empirical Equation Existing in the Literature

Table 4 summarizes the different empirical equations established for the different circular defects and contact conditions representative along the years of the case of GMB-CCL and GMB-GCL composite liners. It should be noted that existing empirical equations included in Table 4 for circular holes in the GMB can only be used for the following values of the parameters (Giroud & Touze-Foltz 2005, Touze-Foltz & Giroud, 2003) :

- small circular defects having radii between 1×10^{-3} and 5.64×10^{-3} m (i.e. a circular defect area of 1 cm^2);
- large circular defects having radii between 0.5×10^{-1} and 3×10^{-1} m;
- hydraulic heads ranging from 0.03 to 3 m;
- hydraulic conductivities of the soil component of the composite liner (GCL+CCL), k_s, ranging from 1×10^{-10} to 1×10^{-8} m.s^{-1} expressed as:

$$\frac{H_s}{k_s} = \frac{H_L + H_f}{k_s} = \frac{H_L}{k_L} + \frac{H_f}{k_f} \tag{18}$$

With H_L the thickness of the GCL (m), H_f the thickness of the CCL (m), k_L the hydraulic conductivity of the GCL (m/s) and k_L the hydraulic conductivity of the CCL (m/s).

- thickness of the soil layer component of the composite liner (GCL+ CCL), H_s, ranging from 0.3 to 5 m.

Table 4- Empirical equations existing in the litterature obtained for small circular defect having diameters in the 2 to 20 mm range, for large circular defect having diameters in the 100 to 600 mm range.

Defect TYPE	Contact condition	Empirical equation	References
Small circular defect 2<Φ<20mm	Poor (*)	$Q_L = 1.15\, h_w^{0.9}\, a^{0.1}\, k_s^{0.74}\left[1+0.1\left(\frac{h_w}{H_s}\right)^{0.95}\right]$	(Giroud 1997)
	Good(*)	$Q_L = 0.21 h_w^{0.9}\, a^{0.1}\, k_s^{0.74}\left[1+0.1\left(\frac{h_w}{H_s}\right)^{0.95}\right]$	(Giroud 1997)
	Excellent (*)	$Q_L = 0.096 h_w^{0.9}\, a^{0.1}\, k_s^{0.74}\left[1+0.1\left(\frac{h_w}{H_s}\right)^{0.95}\right]$	Touze-Foltz et Giroud (2003)
	GMB-GCL(**)	$Q_L = 2\times10^{-4}\, h_w^{0.87}\, a^{0.07}\, k_s^{0.64}\left[1+0.31\left(\frac{h_w}{H_s}\right)^{0.79}\right]$	Touze-Folz and Barroso (2006)
	GMB-GCL(***)	$Q_L = 9.405\times10^{-8}\, h_w^{0.91}\, a^{0.27}\, k_s^{0.26}\left[1+0.34\left(\frac{h_w}{H_s}\right)^{0.68}\right]$	Bannour and Touze (2019)
Large circular defect 100<Φ<600mm	Poor (*)	$Q_L = 2.60\, h_w^{0.84}\, a^{0.18}\, k_s^{0.77}\left[1-0.1\left(\frac{h_w}{H_s}\right)^{0.027}\right]$	Touze-Foltz et Giroud (2005)
	Good(*)	$Q_L = 0.64 h_w^{0.84}\, a^{0.18}\, k_s^{0.77}\left[1-0.1\left(\frac{h_w}{H_s}\right)^{0.027}\right]$	Touze-Foltz et Giroud (2005)
	Excellent(*)	$Q_L = 0.33 h_w^{0.84}\, a^{0.18}\, k_s^{0.77}\left[1-0.1\left(\frac{h_w}{H_s}\right)^{0.027}\right]$	Touze-Foltz et Giroud (2005)
	GMB- GCL (**)	$Q_L = 0.116\, h_w^{0.54}\, a^{0.4}\, k_s^{0.82}\left[1-0.22\left(\frac{h_w}{H_s}\right)^{-0.35}\right]$	Touze-Folz and Barroso (2006)
	GMB-GCL(***)	$Q_L = 3.03\times10^{-3}\, h_w^{0.65}\, a^{0.86}\, k_s^{0.64}\left[1+0.01\left(\frac{h_w}{H_s}\right)^{0.56}\right]$	Bannour and Touze (2019)

(*) GMB-CCL contact conditions; (**) for GCLs whose hydraulic conductivity are lower than 10^{-10} m.s^{-1}; (***)for GCLs whose hydraulic conductivity are greater than 10^{-10} m.s^{-1}

Table 5. Comparison between interface transmissivity and flow rate calculation depending of contact configuration and conditions

Lining system	Contact condition	K_s/ K_L (m/s)	Interface transmissivity (m^2/s)	Empirical flow rates (m^3/s)
GMB-drainage layer (Toricelli)	-	-	-	1.23×10^{-04}
GMB-CCL	Poor	10^{-10}	1.92×10^{-08}	5.05×10^{-09}
	Good	10^{-10}	3.08×10^{-09}	9.22×10^{-10}
	excellent	10^{-10}	1.17×10^{-09}	4.21×10^{-10}
GMB-GCL	GMB-GCL (virgin)	10^{-11}	7.89×10^{-11}	3.00×10^{-12}
	GMB-GCL (aged)	10^{-10}	8.46×10^{-11}	3.94×10^{-12}
		10^{-08}	1.67×10^{-11}	1.30×10^{-11}
		10^{-06}	3.29×10^{-11}	4.32×10^{-11}

Empirical equations for poor and good contact condition for GMB-CCL composite liners gives higher flow rate values compared to GMB-GCL composite liners even if GCLs present hydraulic conductivity larger than 10^{-10} m.s^{-1} and altered by their environment due to cation exchange and wet dry cycles.

5.4. Comparison between Different Composite Liners Flow Rates

A comparative study is presented in Table 5 in order to highlight the importance of contact condition on the flow rate depending on the materiel underlying the GMB. All calculations were performed for a 4 mm diameter circular defect, a 0.3 m hydraulic head and a thickness of the soil liner H_s equal to 5 m.

when using only a GMB presenting a hole over a drainage layer, the flow rate obtained was equal to 1.23×10^{-4} m^3.s^{-1} which is 5 to 6 order of magnitude larger than the flow rate through GMB-CCL composite liner (4.21×10^{-10} m^3.s^{-1} $<Q<5.05\times10^{-10}$m^3.s^{-1}) depending on contact condition. This result emphasizes the fact the the presence of a low permeability soikl layer underneath a GMB reduced significantly the amount of leakage when there is a hole in the GMB. Furthermore, using empirincal equations, when comparing flow rates through GMB-CCL and GMB-GCL composite liners it is clear that the flow rate obtained in the first case could results in higher flow rate than in the case of virgin and aged GCLs (one to two order of magnitude for flow rate and interface transmissivity). This empirical results suggest that the combination of a GCL with a GMB could reduce the amount of leakage compared to GMB-CCL composed liner even if the GCL is aged. As a consequence the GCL, even aged, could maintain its hydraulic performance in combination with a GMB.

5. CONCLUSION

Geomembranes and GCLs have been sucessfully used along time to ensure lining, especially at the bottom of landfills. The objectve of this paper was to make a synthesis of proofs that geomembranes and GCLs work in a symbiotic way. The discussion was based on data for diffusive and advective transfers.

As regards difusive transfers, only the diffusion of inorganic compounds was discussed. Inorganic compounds do not diffuse through geomembranes. On the contrary, they diffuse through geosynthetic clay liners and can be attenuated on the bentonite. The only way they

can thus reach the bentonite is in case a hole exists in the geomembrane. There the advective transfers appear.

In that case, the results of experiments carried out at the decimetric and the metric scale were presented. Results from numerical modelling are also given, together with an update of existing empirical equations, in order to include the possibility to predict flow rates when the GCL has significantly aged through cation exchange and wet-dry cycles. Results tend to show that the impact of the geotextile on the flow rate depends on whether it is used on its own at the contact with a CCL or as part of a GCL. Significantly larger flow rates were obtained in the case a geotextile was used in combination with a CCL, as compared to the case the geotextile is part of the GCL, in relation to the suction exerted by the bentonite in the GCL, whether aged or not through cation exchange phenomena and wet-dry cycles and the ability of the bentonite to swell has been reduced.

Experimental quantification (at small and large scale) of advective transfers highlighted very low flow rates and interface transmissivities tin composite liners involving GCLs (when the GMB is presenting holes) or multicomponent GCLs (when the coating or lamination is presenting holes) compared to GMB/CCL or GMB/geotextile/CCL composite liners.

Empirical equations for calculating flow rate through composite liners have been succefully uppdated using contact the condition developped for GMB-GCL and taking into account virgin and aged GCLs. As the empirical equations are much simpler than the analytical solutions, they provide design engineers with a practical tool for evaluating flow rates through composite liners.

In summary, in addition to their contribution to reinforce the barrier against soil and groundwater leakage contamination, GCLs could reduce the amount of leakage through composite liner even if they loose there hydraulic performances due to cation exchange and wet dry cycles, in relation with their association to a geomembrane, even that this geomembrane is damaged.

REFERENCES

AFNORa. EN ISO 10318. “Geosynthetics — Terms and Definitions”.

AFNORb. EN 14150. “Geosynthetic barriers - Determination of permeability to liquids”.

AFNORc. NF P 84-705. “Geosynthetic Barriers — Determination of the Swelling, Flow and Permeability Characteristics of Geosynthetic Clay Liners (Gcl) Using an Oedopermeameter — Characterisation Test and Performance.

Abdelrazek, A.Y. and Rowe, R. K., (2019). “Interface transmissivity of conventional and multicomponent GCLs for three permeants”, Geotextiles and Geomembranes, Vol. 47, pp. 60–74.

Ahel, M. and Tepic, N., (2000). “Distribution of polycyclic aromatic hydrocarbons in a municipal solid waste landfill and underlying soil. Bull”, Environ. Contam. Toxicol.

ASTM D5887 / D5887M, (2016). “Standard Test Method for Measurement of Index Flux Through Saturated Geosynthetic Clay Liner Specimens Using a Flexible Wall Permeameter”.

Abuel Naga, H. and Bouazza, A., (2010). “A Novel Laboratory Technique to Determine the Water Retention Curve of Geosynthetic Clay Liners”, Geosynthetics International, Vol.17, N°5, pp. 313-322.

August, H. and Tatsky, R., (1984). "Permeabilities of commercially available polymeric liners for hazardous landfill leachate organic constituents", In: Proceedings International Conference on Geomembranes, Denver, USA, pp. 163-168.

Bannour, H., Barral, C. and Touze-Foltz, N., (2013b). "Flow rate in composite liners including GCLs and bituminous geomembranes", International conference on Geotechnical engineering. Hammamet, 21-23 Février 2013.

Bannour, H., Barral, C. and Touze-Foltz, N., (2015). "Altered geosynthetic clay liners: effect on the hydraulic performance of composite liners.", Eur. J. Environ. Civ. Eng. Vol. 19, N° 9, 1155-1176.

Bannour H., Goblet, P., Mendes, M. and Touze Foltz, N., (2016b). "Numerical study of advective flow through composite liners", Environmental geotechnics.

Bannour, H. and Touze-Foltz, N., (2015). "Flow-rate measurements in meter-size multicomponent geosynthetic clay liners", Geosynth. Int, Vol. 22, N°1, pp.70-77.

Bannour, H. and Touze-Foltz, N., (2019)." Empirical equations for calculating the rate of liquid flow through GMB-GCL composite liners for GCLs subjected to cation exchange and wet dry cycles" Proccedding of the The 17th African RegionaL Conference on Soil Mechanics and Geotechnical Engineering Cap Town south africa, (submitted), 7 - 9 October 2019.

Bannour, H., Barral, C. and Touze-Foltz, N., (2013a). "Flow rate in composite liners including GCLs and bituminous geomembranes", In: International Conference on Geotechnical Engineering 2013, ICGE'13, Hammamet, Tunisia, February 21-23, pp. 809-819.

Bannour, H., Touze-Foltz, N., Courté, A. and von Maubeuge, K.P., (2013b). "Interface transmissivity measurement in multicomponent geosynthetic clay liners", In: von Maubeuge, Kent P., Kline, J.P. (Eds.), Current and Future Practices for the Testing of Multi-component Geosynthetic Clay Liners, ASTM STP 1562, pp. 47-61.

Barral, C., Touze-Foltz, N., Loheas, E. and Croissant, D., (2012). "Comparative study of hydraulic behaviour of Geosynthetic Clay Liners exhumed from a landfill cover and from a dam after several years in service", Paper presented at the Eurogeo 5, Valence, Spain.

Barroso, M., (2005)." Fluid Migration through Geomembrane Seams and through the Interface between Geomembrane and Geosynthetic Clay Liner". Ph.D. Thesis. University Joseph Fourier of Grenobl (France) and University of Coimbra (Portugal), p. 215.

Barroso, M., Lopes, M. and Bergamini, G., (2010). "Effect of the Waste Pressure on Fluid Migration through Geomembrane Defects", Paper presented at the Proceedings 9 ICG, Guaruja,Brazil.

Barroso, M., Touze-Foltz, N. and von Maubeuge, K., (2008). "Influence of the Textured Structure of Geomembrane on the Flow Rate through Geomembrane Gcl Composite Liners", Paper presented at the EuroGeo4.

Barroso, M., Touze-Foltz, N., von Maubeuge, K.; Pierson, P.,(2006)."Laboratory Investigation of Flow Rate through Composite Liners Consisting of a Geomembrane, a Gcl and a Soil Liner", Geotextiles and Geomembranes,Vol. 24, pp. 139-155.

Benson, C.H., (2013). "Impact of subgrade water content on cation exchange and hydraulic conductivity of geosynthetic clay liners in composite barriers", Coupled Phenomena in Environmental Geotechnics, pp. 79–84.

Benson, C.H., Thorstad, P.A., Jo, H.Y. and Rock, S.A., (2007)." Hydraulic performance of geosynthetic clay liners in a landfill final cover. Journal of Geotechnical and Geoenvironmental Engineering" , Vol.133, No.7, pp. 814–827.

Bouazza A., Jefferis S. and Vangpaisal T., (2007).” Investigation of the effects and degree of calcium exchange on the Atterberg limits and swelling of geosynthetic clay liners when subjected to wet–dry cycles”.,Geotextiles and Geomembranes, Vol. 25, pp.170-185.

Brown, K.W., Thomas, J.C. and Lytton, R.L., (1987). “Quantification of Leakage Rates through Holes in Landfill Liners”, US EPA Report CR810940.

Cartaud, F., Touze-Foltz, N. and Duval, Y., (2005a). “Experimental investigation of the influence of a geotxtile beneath the geomembrane in a composite liner on the leakage through a hole in the geomembraner”, Geotextiles and Geomembranes, Vol. 23, pp. 117–143.

Cartaud, F., Goblet, P. and Touze-Foltz, N., (2005b). “ Numerical simulation of the flow in the interface of a composite bottom liner”,Geotextiles and Geomembranes, Vol. 23, pp. 513–533.

Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste.

Goblet, P., (2002). “ Programme METIS simulation d’écoulement et de transport en milieu poreux et fracture´—Notice de conception, Technical report LHM/RD/02/06, Ecole Nationale Supérieure des Mines de Paris, Centre d’Informatique Géologique.

Giroud, J.-P., (1997). “Equations for Calculating the Rate of Liquid Migration through Composite Liners Due to Geomembrane Defects”, Geosynthetics International, Vol.4, N°(3-4), pp. 335-348.

Giroud, J.-P. and Bonaparte, R., (1989). “Leakage through Liners Constructed with Geomembranes .2. Composite Liners”, Geotextiles and Geomembranes, Vol. 8, N°2, pp. 71-111.

Giroud, J.-P., Khatami, A. and Badu-Tweneboah, K., (1989). “Evaluation of the Rate of Leakage through Composite Liners”, Geotextiles and Geomembranes, Vol.8, N°4, pp. 337-340.

Giroud, J.-P. and Plusquellec, H., (2017). “Water, canals and geosynthetics. Keynote Lecture, Proceedings Geoafrica Conference, Marrakech”, Morocco, pp. 53-112.

Giroud, J.-P. and Touze-Foltz, N., (2005). “Equations for Calculating the Rate of Liquid Flow through Geomembrane Defects of Uniform Width and Finite or Infinite Length”, Geosynthetics International, Vol.12, N°4, pp. 191-204.

Egloffstein, T.A., (2002). “Bentonite as sealing material in geosynthetic clay liners-Influence of the electrolytic concentration, the ion exchange and ion exchange with simultaneous partial dessiccation on permability. Clay Geosynthetic Barriers”, pp. 141-151.

Foose, G.J., Benson, C.H. and Edil, T.B., (2001). “Predicting leakage through composite landfill liners”, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 127, N°6, pp. 510-520.

Fukuoka, M., (1986).” Large Scale Permeability Test for Geomembrane Subgrade System”, Paper presented at the Third International Conference on Geotextiles, Vienne, Autriche.

Harpur, W.A., Wilson-Fahmy, R.F. and Koerner, R.M., (1993). “Evaluation of the Contact between Geosynthetic Clay Liners and Geomembranes in Terms of Transmissivity”, Paper presented at the Geosynthetic Liner Systems: Innovations, Concerns and Design, Proceedings of a Geosynthetic Liner Systems Seminar held in Philadelphia, USA.

Hiroshi, A., Toshihiko, M. and Nobutoshi, T., (2002). “Endocrine disrupters in leachate from two MSW landfills of different waste compositions in Japan”, In: Proceedings of the 2nd Asian Pacific Landfill Symposium, Seoul 2002, pp. 728-736.

Hsuan, G., Schroeder, H.F., Rowe, R.K., Müller, W.; Greenwood, J., Cazzuffi, D. and Koerner, R.M., (2008). “Long-term performance and lifetime prediction of

geosynthetics", Keynote lecture. Proceedings Eurogeo 4, Fourth Eu-ropean conference on geosynthetics, Edinburg, Scotland, 40 p.

Lange, K., Rowe, R.K. and Jamieson, H., (2009). "Diffusion of metals in geosynthetic clay liners", Geosynth. Int., Vol. 16 , N°1, pp. 11-27.

Lange, K., Rowe, R.K. and Jamieson, H., (2004). "Metal migration in geosynthetic clay liners", In: 57th Canadian Geotechnical Conference, Session 3D, pp. 15-22.

Lake, C.B. and Rowe, R.K., (2000). "Diffusion of sodium and chloride through geosynthetic clay liners", Geotext. Geomembr., Vol. 18, pp 103-31.

Lake, C.B. and Rowe, R.K., (2004). "Volatile organic compound diffusion and sorption coefficients for a needle-punched GCL", Geosynth. Int., Vol. 11, N° 4, pp. 257-272.

Lin, L.C. and Benson, C.H., (2000). "Effect of Wet-Dry Cyling on swelling and hydraulic conductivity of GCLs", Geotechnical and Geoenvironmental Engineering, January 2000.

McDonald, M.G. and Harbaugh, A.W., (1988). "A modular three-dimensional finite-difference ground-water flow model", Techniques of water resources investigations of the united states geological survey, US Government Printing Office, Washington DC.

MEEDDAT, (2009). "Guide De Recommandations, À L'usage Des Tiers Experts, Pour L'évaluation De L'équivalence En Étanchéité De Site De Stockage De Déchets". Version 2, (pp. 52 p): Environmental Ministry.

Meer S.R. and Benson C.H., (2007). "Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers", Journal of Geotechnical and Geoenvironmental Engineering, Vol.133, pp. 550-563.

Melchior, S., (2002). "Field studies and excavation of geosynthetic clay barriers in landfill covers", Clay Geosynthetic Barriers, pp. 321–330.

Mendes, M. J. A., Touze-Foltz, N., Palmeira, E. M. and Pierson, P., (2010). "Influence of Structural and Material Properties of Gcls on Interface Flow in Composite Liners Due to Geomembrane Defects", Geosynthetics International, Vol.17, N°1, pp. 34-47.

Mendes, M.J.A., Touze-Foltz, N., Gardoni, M. and Mazeas, L., (2014). "Diffusion of phenolic compounds through polyethylene films", Geosynth. Int, Vol. 21, N° 2, pp. 137-150.

Mendes, M.J.A., Touze-Foltz, N., Gardoni, M., Ahari, M. and Mazeas, L., (2013). "Quantification of the diffusion of phenolic compounds in a virgin GCL and in a GCL after contact with a synthetic leachate", Geotext. Geomembr, Vol. 38, pp.16-25.

Oman, C. and Hynning, P.A., (1993). "Identification of organic compounds in municipal landfill leachates". Environ. Pollut. Vol.80, N°3, pp. 265-271, Vol.65, N°2, pp. 236-243.

Petrov, R.J., Rowe, R.K. and Quigley, R.M., (1997). "Selected factors influencing GCLs hydraulic conductivity", J. Geotech. Geoenvironmental Eng, Vol.123, N°8, pp. 683-695.

Pinel-Raffaitin, P., Ponthieu, M., Amouroux, D., Mazeas, L., Donard, O.F.X. and Potin-Gautier, M., (2006). "Evaluation of analytical strategies for the determination of metal concentrations to assess landfill leachate contamination", J. Environ. Monit., Vol.8, pp. 1069-1077.

Richards L.A., (1931)." Capillary conduction of liquids through porous medium", Physics, Vol.1, N°11, pp. 318–333.

Robinson, H.D., Knox, K., Van Santen, A. and Tempany, P.R., (2001). "Compliance of UK landfills with EU pollution emissions legislation: development of a reporting protocol", In: Proceedings Sardinia 2001, Eighth International Waste Management and Landfill Symposium, pp. 21-30. Cagliari, Italy, 1-5 October 2001.

Rosin-Paumier, S., Touze-Foltz, N., Mazeas, L. and Guenne, A., (2011). "Quantification of volatile organic compounds diffusion for virgin geosynthetic clay liners and for a GCL after contact with a synthetic leachate", J. Geotech. Geoenvironmental Eng., Vol.5, N°.11, pp.1039-1046.

Rowe, R.K., (1998). " Geosynthetics and the minimization of contaminant migration through barrier systems beneath solid waste", Keynote Lecture, Proc. Sixth International Conference on Geosynthetics, Atlanta, Vol. 1, pp. 27-103, Industrial Fabrics Association International, St .Paul. (This paper can be downloaded from www.geoeng.ca).

Rowe, R.K., (2005). "Long-term performance of contaminant barrier systems", 45th Rankine Lecture Geotechnique, Vol. 55, N°9, pp. 631-678.

Rowe, R.K., (2007). "Advances and Remaining Challenges for Geosynthetics in Geoenvironmental Engineering Applications", Soils and Rocks, São Paulo, Vol. 30, N°1, pp. 3-30.

Rowe, R.K., (2012). "Short- and long-term leakage through composite liners", The 7th Arthur Casagrande Lecture Can. Geotech.J. , Vol.49, N°2 , pp. 141-169.

Rowe, R.K., (2017). "Protecting the environment with geosynthetics". The 53rd Karl Terzaghi Lecture, ppt presentation (complimentary copy), 100p.

Rowe, R.K. and Abdelatty, K., (2012). "Modeling contaminent transport through composite liner with a hole in the geomembrane", Journal of geotechnical and geoenvironmental engineering, Vol. 49, pp. 773-781.

Rowe, R.K. and Abdelatty, K., (2013). "Leakage and contaminant Transport through a single hole in the GMB component of a composite liner", ASCE J. Geotechnical and Geoenvironmental Engineering, Vol. 139, N°7, pp. 357–366.

Rowe, R.K. and Booker, J.R., (1987). "An Efficient Analysis of Pollutant Migration through Soil. Numerical Methods for Transient and Coupled Problems", In: Lewis, R.W., Hinton, E., Bettess, P., Schrefler, B.A. (Eds.). Wiley, New York, pp. 13-42.

Rowe, R.K. and Brachman, R.W.I., (2004). "Assessment of equivalence of composite liners", Geosynthetics International, Vol. 11, N°4, pp. 273-286.

Rowe, R.K., Lake, C.B. and Mukunoki, T., (2005). "BTEX diffusion and sorption for a geosynthetic clay liner at two temperatures", J. Geotech. Geoenvironmental Eng., Vol. 13, N°10, pp. 1211-1221.

Rowe, R.K., Quigley, R.M.; Brachman, R.W.I. and Booker, J.R., (2004). "Barrier Systems for Waste Disposal Facilities", second ed. E&F Spon, p. 587.

Saidi, F., Touze-Foltz, N. and Goblet, P., (2006). "2d and 3d Numerical Modelling of Flow through Composite Liners Involving Partially Saturated Gcls", Geosynthetics International, Vol.13, N°6, pp. 265-276.

Sangam, H.P., Rowe, R.K., (2001). "Migration of dilute aqueous organic pollutants through HDPE geomembranes", Geotext. Geomembr., Vol. 19, N°6, pp. 329-357.

Siemens, G., Take, W.A., Rowe, R.K. and Brachman, R.W.I., (2012). Numerical investigation of transient hydration of unsaturated geosynthetic clay liners, Geosynthetics International, Vol. 19, No. 3, pp. 232-251.

Sisinno, L.S., Oliveira-Filho, E.C., Dufrayer, M.C., Moreira, J.C. and Paumgartten, J.R., (2000). "Toxicity evaluation of a municipal dump leachate using zebrafish acute tests", Bull. Environ. Contam. Toxicol., Vol. 64 , N°1, pp.107-113.

Southen, J.M. and Rowe, R.K., (2005). "Laboratory Investigation of Geosynthetic Clay Liner Desiccation in a Composite Liner Subjected to Thermal Gradients", Journal of Geotechnical and Geoenvironmental Engineering, Vol. 131, N°.7, pp. 925–935.

Takigami, H., Matsui, S., Matsuda, T. and Shimizu, Y., (2002). "The Bacillus subtilis recassay: a powerful tool for the detection of genotoxic substances in the water

environment. Prospect for assessing potential impact of pollutants from stabilized wastes", Waste Manag, Vol.22, N°2, 209-213.

Touze-Foltz, N., (2002). "Evaluation of the Hydraulic Transmissivity in Soil Liner" Geomembrane Interfaces. Paper presented at the Proceedings of the Seventh International Conference on Geosynthetics, Nice, France.

Touze-Foltz, N., (2010). "State of the art and durability insights regarding the use of geosynthetics for lining in hy-draulic and environmental applications", Proceedings 9th International Conference on Geosynthetics, Guaruja, Brazil, pp. 511-530.

Touze-Foltz, N., (2015)."Quantification of flow rates through virgin and exposed geomembranes and multicomponent geosynthetic clay liners", Proceedings of the The 2nd International GSI-Asia Geosynthetics Conference (GSI-Asia 2015), Seoul, Korea (Rep.), June 24-26.

Touze-Foltz, N. and Barroso, M., (2006). "Empirical Equations for Calculating the Rate of Liquid Flow through Gcl-Geomembrane Composite Liners", Geosynthetics International, Vol. 13, N°2, pp.73-82.

Touze-Foltz, N. and Giroud, J.P., (2003). "Empirical Equations for Calculating the Rate of Liquid Flow through Composite Liners Due to Geomembrane Defects", Geosynthetics International, Vol.10, N°6, pp. 215-233.

Touze-Foltz, N., Barroso, M. and Cartaud, F., (2006). "Experimental investigation of flow rates through composite liners at the metric scale", Proceedings 8th International Conference on Geosynthetics, Yokohama, Japan, pp. 305-308.

Touze-Foltz N., Lupo M. and Barroso M., (2008). "Geoenvironmental applications of geosynthetics", Keynote Lecture, Proceedings Eurogeo 4, 98p.

Touze-Foltz, N., Bannour, H., Barral, C. and Stoltz, G., (2016)."A review of the performance of geosynthetics for environmental protection", Geotextiles and Geomembranes, Vol. 44, pp. 656-672.

Touze-Foltz, N., Croissant, D., Rosin-Paumier, S., Pirrion, T. and Ouvry, J.F., (2010b). "Performance of a GCL in a landfill cover after six years in service", In: 3rd International Symposium on Geosynthetic Clay Liners, Würzburg, Germany, pp. 83-91.

Touze-Foltz, N., (2018). "Healing the world : A geosynthetics solution", Giroud Lecture, Proceedings of the 11th International Conference on Geosynthetics, 16-21 September 2018, Seoul, Korea.

Touze-Foltz, N., Rowe, R. K. and Duquennoi, C., (1999). "Liquid Flow through Composite Liners Due to Geomembrane Defects: Analytical Solutions for Axi-Symmetric and Two-Dimensional Problems", Geosynthetics International,Vol. 6, N°6, pp. 455-479.

Von Maubeuge, K.P., Sreenivas, K. and Pohlmann, H., (2011). "The New Generation of geosynthetic clay liners". Seminar Geosynthetics India' 11 and an Introductory course on Geosynthetics, Chennai (Tamil Nadu), India, 8p.

Zanzinger, H. and Touze-Foltz, N., (2009). "Clay geosynthetic barriers performance in landfill covers", In: GeoAfrica 2009 Cape Town 2-5 September 2009, pp. 175-184.