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Flow-rate measurements in meter-size multicomponent geosynthetic clay liners

H. Bannour^{1,*}, N. Touze-Foltz²

ABSTRACT: To quantify the flow rate through multicomponent geosynthetic clay liners (GCLs), three different meter-sized specimens from different manufacturers were characterized in a dedicated experimental column. This study allows quantification of the interface transmissivity of multicomponent GCLs when the coating or attached film is damaged over an area large enough to make edge effects negligible. For all multicomponent GCLs characterized, the coating or attached film was less than 0.7 mm thick. Steady-state results indicated flow rates ranging from 4.61 × 10^{-12} to 3.01×10^{-11} m³/s with interface transmissivities ranging from 1.20×10^{-11} to 7.59×10^{-11} m²/s, which are broadly in line with flow rates obtained from conventional geomembrane (GM)-GCL composite liners. Consequently, when the coating or attached film is damaged, the thickness and rigidity of the coating or attached film appears not to affect the steady-state flow rate and interface transmissivity, which leads to a good contact at the interface.

KEYWORDS: Geosynthetics, environmental applications, landfill liner, transmissivity, multicomponent geosynthetic clay liners (GCLs), experiment.

*Corresponding author

1 Irstea, HBAN Unit, Antony, France. Tel: +33-1 40 96 65 25; Fax: +33-1 40 96 62 70; E-mail: hajer.bannour@irstea.fr 2 Irstea, HBAN Unit, Antony, France. Tel: +33-1 40 96 60 39; Fax: +33-1 40 96 62 70; Email: nathalie.touze@irstea.fr

1. INTRODUCTION

In geotechnical and civil-engineering applications, geosynthetics are used as long-term barriers against fluids. For example, geomembranes (GMs) and geosynthetic clay liners (GCLs) serve as sealers in landfills, dams, dikes, ponds, etc. In the document "Recommended Descriptions of Geosynthetics Functions, Geosynthetics Terminology, Mathematical and Graphical Symbols" of the International Geosynthetics Society, GCLs are defined 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." Recently, multicomponent GCLs have been developed, which are GCLs with a coating or attached film. In terms of hydraulic properties, these GCLs fall between geomembranes and GCLs (von Maubeuge et al., 2011; Cleary and Lake, 2011, Barral and Touze-Foltz, 2012).

The ASTM D35 terminology task group is currently discussing the following proposed definitions, which might be added to the ASTM terminology standard D4439 (von Maubeuge et al., 2011):

(i) A multicomponent GCL is a GCL with an attached film, coating, or membrane decreasing the hydraulic conductivity or protecting the clay core or both,

(ii) An adhered GCL is a GCL product in which the clay component is bonded to a film or membrane by adhesion, and

(iii) A coated GCL is a GCL product with at least one layer of a synthetic substance applied to the GCL as a fluid and allowed to solidify (von Maubeuge et al. 2011).

To ensure clarity, this terminology is adopted in this paper.

Multicomponent GCLs have recently been put on the market despite no devices existing that can characterize them especially as regards transfer of pollutants through the GCLs. The objective of this paper is to determine the hydraulic performance (i.e., flow rate and interface transmissivity) of multicomponent GCLs whose coating or attached film has a circular hole. Experiments using various GCL configurations have determined the flow rates in GM/GCL composite liners (Harpur et al., 1993; Barroso et al., 2006a; 2008; 2010; Mendes et al. 2010; Rowe and Abdellaty, 2012; Bannour et al., 2013a; 2013b). In addition, the effect of contact quality at the interface between GM and GCL was evaluated for textured GMs in contact with GCLs (Barroso et al., 2008; Bannour et al., 2013a). The experimental results were reproducible and showed that the texture has little impact on steady-state flow rates. Other research evaluated how the nature of the bentonite, sodium, or calcium bentonite and the structure of the GCL affected flow rates in the GCL (Mendes et al., 2010) and concluded that the nature of the bentonite and the manufacturing process of the GCLs studied did not affect the GM/GCL interface transmissivity under conditions of steady-state flow.

For multicomponent GCLs, Barral and Touze-Foltz (2012) proposed an experimental device that quantified the flow rate through multicomponent GCLs with coatings or attached films that were not damaged. This study showed that flow rates for multicomponent GCLs from two different manufacturers are one order of magnitude larger than flow rates usually measured for virgin GMs (i.e., 10^{-5} m³/m²/d) but are significantly less than the flow rate for typical GCLs.

A preliminary study considered the case in which the coating or laminated film is damaged. This study considered the decimeter scale in quantifying the flow rate and the resulting transmissivity in a multicomponent GCL (Bannour et al., 2013b). Two of the multicomponent GCLs tested, with an attached film at their surface, had to be prehydrated under a low hydraulic head to ensure that the flow rates could be measured and would decrease with time as usually occurs in composite liners containing a GCL. To improve the analysis of the results, additional experiments were undertaken in which a GM was added on top of the multicomponent GCLs. This addition increased the rigidity, thereby improving the distribution of the load, which consisted of the top granular plate and the 50 kPa of confining stress. The addition of the GM

led to a decrease in flow rates and interface transmissivity with respect to the case with no GM. Results obtained at the decimeter scale raised the question of whether a scaling effect, which was not previously observed in GM/GCL composite liners, could explain the different flow rates and interface transmissivities (Touze-Foltz et al., 2006).

The present study quantifies the meter-scale flow rate and resulting interface transmissivity of a multicomponent GCL whose film or coating is damaged. To determine how the thickness of the coating or attached film affects flow rates and interface transmissivity, the meter-scale results are compared with previously obtained decimeter-scale results. Working on the meter scale is appropriate because the area studied is close to that encountered by GM/GCL composite liners in real situations of barriers in landfill areas, where edge effects are negligible (Touze-Foltz et al., 2006).

The remainder of this paper begins with a presentation of the materials characterized in this study and outlines the large-scale experimental procedure. Next, the flow rates, interface transmissivity, and water-content distribution in multicomponent GCLs are presented, discussed, and compared with results obtained from decimeter-scale measurements done on the same multicomponent GCLs and with published results of flow rate and interface transmissivity in composite liners with GCLs.

2. EXPERIMENTS

2.1. Materials and methods

2.1.1. Elastomer plate

A 0.06-m-thick elastomeric plate was used at the bottom of the experimental column as a substitute for the compacted clay liner (CCL) conventionally used under the GCL in interface

transmissivity experiments. It consists in a polymetric plate presenting a higher elasticity and is similar to the one used by Stoltz et al. (2013) in puncture-protection experiments.

2.1.2. Multicomponent GCLs

Three different multicomponent GCLs, each from different manufacturers, were measured in this study. All three were made from a needle-punched GCL with the addition of either a coating or a film.

The first multicomponent GCL (GCL 1) is a coated GCL. The polyolefin polymer coating is added in the fluid state directly onto the woven component of the GCL. This strategy allows the polymer coating to penetrate into the woven structure, surround the needle-punched fibers from the nonwoven carrier geotextile, and attach firmly, uniformly, and in a directionally independent manner to the entire woven GCL component. GCLs 2 and 3 were manufactured with an attached film (Figure 1). Details of the various multicomponent GCLs are given in Table 1, which includes cover and carrier geotextile types, bonding types, film or coating thickness according to EN ISO 9863-1, total dry mass per unit area of the coating or the attached film and, finally, measured total dry mass per unit area of specimen (EN ISO 14149). After the experiments, the mass per unit area of dry bentonite in the specimens was measured. To obtain the mass per unit area of geosynthetics, results from three 0.09-m-diameter specimens

taken from the remainder of the sample (i.e., the part not previously characterized) were averaged after removing the bentonite and cleaning the geosynthetics.

Figure 1 shows the surface of the coating or the attached film on top of each multicomponent GCL. The wrinkling of the film varies depending on the product used. No wrinkling occurs in the attached film of GCL 2. The initial water content of all multicomponent GCLs characterized was approximately 10%.

2.1.3. Protective geotextile

To protect the coating or attached film from puncturing during installation of the granular layer, a nonwoven geotextile was put on the top of the multicomponent GCLs. To adequately protect the GM liner, Stoltz et al. (2013) suggest a minimum mass per unit area of geotextile of 1000 g/m². For the present experiments, a protective geotextile with a mass per unit area of 1200 g/m² was selected for the experimental column used. For experiments performed at the metric scale, the protective geotextile was placed on top of the multicomponent GCLs to inhibit penetration by the 0.25-m-thick gravel layer. To reproduce the same experimental conditions as used at the decimeter scale, an additional experiment was performed on GCL 2 in which the geotextile was not added on the top of the multicomponent GCL; no significant changes in transient or steady-state flow rate were observed. This observation shows that the protective geotextile, which was added to prevent penetration of the GM by the gravel layer, does not influence the flow rate of the multicomponent GCL.

2.1.4. Granular layer

A 0.25-m-thick drainage layer, consisting of 25- to 35-mm-diameter gravel, was used on top of the protective geotextile over thickness to transfer the load from the mechanical press.

2.2. Meter-scale apparatus and experimental setup

The experimental setup consisted of a 1-m-diameter cell as previously described by Cartaud et al. (2005a) and Touze Foltz et al. (2006). The cell is composed of three parts (see Figure 2): (a) a bottom part with a round base plate fixed to the beam of a hydraulic press that applies a compressive stress; (b) an intermediate 1-m-diameter cylinder 0.3 m high fixed to the base plate for accommodating the simulated liner and granular layer; and (c) a stainless-steel plate for applying the compressive stress. An elastomeric plate was placed at the bottom of the cell and a

1-m-diameter multicomponent GCL specimen was placed above the plate. A circular 4-mmdiameter hole was cut in the center of the coating or attached film of the multicomponent GCL. A special "Y" connection was glued over the discontinuity in the coating or attached film, and a pipe was inserted in each branch of this connection: one pipe was connected to a Mariotte bottle to allow flow-rate measurements and the other pipe was used as a purge (Figure 3). Next, a 1200 g/m² geotextile was placed above the multicomponent GCL to prevent it from being penetrated by the gravel. The stainless-steel plate was placed above the gravel layer and a normal 50 kPa compressive stress was applied by the hydraulic press. Finally, the liquid supply was activated and experiments started. The hydraulic head is applied vertically at the level of the hole in the geomembrane. Then the flow takes place horizontally in the interface and jointly vertically in the GCL. To compare measured flow rates with published values, experiments were carried out with a 0.3 m hydraulic head.

3. **RESULTS AND DISCUSSION**

3.1. Steady-state flow rate, interface transmissivity, and water-content distribution

Figure 4 shows the flow-rate dynamics found experimentally for the three multicomponent GCLs. When applying the 0.3m hydraulic head using the Mariotte bottle, the water flows directly in the Y connection glued over the hole. It penetrates the interface between the coating or attached film and the underlying GCL before hydrating the GCL. The flow rate was obtained only upstream of the cell, which shows that the meter scale of the experiment was sufficient to appropriately reproduce, with no edge effects, a real multicomponent GCL in the liner area.

The measured flow rates decreased gradually to steady-state values of 4.61×10^{-12} , 4.36×10^{-12} , and 3.01×10^{-11} m³/s for multicomponent GCL 1, GCL 2, and GCL3, respectively. Steady-state has to be understood here as corresponding to stabilization of the flow

rate at the upstream side. The interface transmissivities was back calculated by using the analytical solution developed by Touze Foltz et al. (1999) in the case of a circular defect in the GM. This solution assumes that (i) the interface transmissivity is uniform so that the wetted area obtained is circular, (ii) the liquid flow in the transmissive layer is radial, (iii) the flow occurs under steady-state conditions, (iv) the CCL, the GCL, and the GM-GCL interface are saturated, and (v) the additional flow through the passive barrier (CCL + GCL) is one dimensional and vertical. The final flow rates (steady-state conditions) measured in transmissivity experiments were used in Equation 1:

$$Q = \pi r_0^2 k_s \frac{h_w + d}{H_s} - 2\pi r_0^2 \theta \alpha \left[A I_1(\alpha r_0) - BK_1(\alpha r_0) \right]$$
(1)

$$\alpha = \sqrt{\frac{k_s}{\theta d_s}} \tag{2}$$

$$A = -\frac{h_{w}K_{0}(\alpha R) + H_{s}(K_{0}(\alpha R) - K_{0}(\alpha r_{0}))}{K_{0}(\alpha r_{0})I_{0}(\alpha R) - K_{0}(\alpha R)I_{0}(\alpha r_{0})}$$
(3)

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

with

$$AI_1(\alpha R) + BK_1(\alpha R) - H_s = 0$$
⁽⁵⁾

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.

Interface transmissivity calculated using the analytical solution were 2.10×10^{-11} , 8.97×10^{-11} , and 7.59×10^{-11} m²/s, for multicomponent GCL 1, GCL 2, and GCL3 (Table 2), respectively. At the end of the experiment, the water-content distribution in the multicomponent GCLs was quantified and the results, which are based on the sampling performed, are plotted in Figure 5. After flow-rate stabilization, the water-content distribution was measured in 37 0.1-m-diameter multicomponent specimens, according to the scheme presented in Figure 6. This method of sampling GCLs to determine the water content repartition is consistent with that

presented by Touze-Foltz et al. (2006). The radius of the wetted area calculated by using the analytical solution developed by Touze Foltz et al. (1999) were 0.05, 0.14, and 0.28 m for multicomponent GCL 1, GCL 2 and GCL3, respectively.

3.2. Performance of multicomponent GCLs

Despite a mass per unit area of 4.40 kg/m², multicomponent GCL 1 had small steady-state flow rates ($Q = 4.61 \times 10^{-12} \text{ m}^3/\text{s}$), which is attributed to the coating that is directly laminated to the covering geotextile of the multicomponent GCL (assuming good contact at the interface). As shown in Figure 4, multicomponent GCL 3 had lower transient and steady-state flow rates on the meter scale ($Q = 3.01 \times 10^{-11} \text{ m}^3/\text{s}$) compared with multicomponent GCL 2 $(O = 4.36 \times 10^{-12} \text{ m}^3/\text{s})$, despite both multicomponent GCLs having a surface film attached by the same production process (Table 2). Compared with multicomponent GCL 2, GCL 3 had a larger wetted-area radius (0.28 m vs 0.14 m) and water-uptake capacity, which may be explained by (i) the mass per unit area of each specimen (6.44 kg/m² for GCL 2 vs 4.27 kg/m² for GCL 3); (ii) the presence of wrinkles on the attached film, which allows water to migrate more easily (this was the case in particular for high transient flow rates, i.e., flow rates approximately one to two orders of magnitude higher than those obtained with multicomponent GCL 1 and 2), and (iii) the possible influence of swelling-index measurements taken on multicomponent GCL 2 and 3 (these were done to evaluate the swelling of the bentonite part of the GCL and could have influenced the contact quality at the interface between the GCL and attached film). The results show that multicomponent GCL 2 swells more than multicomponent GCL 3 (measurements performed following XP P 84-703 gave swell indices of 29 cm³/2g for GCL 2 and 24 cm³/2g for GCL 3). These observations means that multicomponent GCL 2 benefits from better interface contact than multicomponent GCL 3, which is attributed to a better contact between the attached film and the cover geotextile of the

multicomponent GCL. The superior contact is likely due to greater swelling when the bentonite hydrates and the more uniform distribution of bentonite in GCL 2, as determined by the greater mass per unit area (Bostwick et al. 2010).

3.3. Decimeter- vs meter-scale flow-rate dynamics along multicomponent GCL interfaces

Figure 7 compares the decimeter- and meter-scale flow-rate dynamics in multicomponent GCLs from Bannour et al. (2013b). The meter-scale steady-state results are one order of magnitude less the decimeter-scale results, as seen in Table 5. These results were obtained with steady-state flow rates ranging from 4.61×10^{-12} to 3.01×10^{-11} m³/s for the meter-scale experiments and from 1.53×10^{-11} and 2.18×10^{-10} m³/s for the decimeter-scale experiments. This observation shows the importance of the effect of scale for multicomponent GCLs: a sufficiently large area must be studied (i) to minimize the edge effects observed at the decimeter scale, which may generate preferential flow paths in the absence of nonuniformities such as wrinkles in the attached film, and (ii) so that the radius of the experimental device is consistent with the wetted area.

3.4. Comparison with GM-GCL composite liner

Decimeter-scale results obtained by Bannour et al. (2013b) highlight the fact that the flow rate was influenced by the thickness of the polymeric component (i.e., the coating or attached film with or without an additional 2-mm-thick high-density polyethylene "HDPE" GM): the flow rate was one order of magnitude less for a 2-mm-thick HDPE GM on the top of the multicomponent GCL than for no GM. Decimeter-scale flow rates obtained with multicomponent GCLs were one to two orders of magnitude larger compared with those for a GM-GCL composite liner.

Figure 8 compares meter-scale flow-rate dynamics along multicomponent GCL interfaces obtained in this study with results from the study of Touze Foltz et al. (2006) on conventional GM-GCL composite liners. Steady-state flow rates are comparable for both configurations; the average flow rate for the GM/GCL composite liner is 4.09×10^{-12} m³/s. This finding shows that, as found in the meter-scale experiment with a geomembrane, neither the thickness nor the rigidity of the coating or attached film significantly influences flow rates.

Thus, even if the reduced thickness of the coating or attached film decreases rigidity in comparison with the 2-mm-thick geomembrane and decreases the uniformity of load transmission by the granular layer, no impact on flow rate is detected. This phenomenon is probably connected to the bentonite swelling sufficiently to reduce the interface thickness; similar to what occurs in the GM/GCL composite liner.

These findings emphasize that, to quantify flow rates in multicomponent GCLs with the coating or attached film exhibiting a hole on the meter scale, it is necessary to perform meter-scale experiments.

3.5. Synthesis of transmissivity values in GM-GCL composites liners and multicomponent GCLs

Figure 9 gives an overview of published interface transmissivity data and data from this study. For meter-scale experiments with multicomponent GCLs, all data fall under the GM/GCL contact condition defined by Touze Foltz and Barroso (2006), which links the interface transmissivity θ to the hydraulic conductivity k_{GCL} of the GCL by using Equation 1:

$$\log_{10}\theta = -2.2322 + 0.7155\log_{10}k_{GCL} \tag{1}$$

Results obtained for the interface transmissivity are broadly in line with the interface transmissivity found in previous studies that used conventional GM/GCL composite liners. This correlation suggests that, for meter-scale experiments, the thickness and rigidity of the coating

or attached film does not significantly influence the interface transmissivity when the coating or attached film is damaged. Consequently, for a 4-mm-diameter hole, the characteristics of advective transfers through damaged multicomponent GCLs are identical to those through conventional GM/GCL composite liners.

Note, however, that this result does not imply that all aspects of the performance are identical. In fact, the flow rate through an undamaged multicomponent GCLs is one order of magnitude larger than that through an undamaged GM (Barral et al., 2012). In addition, when addressing performance, other considerations regarding mechanical performance, chemical compatibility, and durability are imposed.

4. CONCLUSION

The purpose of this study was to compare the hydraulic performance of a multicomponent GCL with that of a conventional GM-GCL composite liner. To this end, the flow rate and interface transmissivity in multicomponent GCLs was evaluated for the case of a damaged coating or attached film.

For the surface area of the multicomponent GCL to be representative of a real situation, meterscale flow-rate experiments were performed, and the following results were obtained:

- To measure flow rates through multicomponent GCLs, the meter scale is better than the decimeter scale because it avoids edge effects that are likely to influence the experimental results. Consequently, the area studied is close to that encountered by GM/GCL composite liners in real situations of barriers in landfill areas, where edge effects are negligible.
- The meter-scale steady-state flow rate and interface transmissivity obtained were broadly in line with flow rates obtained in previous studies that used conventional composite liner GM/GCL. This correlation emphasizes the fact that, for flow-rate

measurements through a multicomponent GCL with a damaged coating or attached film, the thickness and rigidity of the coating or attached film does not affect the hydraulic behavior of the multicomponent GCL in comparison with conventional composite liners (GM/GCL).

- The swell index and mass per unit area of bentonite in multicomponent GCLs influence the flow rate when a film is attached (glued) to the cover geotextile of the GCL. It is thus important for the mass of bentonite in the GCL to be sufficient so that the swelling capacity of samples leads to better contact at the interface and better performance of the multicomponent GCL.

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NOTATIONS

Basic SI units are given in parentheses.

Q	the flow rate (m^3/s)
r ₀	the circular-defect radius (m)
m _f	Film or coating measured total dry mass per unit area (kg/m^2)
R	radius of the wetted area (m)
e _f	Film or coating thickness (mm)
k _{GCL}	the hydraulic conductivity of the liner GCL (m/s)
ks	the hydraulic conductivity of the liner GCL + CCL (m/s)
$H_{\rm w}$	the hydraulic head (m)
H _s	the thickness of the soil component of the GCL + CCL composite liner (m)

d the thickness (m) of the GCL + CCL liner (m)θ interface transmissivity (m^2/s) α, A, B parameters (dimensionless) I_1, K_1 first-order modified Bessel functions zeroth-order modified Bessel functions (dimenionless) I_0, K_0 ω water content (%)

ABBREVIATIONS

CCL	compacted clay liner
GCL	geosynthetic clay liner
GM	geomembrane
HDPE	high-density polyethylene

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Multicomponent	Cover GTX	Carrier GTX	Bonding	Film or	Film or coating	Measured total
GCL				coating	measured total	dry mass per
				thickness (m)	dry mass per	unit area of
					unit area	specimen
					(kg/m ²)	(kg/m^2)
1	Woven	Nonwoven	Coated	$0.0004 < e_f <$	$0.25 < m_f < 0.4$	4.40
				0.0007		
2	Nonwoven	Woven	Attached	~0.00045	~0.2	6.44
			(glued)			
3	Woven	Nonwoven	Attached	~0.00025	~0.2	4.27
			(glued)			

Table 1 Multicomponent GCLs used in this study.

Table 2 Flow rate, hydraulic conductivity, and interface transmissivity measured and

 calculated by using the analytical solution for steady-state meter-scale conditions. Also shown

 are published results related to multicomponent GCLs.

	G (3)		0 (2)	D 11 0
Multicomponent GCL	$Q(m^3/s)$	K _{GCL} (m/s)	θ (m ² /s)	Radius of
				wattad area P
				welleu alea K
				(m)
				(111)
	10			
GCL 1 (m)	4.61×10^{-12}	2.08×10^{-11}	1.20×10^{-11}	0.05
	10			
GCL 2 (m)	4.36×10^{-12}	2.66×10^{-11}	8.97×10^{-11}	0.14
		11	11	
GCL 3 (m)	3.01×10^{-11}	2.08×10^{-11}	7.59×10^{-11}	0.28
			11	
Bannour et al. (2013b) GCL 1 (dm)	1.73×10^{-11}	2.08×10^{-11}	3.48×10^{-11}	0.1
			11	
Bannour et al. (2013b) GCL 2 (dm)	1.53×10^{-11}	2.66×10^{-11}	3.07×10^{-11}	0.1
	10			
Bannour et al. (2013b) GCL 3 (dm)	2.18×10^{-10}	2.08×10^{-11}	5.46×10^{-11}	0.1
	11		11	
Bannour et al. (2013b) GCL 1 (dm)+GM	1.39×10^{-11}	2.08×10^{-11}	2.78×10^{-11}	0.1
	11	11	11	
Bannour et al. (2013b) GCL 2 (dm)+GM	2.17×10^{-11}	2.66×10^{-11}	4.41×10^{-11}	0.1
	11	11	11	
Bannour et al. (2013b) GCL 3 (dm)+GM	1.31×10^{-11}	2.08×10^{-11}	2.60×10^{-11}	0.1

Q is the steady-state flow rate (m³/s), K_{GCL} is the steady-state hydraulic conductivity (m/s); θ is the interface transmissivity

 (m^2/s) calculated by using the analytical solution; and *R* is the radius of the wetted area (m).



(a)



(b)



(c)

Figure 1: Photographs of surface of the various multicomponent GCLs studied: (a) GCL 1,

(b) GCL 2, (c) GCL 3.



Figure 2: Column-test apparatus modified from Touze Foltz et al. (2006)



Figure 3: Principle of "Y" connection.



Figure 4: Dynamics of flow rate along multicomponent GCLs interfaces obtained by the meter-scale apparatus





(a)









Figure 5: Water-content distribution in multicomponent GCLs after meter-scale experiment:

(a) GCL 1, (b) GCL 2, (c) GCL 3.



Figure 6: Cartography of 0.1-m-diameter GCL specimens.



Figure 7: Comparison of decimeter- and meter-scale flow-rate dynamics along multicomponent GCL interfaces.



Figure 8: Comparison of meter-scale flow-rate dynamics along multicomponent GCL interfaces obtained in this study at metric scale with published results based on conventional GM-GCL composite liners.



- ▲ Barroso et al (2006) × Bannour et al. (2013b) GCL (dm)
- Barroso et al (2008) Bannour et al. (2013b) GCL (dm)+ GM
- Barroso et al. (2010) △ GCL (m)
- Rowe and Abdellaty (2012)



Figure 9: Overview of published transmissivity data for GCLs in contact with GMs and for multicomponent GCLs.