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Laboratory investigation of flow rate through composite liners consisting of a geomembrane, a GCL and a soil liner

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Abstract

Composite liners comprising a geomembrane (GM) with a circular hole, a geosynthetic clay liner (GCL) and a compacted clay liner were studied in tests conducted at three scales to measure the flow rates at the interface between the GM and the GCL and in the composite liners. The tests conducted aimed at studying the influence of the prehydration of the GCLs, the influence of the confining stress, and the influence of the hydraulic head on flow rates through composite liners due to defects in the GM. Another goal of these tests was to check the feasibility of an extrapolation of results obtained from small-scale tests to field conditions. The results indicate that the prehydration affected flow rate in a different way according to the confining stress applied and the GCL used. These also indicate that the flow rate decreases with the increase in confining stress and that this effect is higher for prehydrated GCLs than for non-prehydrated GCLs. These results show as well that the flow rate increases when the hydraulic head increases. Finally, small-scale tests overestimate the flow as compared to intermediate and large-scale tests and thus flow obtained in small-scale tests represent an upper bound of flow that would be obtained in field conditions.

Keywords: Landfills; Composite liners; Geomembrane defects; Geosynthetic clay liners; Flow rate

1. Introduction

Several different types of lining systems can be used to limit contaminant migration to levels that will result in negligible impact on the environment. The simplest liner consists of either a geomembrane (GM), a compacted clay liner (CCL), or a geosynthetic clay liner (GCL). Whereas any of these materials can be used as a barrier by itself, modern landfills usually combine two or more components, for example, a GM over a CCL, a GM over a GCL, or a GM over a GCL over a CCL, thus creating a composite liner.

In a composite liner, the GM provides the primary resistance to advective flow of contaminants (also termed leakage, and herein simply referred to as flow) as well as to diffusion of some contaminants. Despite all precautions regarding manufacturing, transportation, handling, storage and installation, defects in the GM can occur in sites where a strict construction quality program is implemented. A survey by Nosko and Touze-Foltz (2000), covering about 108 ha, indicated a mean defect density of 12.9/ha. A higher defect density was reported by Rollin et al. (2002), based on a synthesis of studies involving electrical leak detection systems. The mean defect density estimated by these authors was 17.4 holes/ha. A more recent study by Needham et al. (2004) based on permanent in situ monitoring systems, installed at more than 50 landfill sites and covering approximately 102 ha, indicates a mean density of 14.3 holes/ha.

Defects in the GM represent preferential flow paths for leachate migration. Their impact can be minimized by proper design of the landfill liner. For that, it is of primary

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importance to predict the flow rate through composite liners due to defects in the GM. Several studies have been carried out to quantify the flow rate. However, they focused on composite liners consisting either of a GM and a CCL (e.g. Fukuoka, 1986; Brown et al., 1987; Touze-Foltz, 2002, Cartaud et al., 2005a), or of a GM and a GCL (e.g. Estornell and Daniel, 1992; Harpur et al., 1993; Koerner and Koerner, 2002). Composite liners consisting of a GM, a GCL and a CCL have not been studied, despite the popularity of this type of composite liners. In Portugal, for example, this was the design solution adopted in most landfills recently constructed. In France, according to the French Ministry of Environment (MEDD and BRGM, 2002), GCLs have to be used in conjunction with a minimum 0.5 m thick CCL in municipal solid waste landfills. This practice is related to the recommendation made by the European Directive No. 1999/31/EC that regulates the design of landfill liner systems. It establishes that the protection of soil and water must be achieved by combining a geological barrier with an artificial sealing layer (usually a GM). The geological barrier must have a hydraulic conductivity lower than 10^{-9} m/s and be at least 0.5 m thick. According to this directive, if the geological barrier does not fulfill the aforementioned conditions, other materials may artificially complement it, provided that a technically equivalent protection can be achieved. The minimum thickness of the equivalent barrier must be 0.5 m. As the geologic conditions in situ are often very heterogeneous in Portugal, GCLs have been systematically used over 0.5 m CCLs in order to protect the environment.

Two different studies focused on the hydraulic behavior of composite liners consisting of a GM and a GCL. Estornell and Daniel (1992) examined the hydraulic performance of composite liners consisting of punctured GM and three different GCLs (GM-supported, needle-punched, and adhesive bounded). According to these authors, the effectiveness of composite action between a defective GM and the bentonite in the GCLs depends on whether a geotextile separates the defective GM from the bentonite. Harpur et al. (1993) carried out tests to measure the liquid flow beneath a GM with a hole placed over different types of GCLs from which they quantified the transmissivity of the interface. Tests were conducted under two different normal stresses, 7 and 70 kPa, respectively, and under a hydraulic head of 0.3 m. They found interface transmissivities in the range of 6×10^{-12}–2×10^{-10} m^2/s for the four geotextile-supported GCLs, and 3×10^{-12} m^2/s for a GM-supported GCL. They also observed that the final interface transmissivity was similar for both normal stresses. Laboratory tests were also conducted by Koerner and Koerner (2002) to evaluate what amount of flow might result from a needle-punctured GM over a GCL. Flow was measured for four different circular hole scenarios: 3.6 mm in diameter, 1.0 mm in diameter, needle diameter (approximately 0.1 mm), and a 0.1 mm diameter with the needle left in the hole. Tests were conducted under different hydraulic heads in the range of 2.5–60 cm and under a confining stress of 35 kPa. The results obtained indicate that, in general, the flow rate gradually increased as the hydraulic head increased. Under a 0.3 m hydraulic head the flow rate was rather similar (approximately 3×10^{-11} m^3/s), regardless of the size of the hole. In these three studies, the parameters studied were the nature of the GCL, the load, the hole size in the GM and to some extent the hydraulic head. These studies did not focus on the hydraulic performance of composite liner when there is a prehydrated GCL under the GM, despite the recommendation that they should be hydrated under a vertical load after installation in order to reach a better performance. A minimum prehydration at a water content equal to 100% is, for example, suggested by the Comité Français des Géosynthétiques (1998). Furthermore, the influence of the combination of load and prehydration remains unstudied from an experimental point of view. Thus, the purpose of this study was to ascertain the effect of using prehydrated GCLs as compared to non-prehydrated GCLs, as well as the increase in confining stress (load due to waste) and hydraulic head on flow rates through composite liners due to defects in the GM.

The flow rate, through the composite liner consisting of a GM with a circular hole and a GCL over a CCL, was measured under three test conditions (small scale, intermediate scale and large scale). The small-scale tests were carried out to examine the influence of the parameters mentioned above. Other goals of the small-scale tests were to examine the influence of the type of geotextile in contact with the GM (non-woven or woven) and to study the influence of the nature of bentonite (powdered or granular) on flow rate through composite liners. Intermediate-scale (IST) and large-scale (LST) tests were performed to complement the small-scale tests and to check the feasibility of an extrapolation of the results obtained from small-scale tests to field conditions.

2. Materials and methods

2.1. Geosynthetics

A smooth non-treated HDPE GM, 2 mm thick, was used together with three different GCLs. These are described in Table 1 and are called GCL-1, GCL-2 and GCL-3 in this paper. The first two products were supplied by the same manufacturer and were identical, except that the bentonite was granular in GCL-1 and powdered in GCL-2. GCL-3 was supplied by a different manufacturer. These GCLs are commonly used in Portuguese landfills and were selected for this reason.

2.2. Soil

The soil used in the experimental work came from a landfill located west of Portugal. Two samplings carried out, one in late 2001 for the small-scale tests and the second one in 2002 for the IST and LST as the exact amount of

Table 1
Characteristics of GCLs as supplied by the manufacturers

	Specimens	GCL-1	GCL-2	GCL-3
Bentonite layer	Type of bentonite	Natural, Na^+, granular	Natural, Na^+, powdered	Activated Na^+, granular
	Mass per unit area (g/m^2)	4670	4670	5000
Cover material (GTX)	Mass per unit area (g/m^2)	220	220	200
	Type	GTX, PP, NW, needle punched	GTX, PP, NW, needle punched	GTX, PP, NW, needle punched
Carrier material (GTX)	Mass per unit area (g/m^2)	110	110	125
	Type	GTX, PP, W	GTX, PP, W	GTX, PP, W
GCL	Mass per unit area (g/m^2)	5000	5000	5300
	Type	Needle punched	Needle punched	Adhesive bond plus semi-needle punched
	Dry thickness (mm)	6	6	7
	Hydraulic conductivity (m/s)	$\leqslant 5 \times 10^{-11}$	$\leqslant 5 \times 10^{-11}$	$\leqslant 5 \times 10^{-11}$

Notes: GTX = geotextile, PP = polypropylene, NW = non-woven, W = woven, Na^+ = sodium.

Table 2
Characteristics of soils used

Specimen	Percent fines (%)	Percent clay (%)	Atterberg limits			Proctor modified		k (m/s)
			LL (%)	LP (%)	PI (%)	ω_{opt} (%)	γ_d max (kN/m^3)	
S-1	73.6	40.5	54.2	23.7	30.5	13.6	19.1	8×10^{-11}
S-2	37.7	17.0	33.1	19.7	13.4	8.1	21.3	3×10^{-10}

Notes: percent fines = percent passing the USA No 200 sieve (openings of 75 μm); percent clay = percent finer than 0.002 mm; LL = liquid limit; LP = plastic limit; PI = plasticity index; ω_{opt} = optimum water content; $\gamma_d$max = maximum dry unit weight; k = hydraulic conductivity of the soil.

soil necessary for all tests had not been foreseen. The second sampling could not be performed in the same location as the first one as the GCL and GM had been installed in the first location. Both locations correspond to different soils from a geotechnical point of view due to the geological conditions occurring on site. They consist of 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. The Cretaceous formations outcrop at the southern portion of the landfill consist of intercalations of clayey soils, sandy silts and sandstones.

Soils are referred to herein as S-1 and S-2. Soil S-1 was used in small-scale tests carried out with GCL-1, and soil S-2 was used in all the other tests, namely small-scale tests carried out with GCL-2 and GCL-3, IST and LST. Table 2 summarizes the relevant geotechnical characteristics of these soils for the preparation of the composite liner and for the interpretation of test results.

Proctor modified was used instead of standard Proctor to measure the optimum water content (ω_{opt}) and the corresponding maximum dry unit weight (γ_d max) because the mechanical energy applied by this test is closer to the mechanical energy applied by modern field equipments than the mechanical energy applied by the standard Proctor.

2.3. Small-scale tests

Small-scale tests were carried out in a circular perspex cell specially designed to measure the flow rate through composite liners and as previously described by Touze-Foltz (2002), Touze-Foltz et al. (2002) and Cartaud and Touze-Foltz (2004). Briefly, the cell consists of four parts: (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, to accommodate 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, 6 cm high that accommodates the granular cover plate. About 4.5 kg of soil was compacted inside the base cylinder in two lifts approximately 2.1 cm thick, to a water content of approximately 2% above the ω_{opt} indicated in Table 2. This operation was made using a hand packer. The excess soil material was carefully cut to yield a smooth surface. Then the GCL specimen was placed on top of the soil, usually with the non-woven geotextile on top. This was followed by the installation of the GM with a 3 mm circular hole at its center. Then, the granular cover plate was placed above the GM. The base and upper parts of the cell were then secured with retaining threaded rods. The cell was placed in a press, which allowed the application of confining stresses. 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 can be set to a specified hydraulic head that can be kept constant during the entire test (constant head tests). Fig. 1 shows the schematic of the small-scale test.

Tests were carried out to study the relative importance of some parameters that govern the flow rate through composite liners due to defects in the GM, namely the pre-hydration of GCLs, the confining stress over the GM liner and the hydraulic head applied on top of the GM. These issues were analyzed based on results obtained in tests carried out with GCL-1 and GCL-3. Other goals of the tests were to study the influence of the type of geotextile in contact with the GM (non-woven or woven) and to study the influence of the nature of bentonite (powdered or granular) on flow rate through composite liners. These issues were studied based on the results obtained in tests conducted with GCL-2. Tests carried out with this latter product were also used to assist in the interpretation of the IST and LST.

Tests were conducted using either non-prehydrated GCL (water content as supplied) or prehydrated to a water content equal to 100% (Table 3). The prehydration process comprised immersing the GCL specimens into tap water during the time necessary to reach a water content equal to 100%. Specimens were then placed inside a watertight bag under a normal stress equal to the one to be used in the flow test (i.e. 50 or 200 kPa), during 1 week, for water content homogenization purposes. This methodology was adopted because it was found that the uniformity of the water content distribution is better when the specimens are kept under load during that testing period (Touze-Foltz et al., 2002). Similar findings were reported by Bouazza et al. (2002).

Non-prehydrated and prehydrated test conditions were chosen to represent two possible approaches used during GCL installation. The non-prehydration represents the field conditions, for example, in landfills, where GCL is installed at its natural water content on a foundation layer, whereas prehydration to a water content of 100% represents the recommendation of the Comité Français des Geosynthétiques (1998).

Three different normal stresses were applied, namely 25, 50 and 200 kPa. The first stress was chosen to allow a comparison with the results obtained in the LST, which for experimental reasons could not be carried out at a larger stress. The second and third confining stresses represent approximately two stress levels that may be exerted on a

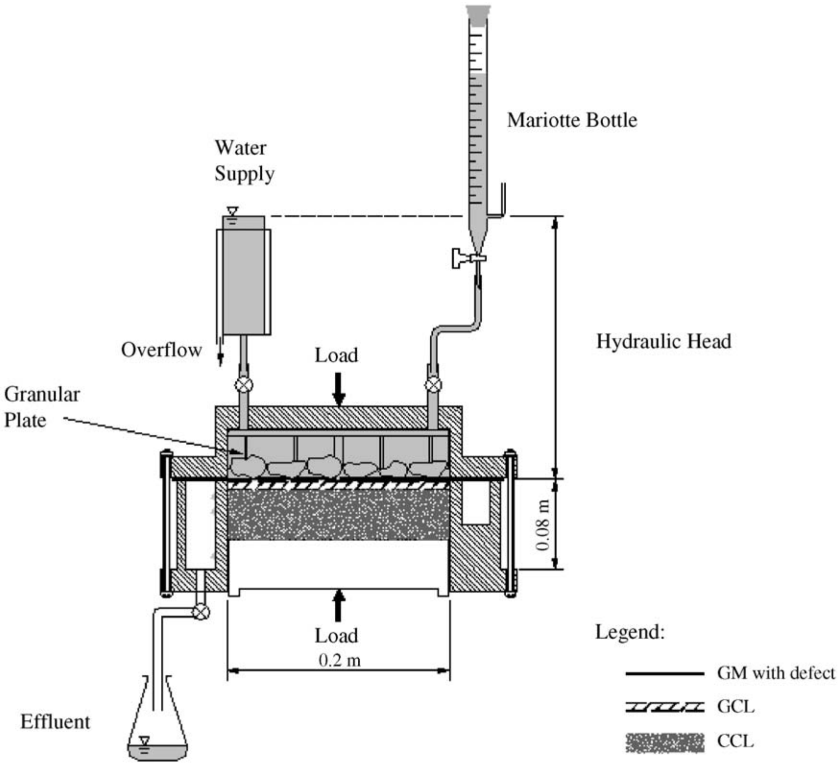

Fig. 1. Schematic of the small-scale test apparatus.

Table 3
Summary of the tests carried out and final flow rates obtained

Test no.	Soil	GCL specimen	GCL status	Initial water content (%)	Final water content (%)	Normal stress (kPa)	Hydraulic head (m)	Final flow rate (m^3/s)
1	S-1	GCL-1	n-ph	10.1	123.4	50	0.3	1.0×10^{-11}
2	S-1	GCL-1	n-ph	13.4	102.0	50	1.2	1.3×10^{-10}
3	S-1	GCL-1	n-ph	11.1	95.1	200	0.3	1.0×10^{-11}
4	S-1	GCL-1	n-ph	10.7	83.8	200	1.2	7.0×10^{-11}
5	S-1	GCL-1	ph	86.6	150.1	50	0.3	5.0×10^{-11}
6	S-1	GCL-1	ph	113.8	163.8	50	1.2	1.7×10^{-10}
7	S-1	GCL-1	ph	89.6	91.2	200	0.3	2.9×10^{-12}
8	S-1	GCL-1	ph	100.1	90.7	200	1.2	5.3×10^{-12}
9	S-2	GCL-2	n-ph	11.3	103.7	50	0.3	1.1×10^{-11}
10	S-2	GCL-2 (inverted)	n-ph	11.3	102.5	50	0.3	5.6×10^{-12}
11	S-2	GCL-2	n-ph	10.3	116.4	25	0.3	1.5×10^{-11}
11b	S-2	GCL-2	n-ph	10.0	111.6	25	0.3	2.4×10^{-11}
12	S-2	GCL-3	n-ph	11.3	149.9	50	0.3	8.7×10^{-12}
13	S-2	GCL-3	n-ph	10.7	134.3	50	1.2	3.5×10^{-11}
14	S-2	GCL-3	n-ph	10.2	104.2	200	0.3	8.5×10^{-12}
15	S-2	GCL-3	n-ph	10.5	95.0	200	1.2	2.9×10^{-11}
16	S-2	GCL-3	ph	100.8	154.2	50	0.3	1.2×10^{-11}
17	S-2	GCL-3	ph	101.3	165.7	50	1.2	3.6×10^{-10}
18	S-2	GCL-3	ph	84.0	95.2	200	0.3	6.6×10^{-12}
19	S-2	GCL-3	ph	98.8	100.6	200	1.2	1.4×10^{-11}
IST	S-2	GCL-2	n-ph	9.5	76.7	50	0.3	2.7×10^{-12}
LST	S-2	GCL-2	n-ph	11.4	83.5	25	0.3	2.5×10^{-11}

Notes: n-ph = non-prehydrated (natural water content); ph = prehydrated (moistened to about 100%); IST = intermediate-scale test; LST = large-scale test.

bottom liner in a landfill. They would correspond approximately to 5 and 20 m of cover waste.

Two hydraulic heads were applied on top of the composite liner, i.e. 0.3 and 1.2 m. The first choice represents the maximum allowable leachate head above the GM in most landfill regulations, whereas the second one can represent the case when the leachate head in a landfill is higher due to, for example, inappropriate operation of the leachate collection system. Regardless of the test scale, the tests were ended when steady state was reached i.e. when (i) the ratio of rate of inflow to rate of outflow was between 0.75 and 1.25 for the last three consecutive flow measurements; (ii) no significant upward or downward trend in flow rate was observed in the last three consecutive readings; and (iii) none of the last three flow rate values was less than 0.75 times the average flow rate value, or greater than 1.25 times the average value. For small-scale tests, it could be observed that 17 days were enough to meet these criteria. Consequently, each test was run for a minimum period of 400 h (17 days).

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 h basis. Tests were conducted in an air-conditioned laboratory. Consequently, water volume variation in the Mariotte bottle due to temperature was negligible. To check that the water volume change in the Mariotte bottle was indeed the flow of water through the composite liner, the evaporation was measured in a 4 mm diameter vertical pipe placed near the test setup and was found to be negligible as compared to flow rates measured, thanks to Mariotte bottles.

2.4. *Intermediate-scale test (IST) and large-scale test (LST)*

IST and LST were carried out to complement the small-scale tests and to check the feasibility of extrapolating the results obtained from small-scale tests to field conditions. The main difference between these two tests is related to the confining stress applied to the composite liner, which is closely related to the test facilities used. LST was run in a square box, 0.9 m deep and 4.84 m^2 in area (2.2 m × 2.2 m), located below ground level.Owing to operational reasons, this test had to be carried out at a confining stress equal to 25 kPa. Thus, even if from a dimensional point of view, it represents better the field conditions than the small-scale tests, from a load point of view it can only represent the first phases of landfill operation, when the load applied by the waste over the lining system is small (i.e. the first lift of waste). To overcome this limitation, an intermediate scale-test was performed at a higher confining stress equal to

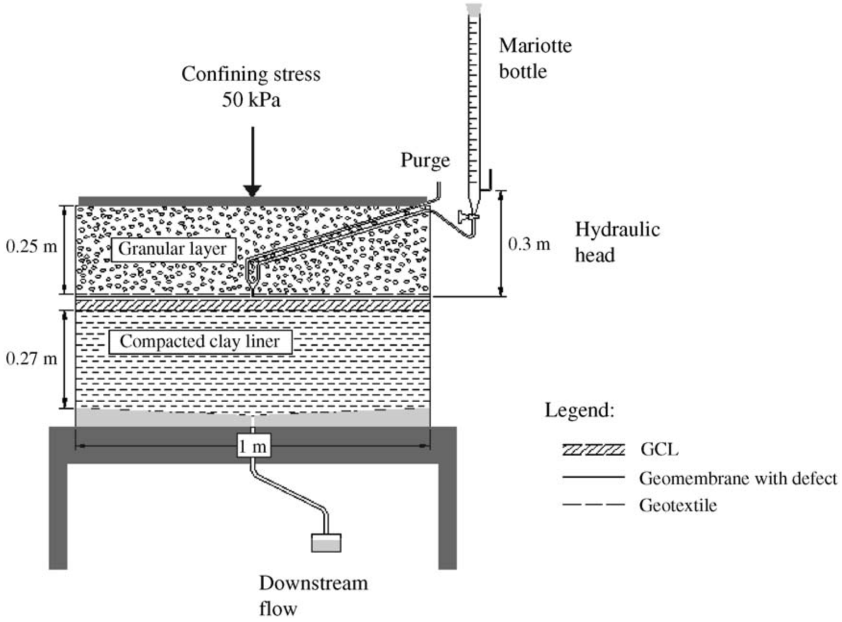

Fig. 2. Schematic of the intermediate-scale test (IST).

50 kPa. This test was carried out in a test cell 1 m in diameter. The same soil and geosynthetics were used in both tests. Tests were performed using non-prehydrated GCLs. Intermediate-scale test lasted about 6.5 months, and large-scale test approximately 6 months.

Fig. 2 gives a schematic of the IST. The experimental device used was previously described by Cartaud et al. (2005a). It consists of three parts: (i) a bottom part with a round base plate fixed on the beam of a hydraulic press that applies the confining stress; (ii) an intermediate cylinder, 1 m in diameter and 0.3 m high, fixed on the base plate, to accommodate the simulated composite liner; and (iii) an upper cylinder, 0.25 m high, to accommodate the granular layer that simulates the drainage layer in a bottom liner of a landfill.

A Pollyanna film and geotextile were placed at the bottom part of the cell to protect the base plate of the cell and to ensure drainage of potential effluents. The soil was then carefully compacted in 4 lifts at its natural moisture content (13.2%). The total thickness of the compacted soil layer was 27 cm. Then, a non-prehydrated GCL-2 specimen at a water content equal to 9.5% was placed above the soil, with the non-woven geotextile on top. An HDPE GM 2 mm thick having a circular hole 3 mm in diameter at its center was installed above the GCL. A special "Y" connection was glued over the hole of the GM. Two pipes were then inserted in this connection. One was connected to the Mariotte bottle to perform flow rate measurements and the other was used as a purge. Finally, a geotextile 828 g/m^2 was placed above the GM to protect it against puncturing by the 25 cm of gravel layer (25/35 mm), which was added on top of the geotextile. This layer was added to simulate the drainage layer in a landfill. Then, a stainless steel plate was placed above the gravel layer. Once this operation was performed, a normal stress of 50 kPa was applied through the hydraulic press. Finally, the water supply was activated and the test started. The test was carried out with a hydraulic head of 0.3 m.

The LST comprises the following layers, from bottom to top (Fig. 3):

- a geotextile, 256 g/m^2, to protect the base of the facility;
- 10 cm of gravel, 25/35 mm, to hold the potential water that could migrate from the soil due to its consolidation under the confining stress applied;
- a geotextile, 642 g/m^2, to separate the materials and to simplify the compaction of the cover soil;
- 27 cm of compacted soil at its natural water content (13.2%); the soil was compacted in 3 lifts, each 9 cm thick;
- GCL-2, non-prehydrated at a water content of 11.4%, installed with the non-woven geotextile on top;
- an HDPE GM, 2.0 mm thick having a circular hole 3 mm in diameter at its center;
- a geotextile, 828 g/m^2, to protect the GM against puncturing;
- a 22 cm thick layer of gravel, 25/35 mm, to simulate the drainage layer in a landfill; and
- layers of concrete cubes (12,084 kg) to apply a final confining stress over the GM of 25 kPa.

It should be noted that in these tests, the soil was compacted at its natural water content as it was impossible to dry the 4500 kg of soil used in both tests. The natural water content of the soil was about 5% above ω_{opt}. The influence of this on hydraulic conductivity of the soil may be small according to Roque (2001). Roque measured the hydraulic conductivity of a clayey soil for several values of

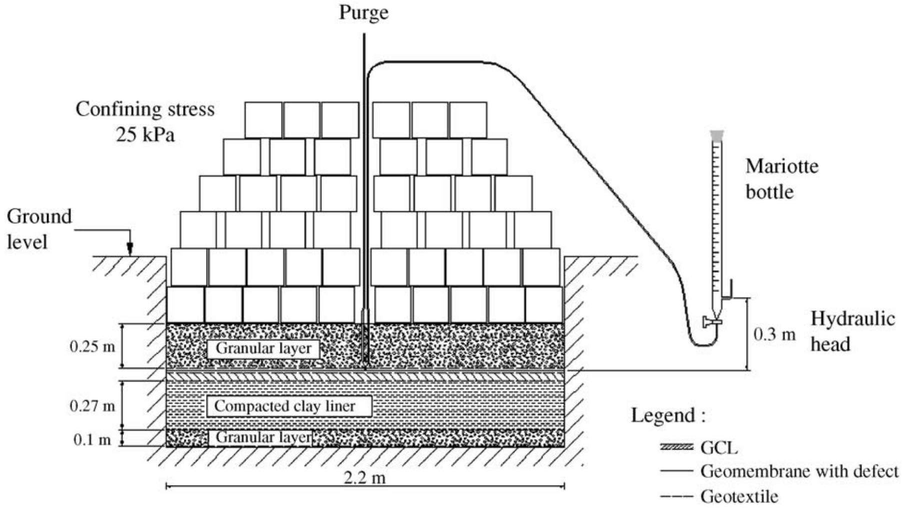

Fig. 3. Schematic of the large-scale test (LST).

water content, namely: 2% below ω_{opt}, ω_{opt}, 2% and 4% above ω_{opt}. Results obtained showed a slight variation on the hydraulic conductivity for the last three values of water content. These results are consistent with the results obtained by Mitchell et al. (1965). On the basis of these findings, it was assumed that the hydraulic conductivity was of the same order of magnitude as the one that would be obtained if the soil was compacted with a moisture content 2% above ω_{opt} (the one used in small-scale tests).

2.5. *Description of tests performed*

Tests 1–8 were performed with GCL-1, either using non-prehydrated specimens (tests 1–4) or prehydrated specimens (tests 5–8). Test 9 was carried out in the same test conditions as the IST, with GCL-2, under non-prehydrated conditions. Test 10 was conducted in the same test conditions as test 9, but with GCL-2 inverted, i.e. with the woven geotextile in contact with the GM. They were conducted using non-prehydrated specimens. Tests 11 and 11b were both conducted using non-prehydrated specimens of GCL-2, in the same test conditions as the LST. Tests 12–19 were performed with GCL-3, either using non-prehydrated specimens (tests 12–15), or using prehydrated specimens (tests 16–19). Test conditions used are detailed in Table 3.

3. Results

3.1. *Small-scale tests*

3.1.1. *Flow rate*

Figs. 4–7 present the evolution of flow rates for GCL-1 and GCL-3, for non-prehydrated and prehydrated specimens. Values of flow rates contain the error bars corresponding to the uncertainty of measurement.

The uncertainty of measurement is a parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measure and, which is a particular quantity that is subject to measurement (Guide EA-4/02, 1999). The measurement depends on a number of input quantities according to the functional relationship that represents the procedure of measurement and the method of evaluation. The uncertainty of the result of a measurement reflects the lack of complete knowledge of the value of the output quantity, for which an infinite amount of information would be required. The phenomena that contribute to the uncertainty and thus to the fact that the result of a measurement cannot be characterized by a unique value are called sources of uncertainty.

The main possible sources of uncertainty in the measurements carried out in the experimental work described in this paper that contribute to uncertainty include: resolution of each equipment used, results of calibrations, approximations and assumptions incorporated in the measurement methods and procedures, and operator influence. The corrected input quantity is then equal to the sum corrections due to resolution, calibrations, approximations and assumptions incorporated in the measurement methods and procedures, and operator. Corrected input quantities were then used to calculate the standard uncertainty of output estimated, which are hereafter simply termed as uncertainty. Thus, differences in tests results are only significant when they are higher than the uncertainties associated to the measurements. Uncertainty calculations are detailed in Barroso (2005). They are not presented here for the sake of brevity.

It should be noted that for some small values presented in Figs. 4–7, the uncertainty value was higher than the flow rate value. In these cases, it was impossible to plot the corresponding error bars. To emphasize the big uncertainty

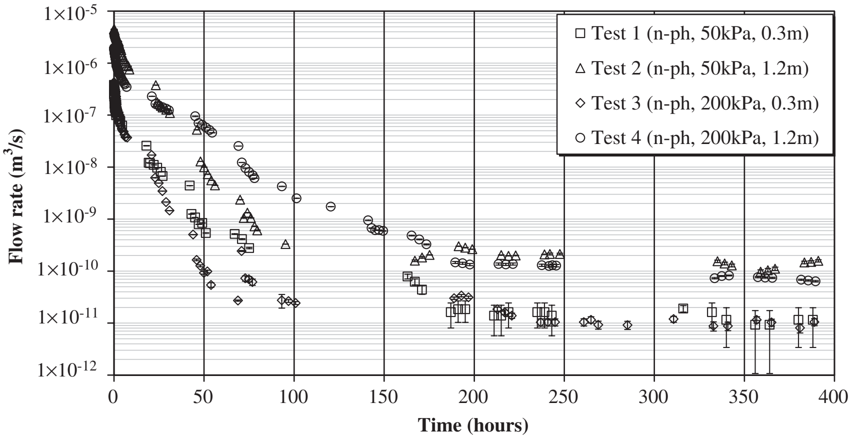

Fig. 4. Evolution of the flow rate in the tests conducted with GCL-1 non-prehydrated.

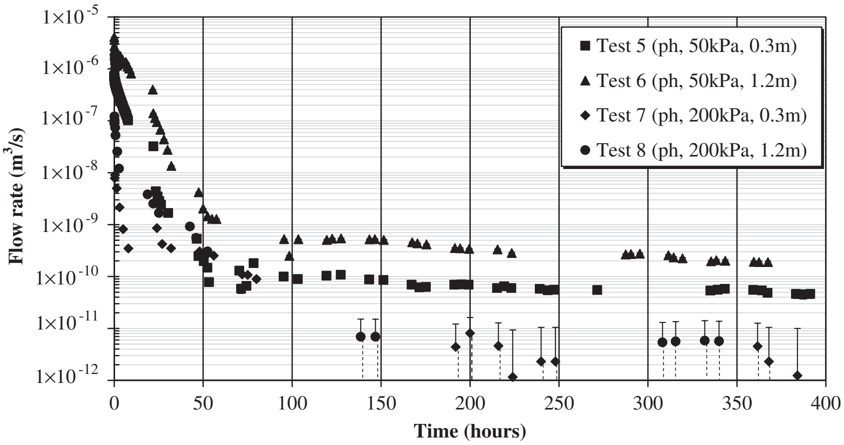

Fig. 5. Evolution of the flow rate in the tests conducted with GCL-1 prehydrated.

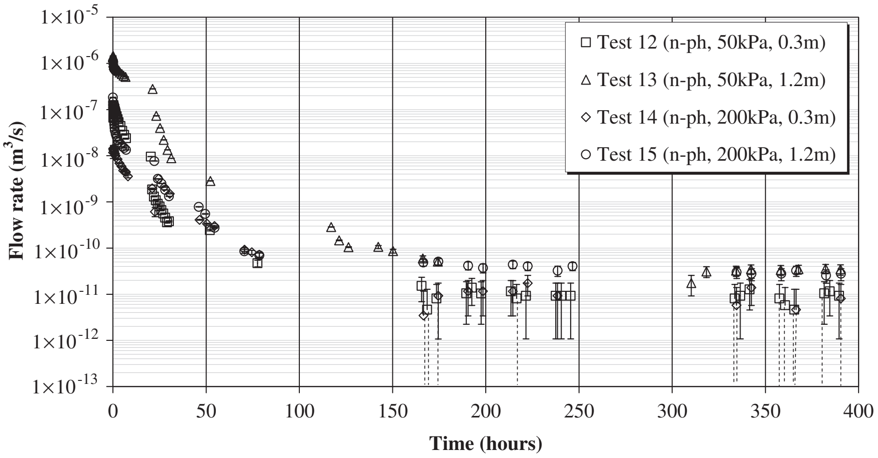

Fig. 6. Evolution of the flow rate in the tests conducted with GCL-3 non-prehydrated.

associated to those measurements, a dashed line was drawn between the value of flow rate and the *x*-axis.

In overall terms, it can be seen that for non-prehydrated GCLs, high flow rates were obtained on tests conducted under a hydraulic head equal to 1.2 m, regardless of the confining stress applied. For prehydrated GCLs, the highest flow rate was obtained on test conducted under a hydraulic head of 1.2 m and a confining stress of 50 kPa. For the other test conditions, GCL-1 and GCL-3 exhibited a different behavior. For GCL-3, differences were within the range of uncertainty after 150 h, whereas for GCL-1, test carried out under 50 kPa and a hydraulic head of 0.3 m

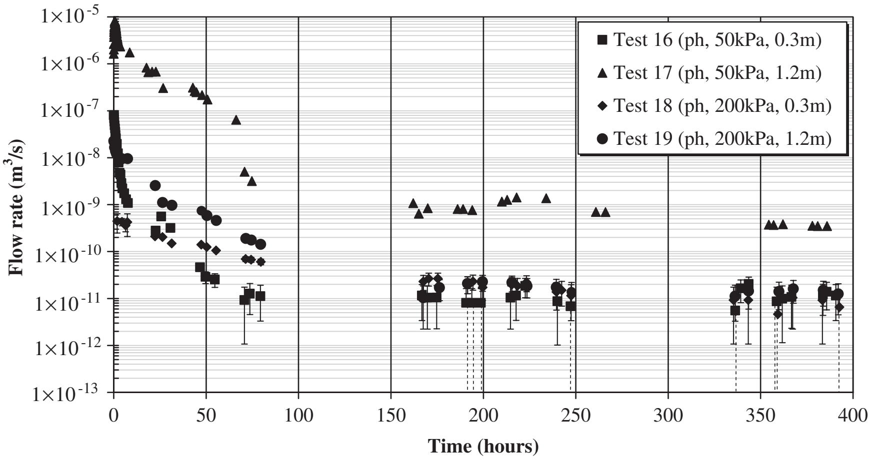

Fig. 7. Evolution of the flow rate in the tests conducted with GCL-3 prehydrated.

also presented a high flow rate. Tests conducted under a confining stress of 200 kPa presented small variations after 150 h.

Final flow rates were also computed by averaging the last three consecutive flow measurements over a minimum time period of 36 h. Results obtained are summarized in Table 3.

3.1.2. Wetted areas

When flow occurs through a composite liner due to a defect in the GM, a fraction of the liquid that flows through the GM defect then flows into the GCL and underlying CCL of the composite liner located directly under the GM defect. However, due to the presence of the interface, a fraction of the liquid that flows through the GM defect then flows laterally to some distance in the interface prior to percolating through the GCL and CCL, hence the concept of a wetted area. The radius of the wetted area can be, either the physical radius of the test cell in the case of laboratory tests as long as some flow can be observed at the outlet of test cell (i.e. effluent flow), or a virtual radius in field conditions.

For all small-scale tests carried out, a flow could be observed at the downstream side of the cell; even though, in some tests, this flow consisted just of some drops of water. Accordingly, the radius of the wetted area corresponds to the physical radius of the test cell.

In order to study the shape of the wetted area, a blue dye was injected in the influent flow in tests 9 and 10 after steady state was achieved (Fig. 8). Although at first glance, the blue dye seems to involve a small area in test 10 carried out with the woven geotextile in contact with the GM, a closer look at the upper surface of the specimen shows some water pathways involving the entire GCL area (right-hand side of Fig. 8). In addition, it can be seen that there were some preferential flow paths all along the GCL specimens. Results obtained tend to show the non-uniformity of the flow in the interface, regardless of the type of geotextile in contact with the GM. The non-uniformity of the flow in the interface is also suggested by the fact that the GM surface in contact with the GCL was never uniformly wet as observed when tests were disassembled.

These results also indicate that the transmissivity of the interface between the GM and the GCL is not uniform. This is closely related with the validity of the existing analytical solutions to predict the flow rate through composite liners due to defects in GM, which are based on the assumption that the wetted area is axi-symmetric and the transmissivity of the interface is uniform.

3.1.3. Soil water content

The soil below the GCL was analyzed in terms of water content. Table 4 shows the initial water content, the final water content and the differences obtained between the initial and the final water contents of the soil specimens. As can be observed, for soil S-1, this parameter increased in all tests, suggesting that the soil slightly absorbed water during the tests as the maximum difference is less than or equal to 2%.

For soil S-2, the variations between the initial and final water content were smaller than for soil S-1. For two tests, the water content of the soil even decreased, suggesting that the soil lost water during those tests.

On the basis of these results, it can be concluded that the variations between initial and final water contents of the soil were negligible in small-scale tests. These results tend to show that the infiltration of water into the soils was negligible. It was therefore assumed that the soil above the GCL specimen had a small impact on flow rate at the interface between the GM and the GCL. Thus, variations in flow rate through a given test cannot be attributed to variations of this property.

3.1.4. GCL specimen water content

In order to study the moisture distribution into the specimens, the water content of the GCL specimens was measured at the end of the tests. This was made by cutting

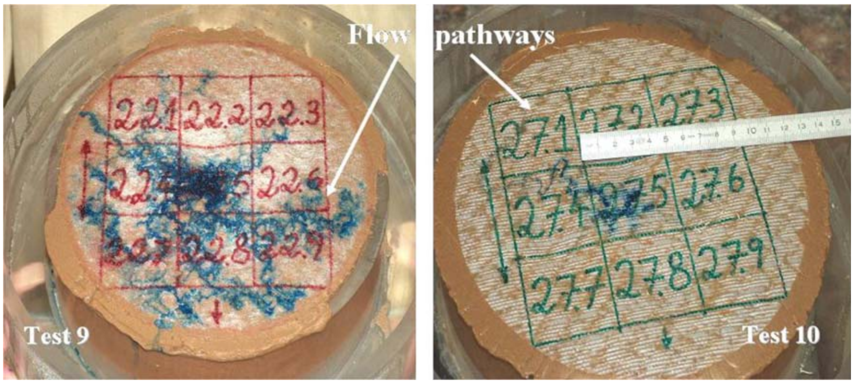

Fig. 8. View of the wetted area observed at the end of tests 9 and 10 carried out with either non-woven geotextile facing the GM or woven geotextile facing the GM.

Table 4
Summary of the soil water contents

Test no.	Soil	Initial water content (%)	Final water content (%)	Difference (%) (final minus initial)
1	S-1	15.2	16.6	1.4
2	S-1	15.3	15.7	0.4
3	S-1	15.4	16.0	0.6
4	S-1	15.2	15.9	0.7
5	S-1	14.9	16.6	1.7
6	S-1	15.2	17.2	2.0
7	S-1	14.8	16.5	1.7
8	S-1	15.1	15.5	0.3
9	S-2	9.9	11.6	1.7
10	S-2	9.5	9.8	0.3
11	S-2	10.2	10.6	0.4
11b	S-2	12.3	12.0	−0.3
12	S-2	9.5	10.5	1.0
13	S-2	9.5	10.2	0.7
14	S-2	9.7	10.1	0.4
15	S-2	9.6	9.8	0.2
16	S-2	9.7	9.8	0.1
17	S-2	9.6	10.6	1.0
18	S-2	10.0	10.1	0.1
19	S-2	10.2	9.7	−0.5

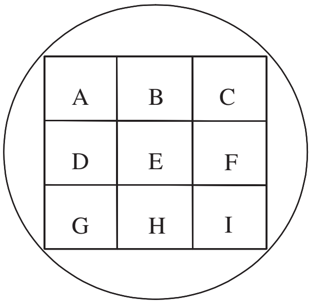

Fig. 9. Schematic of the GCL sub-specimens for measuring the water content.

nine sub-specimens from each GCL specimen. Sub-specimens consisted of squares ($4.7 \times 4.7\,\mathrm{cm}^2$), systematically cut according to a grid drawn on GCL specimens prior to testing and shown at Fig. 9. For comparison purposes, the relative position of the sub-specimens "A" to "I" and the granular plate placed over the GCL specimen during the tests was identical in all tests.

Table 5 presents the results of water content measurements at the end of each test, sorted by sub-specimens. As can be seen in this table, water content distribution is not homogeneous through the GCLs, either for non-prehydrated specimens, or for prehydrated ones. The variation in water contents is related to variations in load through the specimen. Indeed, a common pattern was observed. Most of the highest water contents were observed in sub-specimen "I", which corresponds to a non-contact area between the granular plate and GCL specimens, whereas the lowest water contents were observed in sub-specimens "E" and "F" corresponding to contact points between the GM and granular plate. Despite these variations in water content through the specimens, general trends in the evolution of bulk void ratio and degree of saturation were observed.

The concept of bulk GCL void ratio was first introduced by Petrov and Rowe (1997) in order to homogenize the effects of variable mass of bentonite on GCL height. Bulk GCL void ratio is defined as the ratio of volume of voids within the geotextile and bentonite components of the GCL to the volume of voids within the GCLs. Further details on the computations can be found in Petrov and Rowe (1997). On the other hand, moisture content distribution can be seen in terms of saturation degree. Both bulk void ratios and saturation degrees were calculated for all GCL specimens, based on mean values and are presented in Table 6.

By looking at Table 6, it can be seen that bulk void ratio were lower for tests carried under a confining stress equal to 200 kPa than under a confining stress equal to 50 kPa. The effect of the stress on bulk void ratio was, however, unimportant for tests conducted under lower confining stresses. Similar bulk void ratios were obtained on tests carried out with confining stresses of 50 and 25 kPa. Also, for each GCL, bulk void ratios are rather similar for a given stress. In addition,

Table 5
Summary of GCL water contents for different sub-specimens

Test no.	A	B	C	D	E	F	G	H	I
1	127.8	111.8	125.8	117.2	112.0	114.0	138.4	123.6	140.1
2	103.8	99.2	105.6	94.9	93.7	95.8	112.2	101.4	111.6
3	102.4	82.4	98.3	82.7	85.9	86.2	105.1	93.1	119.9
4	92.1	79.7	88.2	78.1	73.0	79.5	90.0	78.3	95.3
5	156.9	143.4	150.8	142.9	129.7	154.7	149.6	155.7	167.3
6	163.1	175.6	169.6	154.8	148.2	159.0	173.7	164.2	165.7
7	94.7	78.6	97.7	64.0	64.0	93.9	108.5	95.7	123.8
8	93.9	80.3	98.1	84.8	83.5	84.1	99.1	84.0	108.9
9	107.5	94.4	109.0	96.0	94.9	93.8	112.0	103.8	122.1
10	109.2	94.3	109.4	101.0	94.4	94.0	110.6	96.2	113.3
11	119.3	114.2	124.7	101.7	100.5	108.6	128.4	116.8	133.7
11b	115.4	104.1	128.1	102.9	102.3	110.0	111.6	110.1	120.2
12	149.8	134.2	163.1	142.3	133.1	150.0	153.6	147.2	176.0
13	138.2	135.4	149.3	127.4	122.1	121.8	146.4	127.0	141.2
14	98.2	92.3	114.0	92.8	93.3	97.5	120.3	104.8	124.4
15	97.8	71.2	97.1	96.2	85.6	91.3	108.7	87.6	119.3
16	168.2	141.8	160.7	148.6	149.2	137.8	160.1	158.0	163.3
17	172.8	163.6	152.2	148.7	170.4	153.6	168.5	177.7	184.0
18	103.0	93.6	101.7	90.4	89.7	93.1	96.6	99.0	89.4
19	101.9	93.7	106.9	98.0	91.3	100.3	107.0	97.9	108.8

Table 6
Summary of GCL bulk void ratio

Test no.	Soil	GCL specimen	Initial GCL status	Normal stress (kPa)	Hydraulic head (m)	Bulk void ratio	Degree of saturation at the end of the test (%)
1	S-1	GCL-1	n-ph	50	0.3	2.8	96
2	S-1	GCL-1	n-ph	50	1.2	2.5	90
3	S-1	GCL-1	n-ph	200	0.3	2.1	99
4	S-1	GCL-1	n-ph	200	1.2	1.8	100
5	S-1	GCL-1	ph	50	0.3	3.0	100
6	S-1	GCL-1	ph	50	1.2	3.4	100
7	S-1	GCL-1	ph	200	0.3	2.1	94
8	S-1	GCL-1	ph	200	1.2	1.9	100
9	S-2	GCL-2	n-ph	50	0.3	2.4	94
10	S-2	GCL-2 (inverted)	n-ph	50	0.3	2.7	83
11	S-2	GCL-2	n-ph	25	0.3	2.7	93
11b	S-2	GCL-2	n-ph	25	0.3	2.6	91
12	S-2	GCL-3	n-ph	50	0.3	3.4	95
13	S-2	GCL-3	n-ph	50	1.2	3.1	93
14	S-2	GCL-3	n-ph	200	0.3	2.4	94
15	S-2	GCL-3	n-ph	200	1.2	2.3	88
16	S-2	GCL-3	ph	50	0.3	3.6	92
17	S-2	GCL-3	ph	50	1.2	3.9	88
18	S-2	GCL-3	ph	200	0.3	2.2	93
19	S-2	GCL-3	ph	200	1.2	2.3	94

Notes: n-ph = non-prehydrated (water content as supplied); ph = prehydrated (moistened to about 100%).

it can be observed that the saturation degree varied between 83% and 100% for non-prehydrated GCLs, and between 88% and 100% for prehydrated specimens at the end of tests. This suggests that the saturation degree is independent of the initial water content of the GCL specimens, i.e. if specimens were prehydrated or not.

As the liquid-flow through the GM defects depends on the hydraulic conductivity of the underlying layers, which, in turn, is a function of void ratio (Petrov and Rowe, 1997) as well as of the saturation degree, it follows that differences in tests results at steady state can only be attributed to variations in testing parameters, such as the hydraulic head, as the hydraulic conductivity should be very similar in tests performed at a given stress for a given GCL.

3.2. Intermediate-scale test

3.2.1. Flow rate

The evolution of the influent flow rate calculated on a weekly basis for the IST is presented in Fig. 10. The flow decreased with time until a steady state was reached. The final flow rate was equal to $2.7 \times 10^{-12}\,m^3/s$. It was obtained as the mean value of the last ten consecutive flow measurements, over a minimum time period of 10 days.

3.2.2. Wetted area

No flow was observed at the cell boundary where free flow was allowed. Therefore, the size of the wetted area was unknown and field conditions prevail. In order to study the flow patterns in the interface as well as the shape of the wetted area, the blue dye was also injected in the influent flow after steady state was achieved.

Results obtained are illustrated in Fig. 11. As can be noticed, the blue dye involved a 1 cm radius area. This size is small as compared to small-scale tests, whose results suggest that the wetted area should be greater than 10 cm in radius. As the flow rate was very low when the blue dye was injected, and the period of injection was 94 days only, it is suspected that the tracer did not get enough time to reach the edges of the wetted area. Numerical simulations using a tracer mode as performed by Cartaud et al. (2005b) would allow to determine the time necessary for the tracer to reach the edges of the wetted area and the extension of the wetted area but are beyond the scope of this paper.

3.2.3. Soil and GCL water content

As for small-scale tests, the soil and the GCL were analyzed in terms of water content. The results obtained show that the water content of the soil decreased from 12.8% to 11.0% during the test period, indicating that the soil lost water. This decrease seems to be linked with the increase in water content achieved by the GCL. The initial water content of the GCL was 9.5% and after 6.5 months of testing it was 76.7% (mean values), suggesting the GCL absorbed water from the soil in order to reach pore pressure equilibrium. The results obtained are also consistent with the results obtained by Daniel et al. (1993), who observed that the GCLs absorb water from the soil.

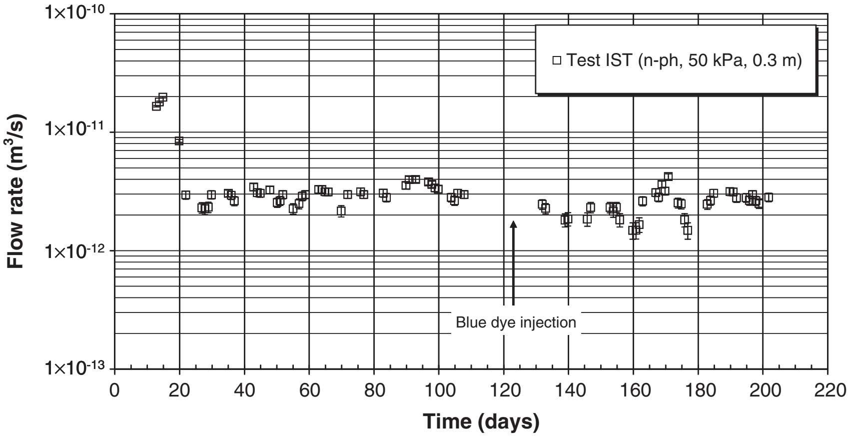

Fig. 10. Evolution of the flow rate in the intermediate-scale test.

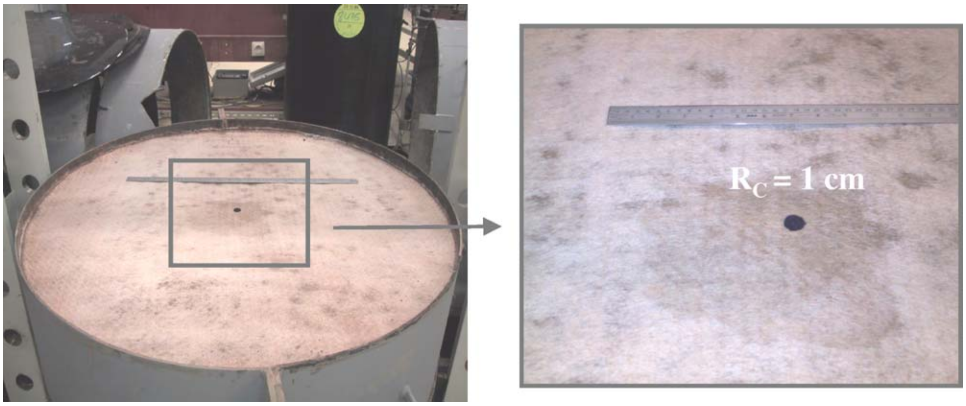

Fig. 11. View of the wetted area observed in the intermediate-scale test.

3.3. Large-scale test

3.3.1. Flow rate

Fig. 12 illustrates the temporal evolution of the daily flow rate for the LST. It must be pointed out that, due to the size of the LST model, the pipe connecting the Mariotte bottle to the hole of the GM created a siphon at the upper point (over the cubes used to apply the confining stress in this test). After a few days of testing, we could observe an air bubble starting to be created at that point. The air bubble was located in the upper part of the pipe. The flow of water between the Mariotte bottle and the GM hole was kept through lower part of the pipe. However, during the test period, air dissolved in tap water or coming from the liner system feed the bubble, causing its growing. In order to guarantee that there was no interruption in water supply to the GM hole, the air bubble had to be removed. To remove the air bubble, the hydraulic head was substantially increased during a couple of minutes, forcing the air bubbles to escape through the purge that was also connected to the GM hole. As can be observed in Fig. 12, after this operation, the flow rate through the composite liner increased, which is consistent with the increase in flow rate observed in small-scale tests when the hydraulic head is increased. It then stabilized again after a certain period of time.

With this cyclic problem of the air bubble growing into the pipe connecting the water supply to the GM hole, which could not be experimentally solved, the continuation of this test would be useless and, therefore, it was ended. Although the variations on flow rate at the end of the test were slight, termination criteria were not entirely fulfilled. A quasi steady-state was thus assumed and a final flow rate was computed. This value was equal to $2.5 \times 10^{-11}\,\text{m}^3/\text{s}$. It corresponds to a mean value of the last ten consecutive flow measurements over a minimum period of 10 days.

3.3.2. Wetted area

For the LST, the size of the wetted area is also unknown a priori, as no edge effects could be noticed. The uniformity of the flow at the interface is unknown too. To overcome this situation, blue dye was injected in the influent flow after achieving the quasi steady-state.

As can be observed at the right-hand side of Fig. 13, the wetted area is not axi-symmetric in this test. However, it should be noted that the wetted area shown by the blue dye

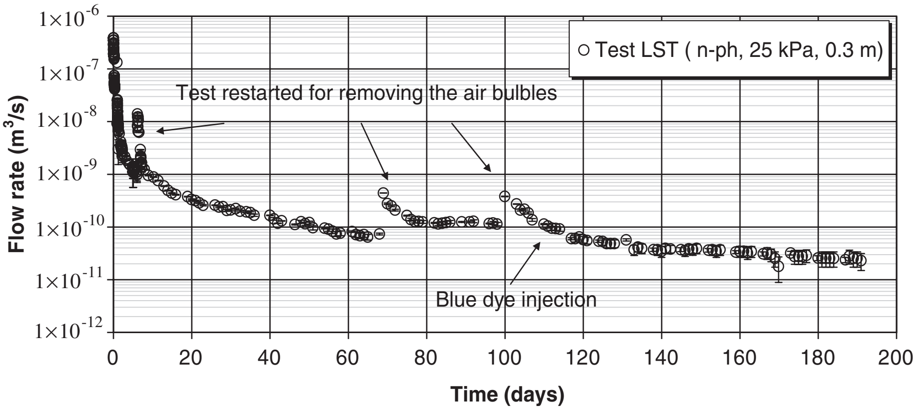

Fig. 12. Evolution of the flow rate in the large-scale test.

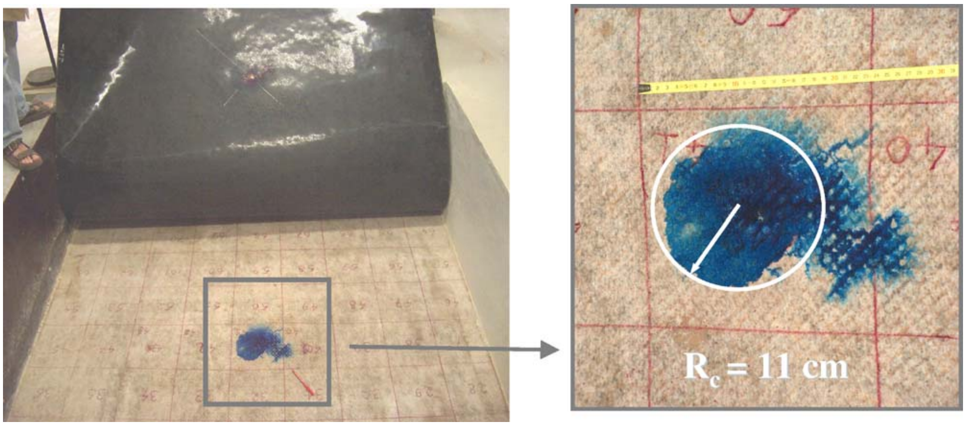

Fig. 13. View of the wetted area observed in the large-scale test.

is certainly not the final one as only a quasi steady-state flow was obtained.

3.3.3. Soil and GCL water content

The soil and the GCL were analyzed in terms of water content. Results obtained show that the soil lost water. Its water content decreased from 13.9% to 11.3% during the test period. Again, this decrease was related with the increase in water content of the GCL, which was able to absorb water from the soil. The initial water content of the GCL was 11.4% and the final water content, after 6 months of testing, was 83.5% (mean values). This increase in water content of the GCL is relatively higher than the one obtained in IST. This may be due to the fact that in the IST, the GCL was submitted to a confining stress of 50 kPa, while in the LST the GCL was submitted to a confining stress of 25 kPa. These findings are consistent with the data presented by Giroud and Daniel (2004). According to these authors, the volumetric content of hydration water, i.e. the amount of water used to hydrate the GCL, decreases with increasing values of the confining stress.

4. Discussion

4.1. Influence of the type of geotextile (non-woven/woven) facing the geomembrane

By comparing the evolution of tests 9 and 10 (Fig. 14), conducted either with the non-woven geotextile in contact with the GM (test 9) or with the woven geotextile (test 10), it can be seen that there is an influence exerted by the way the GCL is installed. Contrarily to what could be expected, during the 350 first hours of test, the specimen with the woven geotextile in contact with the GM presented a higher flow rate than the specimen with the non-woven side up. This unexpected behavior may be related either to bentonite internal erosion in relation to the size of the laboratory model and test conditions, or to bentonite movement into the non-woven structure of the GCL. First, in the test cell, bentonite is not fully maintained at the outlet. Following, due to the relatively high hydraulic gradient applied on the GCL in the test cell, and the lack of confinement of bentonite at the cell boundary at the GCL surface, some bentonite internal erosion occurred. This would not certainly occur on site, but could occur in the test cell due to the lack of confinement of bentonite at the edges and to the hydraulic gradient applied just under the interface. Second, bentonite movement into the non-woven structure of the GCL occurs due to transport, handling and placement of the specimen in cell. Following, it can be expected that some of this bentonite be transported in the interface flow and then collected in the effluent at the cell outlet.

It should be noted that after the first 80 h, the flow stabilized for about 200 h, between 100 and 300 h, and then dropped to an identical value as the one obtained in tests run with the non-woven geotextile facing the GM, remaining stabilized during the rest of the test period, which was longer in this test (about 1000 h) to check the possibility of occurrence of subsequent drops in flow. The reason for the behavior exhibited by the flow rate in test 10 (stabilized for about 200 h and then followed by a drop) was attributed to the result of self-healing of the bentonite, which can occur as the bentonite becomes hydrated. Self-healing of bentonite was reported by Orsini and Rowe (2001) and Rowe et al. (2002), within the scope of a testing program conducted on internal erosion of this type of liner.

As can be seen in Table 6, bulk void ratio and saturation degree are very close in both tests. Comparing the final flow rates obtained in these tests, it is found that it is about 2 times higher in test 9 than in test 10 ($1.1 \times 10^{-11}\,\mathrm{m^3/s}$, for test 9 as compared to $0.6 \times 10^{-11}\,\mathrm{m^3/s}$, for test 10). By taking into account the uncertainties associated with these measurements, this difference is negligible. This finding is consistent with the results obtained by Harpur et al. (1993). It is also in agreement with the results obtained in preliminary tests performed within the scope of the present

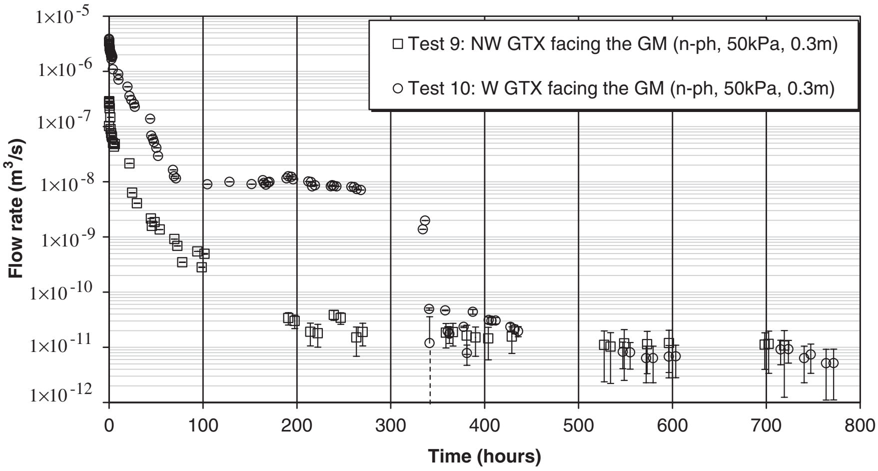

Fig. 14. Comparison of the results in tests carried out with non-woven geotextile (NW GTX) and woven geotextile (W GTX) facing the GM.

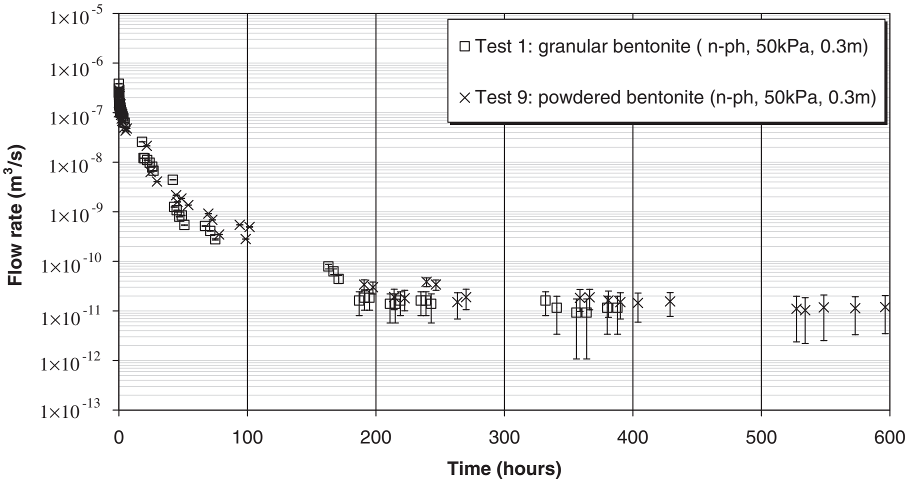

Fig. 15. Comparison of the results in tests carried out with granular and powdered bentonite in GCLs.

research, as reported by Touze-Foltz et al. (2002). For the geotextile mass per unit area investigated, these results tend to show that the type of geotextile has a minor effect on the flow rate, on the long term.

4.2. *Influence of the type of bentonite (granular versus powdered)*

Fig. 15 shows that the evolution in flow rates was identical in tests 1 and 9. Close bulk void ratio and saturation degree values were found in these tests (see Table 6). Similar final flow rates were also obtained in these tests ($1.0 \times 10^{-11}\,\mathrm{m^3/s}$, for test 1 and $1.1 \times 10^{-11}\,\mathrm{m^3/s}$, for test 9). These results suggest that the nature of bentonite (granular or powdered) has little influence on final flow rate in the interface.

These results differ from the results obtained by Harpur et al. (1993), which obtained a transmissivity about one order of magnitude lower for GCL with the powdered bentonite than for GCL with the granular bentonite. Differences between the results obtained in this study and the results obtained by Harpur et al. (1993) might be related with the differences in GCLs studied. Also, the test procedure was different. For small flows, Harpur et al. (1993) performed falling head tests, estimating the flow rate based on water fall in a 7 mm diameter pipe during a certain time interval, whereas in this study, only constant head tests were performed. Therefore, the flow rate measurements were always taken under steady-state conditions.

4.3. *Influence of prehydration*

The influence of prehydration was addressed by comparing the final flow rates (Table 3) obtained in tests carried out under the same testing conditions, either with non-prehydrated, or prehydrated GCLs. However, as can be inferred by the discussion addressed in Section 3.1.4, comparisons between test results can only be made for similar values of bulk void ratio and saturation degree. Thus, comparisons were made between tests 1 and 5, 3 and 7, 4 and 8, 12 and 16, 14 and 18, and 15 and 19. These comparisons tend to show that prehydration affects the final flow rate in a different way according to the confining stress applied and the GCL sample used. For GCL-1, the flow rate was about half order of magnitude higher in tests carried out with the prehydrated specimen than in tests with non-prehydrated specimen under a confining stress equal to 50 kPa. Contrarily, flow rates about one order magnitude higher were found in tests conducted with non-prehydrated specimens than in tests with prehydrated specimens under a confining stress equal to 200 kPa. For GCL-3, the same trend as the one obtained with GCL-1 was found for test conducted under the lowest confining stress. Similar flow rates were, however, obtained with prehydrated and non-prehydrated GCLs under a confining stress equal to 200 kPa, suggesting that, for this product, prehydration had a small impact on flow rate.

On the basis of the above findings, no general trends can be established. It is also difficult to conclude if it is indeed advantageous to prehydrate the GCLs after their installation as recommended by the Comité Français des Géosynthétiques (1998) from the unique point of view of advective transfers through composite liners.

4.4. *Influence of confining stress*

The influence of the confining stress was addressed by comparing the final flow rates obtained in tests carried out under the same testing conditions, either under 50 or 200 kPa. Comparisons made show that the increase in confining stress causes a decrease in flow rate, both for GCL-1 and GCL-3. Nonetheless, a difference was observed between non-prehydrated and prehydrated GCLs. Indeed, the increase in confining stress has a slight effect for non-prehydrated specimens, whereas it has an important influence for prehydrated GCLs.

The decrease of flow with the increase of the stress level can be attributed to the decrease in bulk void ratio observed with the increase of stress level.

The small impact of the confining stress on prehydrated GCLs obtained in this study is consistent with the findings reported by Harpur et al. (1993).

For GCL-2, tested under 25 kPa (tests 11 and 11b) and under 50 kPa (test 9), similar void ratios, saturation degrees and flow rates were obtained. These results suggest that, for low confining stress, the stress applied over the liner system has a negligible influence on flow rate, void ratio and saturation degree, in the case of this GCL.

4.5. *Influence of the hydraulic head*

The influence of the hydraulic head was addressed by comparing the final flow rates (Table 3) obtained in tests carried out under the same testing conditions, either run with a hydraulic head of 0.3 m or run with a hydraulic of 1.2 m. Once again, comparisons were only made for tests with similar values of bulk void ratio and saturation degree. The following test results were thus compared: tests 1 and 2; 3 and 4; 7 and 8; 12 and 13; 14 and 15, 16 and 17 and 18 and 19.

Comparisons made indicate that the flow rate increases with the increase in the hydraulic head, both for GCL-1 and GCL-3 and for non-prehydrated and prehydrated GCLs.

The increase of flow with the increase in hydraulic found in this study is consistent with the findings reported by Koerner and Koerner (2002).

4.6. *Comparison between different scale tests*

Upon comparing the results obtained in IST and small-scale test (test 9), it is found that the final flow rate is about 4 times higher in small-scale tests than in IST ($1.1 \times 10^{-11}\,\mathrm{m^3/s}$, for test 9 as compared to $0.3 \times 10^{-11}\,\mathrm{m^3/s}$, for IST).

Comparing the results obtained in LST and test 11 or test 11b (1.5×10^{-11} and $2.4 \times 10^{-11}\,\mathrm{m^3/s}$, respectively, for tests 11 and 11b; and $2.5 \times 10^{-11}\,\mathrm{m^3/s}$, for LST), it can be observed that the final flow rate is identical, both in the large and in the small-scale tests, considering the uncertainty linked to these measurements. However, these results have to be looked with caution. The fact that the LST was restarted several times, on one hand, increased the flow and, on the other, the steady state could not truly be reached. In fact, it can be observed that the flow was still decreasing after 6 months of testing (see Fig. 12). This tends to indicate that a lower flow rate would have been obtained if the test had been left to run longer so that, in this case again, the small-scale test results overestimate results obtained at field scale.

Despite the discussion addressed above, an important point seems to rise. For test conditions adopted in this study, flow rates obtained in small-scale were in same order of magnitude as that of the flow rates obtained in IST and LSTs, slightly overestimating them. Thus, results obtained from small-scale tests represent an upper bound to flow rates that would be obtained in field conditions.

5. Conclusions

This paper presented and discussed the experimental work performed on flow rates through composite liners involving GCLs due to defects in the GM. Composite liners comprising a GM, with a circular hole, a GCL and a CCL, were simulated in tests conducted at three scales, and the flow rate was measured. small-scale tests were performed using a 0.2 m diameter cell. An intermediate-scale test was conducted using a 1 m diameter cell, and an large-scale test was performed in a square 2.2 m wide test pit facility. The purpose of these tests was to examine the influence of prehydration of the GCLs, the increase in confining stress and the hydraulic head on flow rates through composite liners due to defects in the GM, as well as to compare different scale test results and, thus, to check the feasibility of an extrapolation of results obtained from small-scale tests to field conditions.

The influence of the prehydration of the GCL was studied by carrying out tests either with non-prehydrated (as supplied) or with prehydrated specimens (moistened to water content of 100%). The effect of the confining stress was addressed by performing tests under 50 and 200 kPa. Finally, the influence of the hydraulic head was examined conducting tests with two hydraulic heads: 0.3 and 1.2 m.

The main conclusions that can be drawn from the experimental work performed are as follows: (i) the prehydration affected flow rate in a different way according to the confining stress applied and the GCL used; (ii) the increase in confining stress from 50 to 200 kPa does not seem to affect significantly the value of flow rate for non-prehydrated GCLs, but it seems to have a greater impact on flow rate for prehydrated GCLs; (iii) flow rate increases with the increase of the hydraulic head on the top of the GM and (iv) comparisons between both intermediate-scale and small-scale tests, and large-scale and small-scale tests suggest that, for the confining stresses considered in this study (i.e. 25 and 50 kPa), results obtained from the small-scale tests represent an upper bound of flow that would be obtained in field conditions. Results obtained also suggest that the transmissivity of the interface between the GM and the GCL is not uniform, hence the existing analytical solutions to predict the flow rate through composite liners due to defects in GM present some limitations.

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