INFLUENCE OF THE TEXTURED STRUCTURE OF GEOMEMBRANES ON THE FLOW RATE THROUGH GEOMEMBRANE-GCL COMPOSITE LINERS

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Abstract: Laboratory tests for measuring the flow rate through composite liners due to geomembrane (GM) defects were carried out. Composite liners consisted of a GM, with a circular hole, a geosynthetic clay liner (GCL) and a compacted clay liner (CCL). Four GMs were used: one smooth and three different textured GMs (sprayed-on structure, embossed honeycomb and dimpled structures). Tests were conducted simultaneously at two laboratories (Portugal and France) to check test reproducibility. They were conducted under a hydraulic head equal to 0.3 m and a confining stress equal to 50 kPa. The main goal of this research was to study the influence of the textured structure of GMs on the flow rate and on the corresponding interface transmissivity. Results showed that the tests are reproducible and that the GMs textured surfaces have a small impact on final flow rates (obtained at steady-state), although, at the beginning of the tests, higher flow rates were obtained with smooth GM than textured GMs. This suggests that, at the early phases of the tests, the water flows 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 swells and creates an intimate contact between the GCL and the GM. Based on final flow rates and on observed wetted areas, interface transmissivities were calculated. Values obtained were similar regardless the type of GM used. Also, transmissivities obtained were smaller than the ones estimated by using the empirical equation proposed by Touze-Foltz & Barroso (2006) for "GM-GCL Contact Condition" which was initially defined as a maximum from experimental data presented by Barroso *et al.* (2006). Thus, data obtained in this study are consistent with previously obtained data. Results obtained also suggest that, after steady state achievement, smooth and textured GMs can perform very similarly while contacting GCLs.

Keywords: environmental applications, landfill liner, geomembrane, geocomposite clay liner (GCL), testing, advective flow.

INTRODUCTION

Modern landfills are generally designed to protect the environment against contaminants by using a composite liner. In this type of liner, the geomembrane (GM) provides the primary resistance to advective contaminant flow (also termed leakage, and herein simply referred to as flow), as well as to diffusion of some contaminants. The clay component of the composite liner, compacted clay liner (CCL) or geosynthetic clay liner (GCL), serves to reduce the flow through inevitable holes or defects in the geomembrane. It also provides some attenuation of contaminants that can diffuse through intact GMs or transfer through holes in the GMs.

Unfortunately, despite all precautions regarding manufacturing, transportation, handling, storage and installation, defects in the GM seem to be unavoidable. Defects in the GM represent preferential advective flow paths for leachate migration, which may affect the whole performance of the liner system.

The impact of the defects in the GM can be minimised by proper design of the landfill liner. For that, it is of primary importance to predict the flow rate through composite liners due to the existence of defects in the GM.

There have been some experimental studies for determining the flow rate through composite liners due to GM defects (e.g. Estornell & Daniel 1992, Harpur *et al.* 1993, Koerner & Koerner 2002, Touze-Foltz et al 2002, Cartaud *et al.* 2005, Barroso *et al.* 2006, etc.). Although several experimental studies were conducted on flow rates through composite liners due to GM defects, very little is known about influence of the type of GM (smooth versus textured) on the flow rate and on the interface transmissivivity corresponding to the gap between the GM and the underlying liner. Thus, the main purpose of this study was to ascertain the effect of using textured GMs as compared to smooth GM, on the flow rates through composite liners consisting of a GM, with a circular hole, a GCL and a CCL.

The flow rate was measured through laboratory tests were using a smooth GM, and three textured GMs (sprayed-on structure, embossed honeycomb and dimpled structures). Some of those tests were conducted simultaneously at two laboratories (Portugal and France) to check test reproducibility.

MATERIALS AND METHODS

Soil

The soil used in the experimental work came from a landfill located west of Portugal, from continental deposits of sedimentary Jurassic and Cretaceous formations, comprising different levels of clay, marls, silt-clayey sands and sandstones. Clayey levels (clay and marls) are predominant in Jurassic formations, where the soil was sampled. This soil was previously used by Barroso *et al.* (2006) for carrying out different scale laboratory tests. Measured hydraulic conductivity of this soil was about 3×10^{-10} m/s.

Geosynthetic clay liner

A commercially available GCL was used in this study. It consisted of a layer of natural sodium bentonite powder supported by two geotextiles, held by needlepunched. The upper geotextile, made of polypropylene (PP) fibres, was nonwoven, 220 g/m^2, and the lower geotextile, made of PP fibers, was a woven, 110 g/m^2. According to Barroso (2005), the mass per unit of area was equal to 5000 g/m^2 and the corresponding hydraulic conductivity was equal to 3.7×10^{-11} m/s (measured under a confining stress equal to 50 kPa).

Geomembranes

Four high density polyethylene (HDPE) GMs, 2.00 mm thick, were used in this study, namely: smooth, sprayed-on structure, embossed honeycomb and dimpled structures (Figure 1).

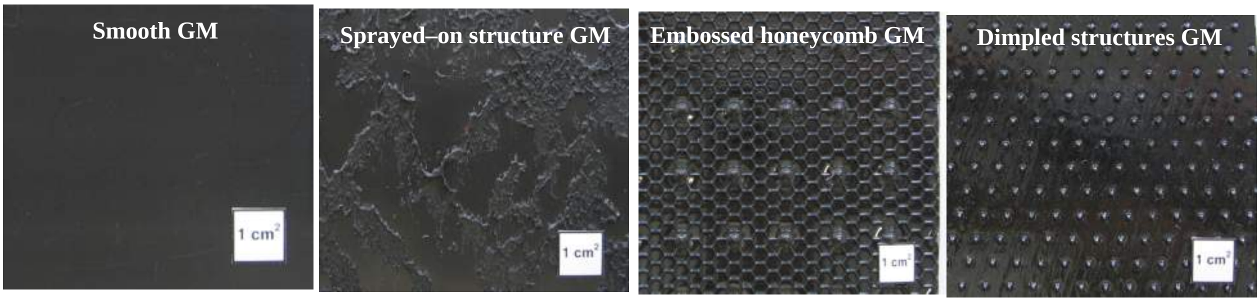

Figure 1. Types of geomembranes used

Test method

The tests were carried out in a circular Plexiglas® cell specially designed to measure the flow rate through composite liners and previously described by Touze-Foltz (2002), Touze-Foltz *et al.* (2002), Cartaud & Touze-Foltz (2004) and Barroso *et al.* (2006). The cell consists of four parts (see Figure 2): (i) a bottom plate supporting the compacted soil layer; (ii) a base cylinder with an inside diameter of 0.2 m and 0.08 m high, for accommodating the compacted soil and GCL specimen; (iii) a granular cover plate to simulate the presence of a granular drainage layer; and (iv) an upper part 0.06 m high that accommodates the granular cover plate.

Briefly, at first, about 4.5 kg of soil was compacted (using a hand packer) inside the base cylinder in two lifts approximately 2.1×10^{-2} m thick, to a water content of approximately 2% above the optimum water content of Proctor modified test. The excess soil material was carefully cut to yield a smooth surface. Then, the GCL specimen was placed on top of the soil, with the non-woven geotextile on top, and, above it, the GM, with a circular hole 3×10^{-3} m in diameter at its centre. Next, the granular cover plate was placed above the GM. The base and upper parts of the cell were held together with retaining threaded rods. The cell was then installed in a mechanical press that applies the confining stress equal to 50kPa. Finally, the top cell was connected to a water supply reservoir, which fed the test during the first hours when the water flow through the composite liner was large. When the water flow decreased, the water reservoir was replaced by a Mariotte bottle, which is more accurate at low flows. Both water reservoir and Mariotte bottle were set to a hydraulic head equal to 0.3 m (constant head tests). This value was chosen because it represents the maximum allowable leachate above the GM in most landfill regulations. Figure 2 shows the schematic of the test.

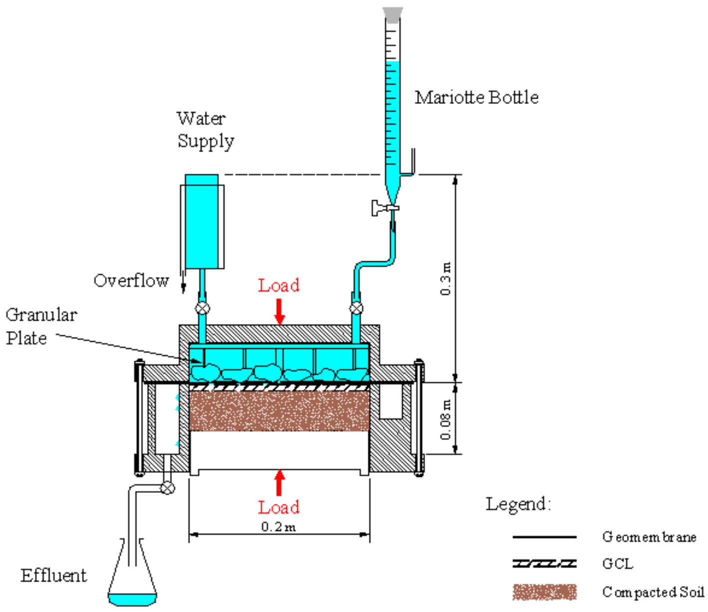

Figure 2. Scheme of the tests apparatus used in tests carried out in Portugal (from Barroso *et al.* 2006)

The tests were ended after the steady-state was reached. Each test was run for a minimum period of 700 hours.

The flow rate was calculated in two different ways: when the radial flow rate at the downstream side of the interface (effluent) was high enough to be measured by weighing, the flow rate was obtained by dividing the volume of effluent collected by the collecting time. When very low or no flow rates could be measured in this way, the total flow rate was calculated based on the volume change of water inside the Mariotte bottle over the time interval. In order to reduce the scatter on flow measurements, the total flow rate was generally recalculated on a 24 hours basis. Also, the uncertainty associated to the measurements was calculated (uncertainty calculations are detailed in Barroso 2005). Corresponding error bars are plotted in figures presented in the next sections.

Tests were conducted in an air conditioned laboratory. Consequently water volume variation in the Mariotte bottle due to temperature was negligible.

RESULTS AND DISCUSSION

Inter-comparison tests

To study the test reproducibility, some of the tests conducted were carried out simultaneously at *Laboratório Nacional de Engenharia Civil* (LNEC), in Portugal, and at Cemagref, in France, where similar experimental devices exist. The main difference between the devices regards to the granular plate used to apply the normal load on the composite liner.

Figure 3 presents the evolution of flow rate for the dimpled structures GMs. By comparing the evolution of the flow rates, it can be seen that there is a difference at the beginning of the tests. A higher flow rate is obtained in tests carried out at LNEC than in test carried out at Cemagref. This may be due to the fact that the GCLs were not used at same initial water content. Indeed, the test performed at LNEC started with the GCL with an initial water content equal to 13.3 %, whereas, at Cemagref, the test began after a two weeks period of prehydration of the GCL. The reason for using different initial water contents at LNEC and at Cemagref is related with the possible internal erosion of GCL observed at Cemagref with this product. Indeed, some bentonite could be observed in the effluent flow. This may be due to the transport/handling of the GCL to Cemagref, as only a small piece of material was supplied. To overcome this problem, the GCL was prehydrated into the test cell by water uptake from the soil, under load, during two weeks. Therefore, the initial water content of the product is not known.

After about 600h, the results obtained are, however, similar in both laboratories. The final mean flow rates are equal to 9.3×10^{-12} m^3/s, in the test carried out at LNEC, and to 1.4×10^{-11} m^3/s, in the test carried out at Cemagref. Taking into account the uncertainties associated to these measurements, this difference can be considered as unimportant.

Similar results were obtained for the other GMs tested. Graphs are not included in this paper for the sake of brevity.

On the basis of the above findings, it can be considered that the tests are fairly reproducible.

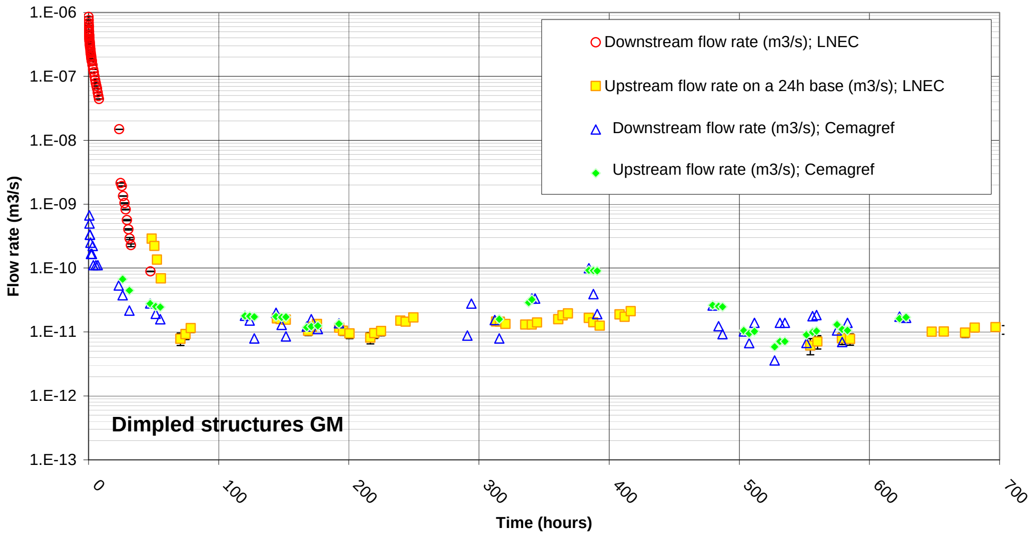

Figure 3. Evolution of the flow rates with time for dimpled structures GM at LNEC and at Cemagref

Comparison between smooth and textured geomembranes

Smooth GM versus sprayed–on structure GM

Figure 4 shows the results obtained for smooth GM and sprayed-on structure GM. The evolution of the flow rates in these tests carried is similar by taking into account the uncertainties associated to the measurements.

Final flow rates close to each other were obtained equal to 1.1×10^{-11} m^3/s and 1.9×10^{-11} m^3/s, respectively for test carried out with smooth GM and sprayed–on structure GM.

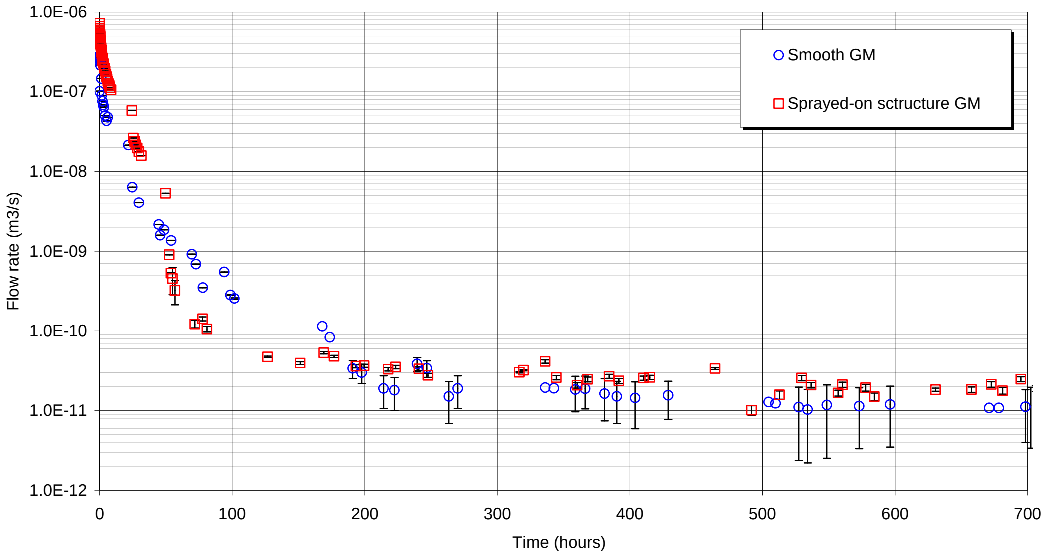

Figure 4. Comparison between the evolutions of flow rates in tests conducted with the smooth and sprayed-on structure GMs

Smooth GM versus embossed honeycomb GM

The results obtained for smooth GM and embossed honeycomb GM are shown in Figure 5. It can be seen that during the initial phase of the test a higher flow rate was obtained in the test conducted with the smooth GM than with the embossed honeycomb GM. However, the difference decreases over the test. Final flow rates equal to 1.1×10^{-11} m^3/s and 7.6×10^{-12} m^3/s were obtained respectively in the tests conducted with the smooth GM and the embossed honeycomb GM. Taking into account the uncertainties associated to these measurements, this difference can be considered as slight.

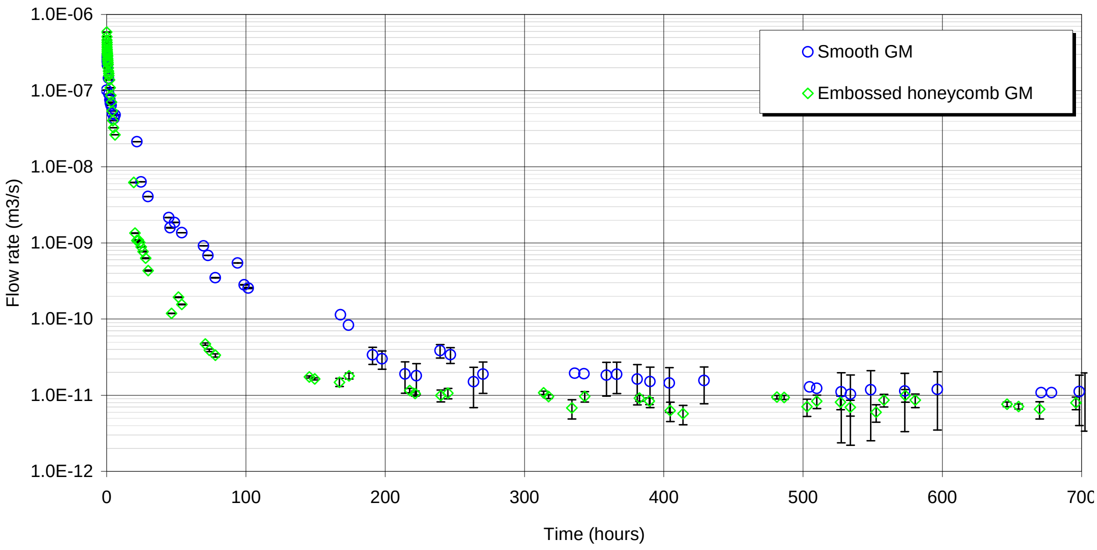

Figure 5. Comparison between the evolutions of flow rates in tests conducted with the smooth and embossed honeycomb GMs

Smooth GM versus dimpled structures GM

Figure 6 depicts the results obtained for smooth GM and dimpled structures GM. As can be seen, there is a discrepancy in the flow rates at the beginning of the tests, with the smooth GM presenting higher flow rates than the dimpled structures GM. It seems that, at early phase of the test, the water flows easily at the interface when the smooth GM is used. The texture may increase the resistance to the water flow by reducing the space available at the interface for the water flow. With time the GCL swells adapting itself to the GM. The thickness of interface reduces and the influence of the texture becomes less important.

Taking into account the uncertainties associated to these measurements, similar final flow rates were obtained: 1.1×10^{-11} m^3/s and 9.3×10^{-12} m^3/s, respectively for test conducted with the smooth and dimpled structures GM.

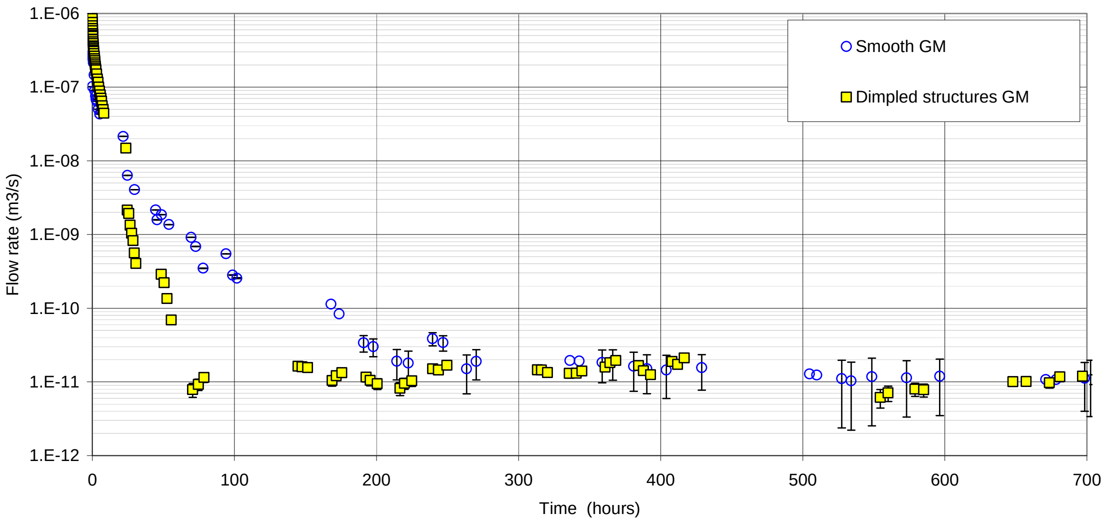

Figure 6. Comparison between the evolutions of flow rates in tests conducted with the smooth and dimpled structures GMs

Comparison between textured geomembranes

Results obtained for all textured GMs are presented in Figure 7. As can be seen, a slightly higher flow rate was obtained in test conducted with sprayed-on structure GM during the whole test.

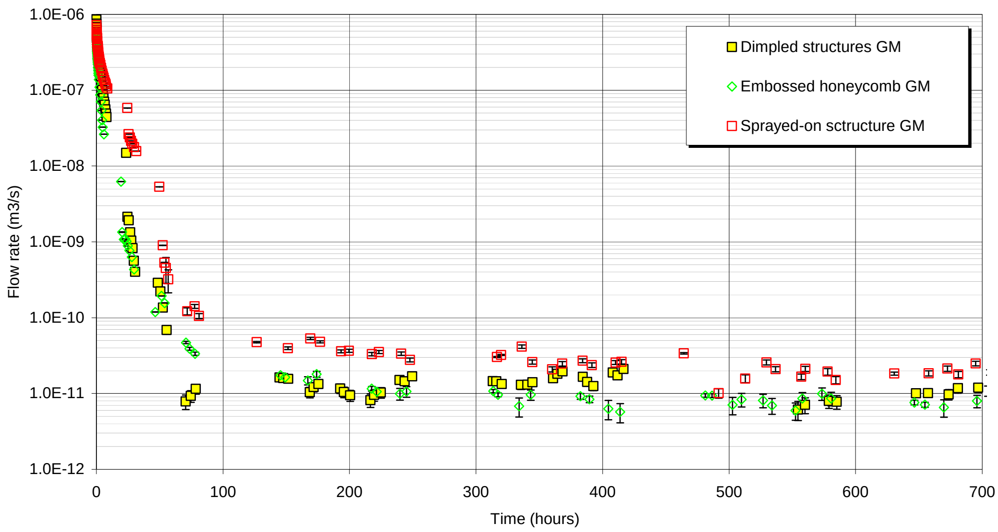

Figure 7. Comparison between the evolutions of flow rates in tests conducted using the textured GMs

Interpretation of experimental results in terms of interface transmissivity

There are two approaches for calculating the interface transmissivity. It can be estimated either based on experimental measurements of flow rate, such as the ones described in this study, or through empirical expressions. Based on the first approach, transmissivity values presented in Table 1 were back calculated by knowing the final flow rates, the hydraulic parameters of the GCL and the underlying soil liner, as well as the size of the testing devices.

Table 1. Final flow rates

Geomembrane	Final flow rate (m^3/s)
smooth	1.1×10^{-11}
sprayed-on structure	1.9×10^{-11}
embossed honeycomb	7.6×10^{-12}
dimpled structures	9.3×10^{-12}

The interface transmissivity was determined based on the analytical solution proposed by Touze–Foltz *et al.* (1999) for a hydraulic head equal to zero at a distance corresponding to the radius of the testing device. Indeed, a flow rate at the outlet of the transmissivity cell was observed in all tests carried out, so the radius of the testing device could be considered equal to the radius of the wetted area. The following equation was used accordingly:

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

where: r_0 is the circular defect radius in m ; k_s is the hydraulic conductivity of the soil component of the composite liner in m/s; h_w is the hydraulic head on top of the geomembrane in m; H_s is the thickness of the soil component of the composite liner in m; θ is the interface transmissivity in m^2/s; I_1 and K_1 are Modified Bessel functions of the first order; and α *in* m^{-1}, A and B in m are parameters given by the following equations:

$$\alpha = \sqrt{\frac{k_s}{\theta H_s}} \qquad (2)$$

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

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

where: K_0 and I_0 are Modified Bessel functions of zero order; and R is the radius of the wetted area in m, which was in most tests the cell radius.

As the soil liner is a combination of a GCL and an underlying soil liner in the case studied in this paper, k_s is the equivalent hydraulic conductivity calculated according to the following equation (Rowe 1998):

$$k_s = \frac{H_{GCL} + H_f}{H_{GCL}/k_{GCL} + H_f/k_f} \qquad (5)$$

where: k_s is the equivalent hydraulic conductivity in m/s; k_f is the hydraulic conductivity of the foundation layer (CCL) in m/s; k_{GCL} is the hydraulic conductivity of the GCL in m/s; H_f is the thickness of the underlying soil in m; and H_{GCL} is the thickness of the GCL in m. H_s is the total thickness of the soil liner (GCL + CCL) in m, given by:

$$H_s = H_{GCL} + H_f \qquad (6)$$

Results obtained in terms of transmissivity are presented in Table 2.

Table 2. Interface transmissivities

Geomembrane	Interface transmissivity (m^2/s)
smooth	2.24×10^{-11}
sprayed-on structure	3.70×10^{-11}
embossed honeycomb	1.44×10^{-11}
dimpled structures	1.82×10^{-11}

As mentioned, the interface transmissivity can also be estimated based on empirical expressions, by knowing the hydraulic conductivity of the foundation layer above the geomembrane. The non-uniformities of the composite liner interface are included in a contact quality factor (contact conditions). Contact conditions were in a first place defined in qualitative terms. However, qualitative definitions are subjective and may lead to different interpretations of a given field case. To overcome this limitation, Rowe (1998) proposed quantitative definitions linking the soil liner hydraulic conductivity to the interface transmissivity for poor and good contact conditions. These quantitative definitions were extended by Touze-Foltz & Giroud (2003) for excellent contact condition. Later on, Barroso & Touze-Foltz (2006) proposed a new contact condition, which they termed as “GM–GCL Contact Condition”, based on experimental data. Quantitative definitions of the contact conditions are given below:

$$\log \theta = -1.7476 + 0.7155 \log k_L \quad \text{for excellent contact condition} \quad (7)$$

$$\log \theta = -1.3564 + 0.7155 \log k_L \quad \text{for good contact condition} \quad (8)$$

$$\log \theta = -0.5618 + 0.7155 \log k_L \quad \text{for poor contact condition} \quad (9)$$

$$\log \theta = -2.2322 + 0.7155 \log k_{GCL} \quad \text{for GM–GCL contact condition} \quad (10)$$

where θ is the interface transmissivity of the interface, k_L is hydraulic conductivity of the soil in contact with the GM, and k_{GCL} is the hydraulic conductivity the GCL component of the composite liner. Equations 1 to 4 can only be used with the following units: θ (m^2/s) and k (m/s).

The interface transmissivity estimated using the Equation 10 was equal to 1.9×10^{-10} m^2/s (for a k_{GCL} equal to $3.7\times10^{-11} m^2/s$, measured under a confining stress equal to 50 kPa). As may be expected, this value of transmissivity is higher than the ones obtained in present study, since the expression for "GM-GCL Contact Condition" was initially defined as an upper bound of experimental data presented by Barroso *et al.* (2006). Therefore, results obtained in this study are in agreement with previously obtained data.

Comparison with field contact conditions

The values of interface transmissivity obtained in this study are plotted against the hydraulic conductivity of the GCL together with the synthetic results obtained using Equations 7 to 10, respectively for poor, good, excellent and GM-GCL contact conditions in Figure 8.

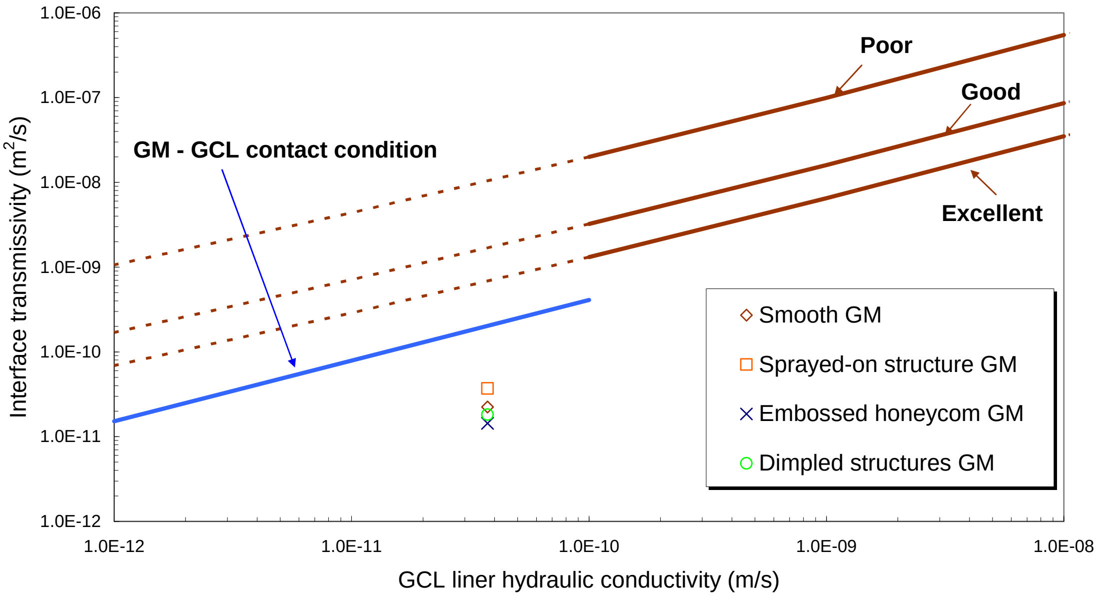

Figure 8. Comparison of experimental results to poor, good, excellent and GM-GCL field contact conditions

As can be seen all experimental values are located below the “GM-GCL Contact Condition” and there is no significant difference between the textured and smooth GMs in terms of interface transmissivity. These findings tend to confirm that the features of the interface are determinant on flow rate through composite liners. It also suggests that, after steady state achievement, smooth and textured GMs can perform similarly.

CONCLUSIONS

This paper presented and discussed the experimental work performed on flow rates through composite liners due to GM defects. Composite liners consisted of a GM, with a 3×10^{-3}m circular hole, a GCL and a CCL. Four GMs were used, namely a smooth GM, a sprayed-on structure GM, an embossed honeycomb GM and a dimpled structures GM.

Tests were performed using a 0.2 m diameter cell, under a hydraulic head equal to 0.3 m and a confining stress equal to 50 kPa. One of those tests was carried out simultaneously at two laboratories (LNEC, in Portugal and

Cemagref, in France) to check test reproducibility. The main purpose of this research was to study the influence of the textured structure of GMs on the flow rate and on the corresponding interface transmissivity.

The results showed that the tests are reproducible and that the final flow rates obtained were similar regardless the type of GM used. Also, transmissivities obtained were smaller than the ones estimated by using the empirical equation proposed by Touze-Foltz & Barroso (2006) for "GM-GCL Contact Condition" which was initially defined as a maximum from experimental data presented by Barroso *et al.* (2006). Thus, data obtained through this study are consistent with previously obtained data. Results obtained also suggest that, after steady state achievement, smooth and textured GMs can perform very similarly while contacting GCLs.

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