Comparative study of hydraulic behaviour of Geosynthetic Clay Liners exhumed from a landfill cover and from a dam after several years in service

C. Barral, Nathalie Touze, E. Loheas, D. Croissant

in : Eurogeo 5, 16-19/09/2012, Valence, ESP

Comparative study of hydraulic behaviour of Geosynthetic Clay Liners exhumed from a landfill cover and from a dam after several years in service

C. Barral
Hydrosystems and bioprocesses Research Unit, Irstea, Antony, France
CNAM, Paris, France

N. Touze-Foltz, E. Loheas, D. Croissant
Hydrosystems and bioprocesses Research Unit, Irstea, Antony, France

ABSTRACT: A significant number of studies have been published on the field performance of Geosynthetic Clay Liners (GCLs) in landfill covers while the use of GCLs in dams and dikes is more recent and therefore needs more studies. Samples of GCLs were exhumed after several years of service from a landfill final cover and from a dam. The samples were tested for water content, swell index, hydraulic conductivity and exchangeable cations. The tests performed showed that the hydraulic conductivity and swell index of the bentonite evolved at the contact of the surrounding soil which contained calcium. Depending of the duration of service of GCL, very different hydraulic conductivities were obtained (up to 3 orders of magnitude) in relation with the number of hydration-desiccation cycles experienced by the GCLs. Those results will be discussed in the light of previous results obtained on excavations and in tests performed with calcium chloride solutions.

1 INTRODUCTION

Geosynthetic Clay Liners (GCLs) are sealing elements which contain bentonite encapsulated between geotextile components. They have been mostly employed to replace clay liners in landfill cover systems over the past years (Egloffstein 2001, Bouazza 2002). A significant number of studies have been published on GCLs behavior based on field data and have underlined several parameters of influence on GCL field performance, as cation exchange and desiccation hydration cycles, for the case of this specific application of GCLs (Touze-Foltz et al. 2010a).

In comparison to landfill applications during the last 20 years, the acceptance of GCLs as sealing systems in hydraulic engineering applications increased more slowly (Heibaum and Fleischer 2010; Werth et al. 2010). Different requirements have to be taken into account for the lining elements for ponds (with permanent hydraulic loads), dams (with permanent or temporary hydraulic loads) or dykes (with wave pressure loads).

The objective of this paper is to present the results obtained on GCL samples exhumed from a landfill cover and from a dam after 8 and 3 years of service respectively.

The small dams under study used as barrier protection against flooding are only subjected to hydraulic loads during short periods when water levels are high following heavy rainfalls; most of the time the dams under study are “dry” and the GCL may be subjected to cation exchange and stressed by desiccation as in landfill covers.

The general features of the landfill cover, of the dam and of the GCL samples at the time of sampling are presented. Recommendations made by Zanzinger and Touze-Foltz (2009) as to how GCLs should be exhumed, transported and tested were followed in order to obtain reliable and complete results. GCLs from landfill cover and from the dam were tested for saturated hydraulic conductivity, water content, swell index and composition of the exchange complex. Samples of the overlying and underlying soils from each field site were also tested for water content, cations in the pore water and carbonate content.

Data from these tests were evaluated in conjunction with data reported by others recent studies conducted on virgin GCL samples in laboratory with Ca dilute solutions and conducted on GCL samples exhumed from landfill covers.

2 EXHUMATION OF GCLS AND COVER SOILS

GCLs were exhumed from a landfill final cover and from a small dam. The landfill site is located in the east of France (continental climate) and receives 730 mm of precipitation annually. GCLs were overlain by a protective geotextile and a 500 mm vegetated surface layer containing some gravels, tile pieces and roots (Fig.1). The dam is located in the west of

France (oceanic climate) where the precipitation is comprised between 700 and 1200 mm/year. This dam is used to prevent flooding during heavy rainfalls and since its construction it has never been subjected to high hydraulic loads (Fig. 2). The cover profile consists of a 200 mm vegetated surface layer with flint stone pieces and roots. A description of both sites is summarized in Table 1. All of the stitch bonded GCLs were originally composed of natural powdered sodium bentonite sandwiched between two woven geotextiles. At the landfill site, samples L-1 and L-2 were exhumed from two adjacent areas whereas in the dam, the two GCLs D-1 and D-2 were installed one on top of the other. In fact the first GCL was installed during a rainfall event and had swelled without confining stress; a second GCL was thus placed above the first one a few days later to address this installation problem.

Figure 1. Landfill cover layer.

Table 1. Description of lining systems at field sites.

	Site			
	Landfill cover		Dam	
Installation date	2003		March 2008	
Sampling date	August 2011		May 2011	
Service life (year)	8		3.17	
Cover soil thickness (m)	0.5		0.2	
Sample name	L-1	L-2	D-1	D-2
Sample location			Above	Below

Figure 2. Dam to prevent flooding.

For both exhumations, the cover soil was carefully removed to a depth near the GCL using a digging machine. The remaining soil was then removed by hand to prevent damage to the GCL. Rectangular GCL samples (0.3×0.6 m) were cut using a razor knife (Fig. 3), transferred onto rigid plates and hermetically sealed in plastic bags to prevent the loss of moisture during transport and storage. All GCL samples were penetrated by fine roots but no cracks in the bentonite were apparent.

Samples of cover soils and subgrades were also collected for the determination of water content and soluble cation content.

Figure 3. Exhumation of GCL samples.

3 TEST METHODS

3.1 *Swell index*

Swell index tests were conducted according to methods described in standard test XP P84-703 (AFNOR, 2002) which is almost similar to ASTM D 5890 (ASTM, 2011). The swell indices of the exhumed GCLs are consistent with typical values obtained for calcium bentonites (<10 mL/2g) (Egloffstein 2001).

Table 2. Summary of properties of exhumed GCLs.

Site	Initial water content (%)	Post test water content (%)	Thickness under 10 kPa (mm)	Bentonite mass per unit area (kg/m^2)	Swell index (mL/2g)	Hydraulic conductivity[a] (m/s)	Post test water content (%)	CEC (meq/100g)	Exchange Cations (cmol/kg) Na	K	Ca	Mg
L-1	55	122	5.0	3.6	< 10	3.2×10^{-7}	122	84.3	8.3	0.9	37.9	2.4
L-2	49	98	6.2	4.1	< 10	2.4×10^{-6}	97	94.2	8.5	1.2	41.9	3.3
D-1	30	74	6.9	5.3	< 10	7.7×10^{-11}	74	85.2	7.5	1.0	29.3	8.3
D-2	83	148	11.8	5.7	11.0	1.0×10^{-10}	148	92.6	19.6	2.3	25.9	8.1

[a] Mean value obtained for the maximum hydraulic gradient

3.2 *Hydraulic conductivity*

Hydraulic conductivity tests were conducted on GCL specimens in rigid-wall permeameters following the procedures in standard test NF P84-705 (AFNOR 2008). The testing device was previously presented in Guyonnet et al. (2005). A 10^{-3} M NaCl solution was used as the permeant liquid; this solution is specified in NF P84-705 as the testing solution and is believed to yield conservative hydraulic conductivities. An average vertical confining stress of 10 kPa was selected to represent the in situ condition in a capping system. Tests are composed of an initial swelling phase and a percolation phase. During the swelling phase in the case of the specimens tested here, no swell occurred at all. Consequently, the percolation phase started when 90% of equilibrium adsorption had occurred. Several hydraulic gradients were applied to specimens, ranging between 1 and 18, corresponding to hydraulic heads depending on the observed hydraulic conductivity of the specimens. When the obtained flow rate was too large, only small hydraulic heads could be applied, in order to ensure that the flow rate could be measured along time considering the capabilities of the measuring devices (Fig.5).

To check that sidewall leakage and preferential flow were not occurring, a blue dye (Brilliant Blue) was added to the influent liquid of all exhumed GCLs at the end of testing. The blue dye spread in a homogeneous way through specimens; no sidewall leakage or preferential flow was evident in any test (Fig. 4).

A synthesis of the hydraulic conductivity values and water contents of bentonite in the GCLs before starting the permeability test and at the end of the permeability test are presented in Table 2. Very high values of hydraulic conductivities were obtained for the GCLs exhumed from the landfill cover (>10^{-7} m/s) (Fig. 5). Lower hydraulic conductivities were obtained for the GCLs exhumed from the dam (~10^{-10} m/s). Those very different results will be subsequently discussed.

Figure 4. GCL specimen after test with the blue dye.

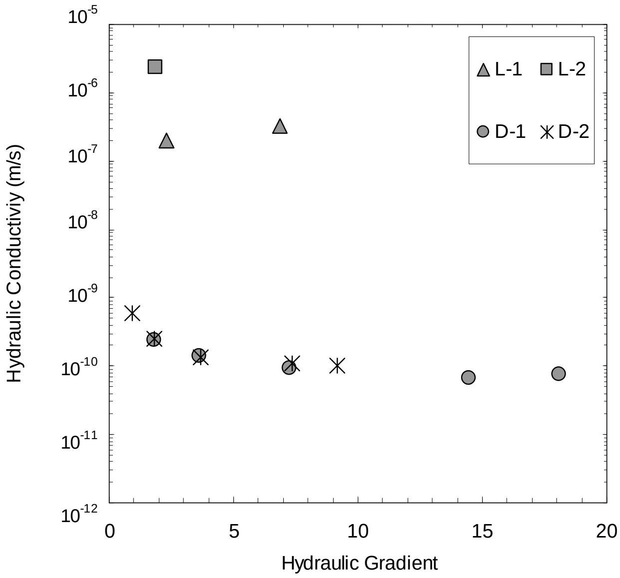

Figure 5. Hydraulic conductivity of exhumed GCLs.

3.3 *CEC and soluble cations*

Cation exchange capacity (CEC) and the mole fraction of cations present in bentonite were determined following the procedures in standard test NF X 31-130 (AFNOR 1999). The CEC values were determined by extraction using the cobaltihexamine chloride method and chemical analysis of the extracts was conducted using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES).

CEC and exchangeable Na, K, Ca and Mg are summarized in Table 2. Cation exchange has occurred nearly completely in the bentonites; Na originally contained in the bentonites was replaced by Ca and Mg originated from overlying soils and from dissolution of carbonates within the GCLs (Guyonnet et al. 2009). Those results are consistent with the low swell indices.

Surprisingly the quantity of Na cations of the bentonite contained in the D-2 GCL sample (GCL sample located below the D-1 GCL sample) is greater than the one measured in the other GCL samples. This tends to indicate that the GCL located above has protected the GCL located below by limiting the water percolation from the overlying soil; the cation exchange was thus slowed down.

3.4 *Cover soils*

Samples were collected from soils above and below GCLs. Water content, CEC and exchangeable Na, K, Ca and Mg were measured for each soil. Methods used to determine CEC and exchangeable cations were the same as those presented for the GCL samples.

Properties of the soils are summarized in Table 3. Ca is the dominant cation in the exchange complex of the landfill cover layer and subgrade. Ca and Na cations are equally abundant in the soil cover of the dam whereas Na appears as the dominant exchangeable cation present in the underlying soil of the dam. This result is consistent with the greater quantity of Na cations contained in the D-2 GCL bentonite sample.

4 DISCUSSION OF GCL PROPERTIES

4.1 *Comparison with tests performed in laboratory with calcium chloride solutions*

Many studies showed that the hydraulic conductivity of GCLs is sensitive to the concentration of the permeant solution and the cation valence (Lin & Benson 2000, Jo et al. 2001, Vasko et al. 2001, Lee et al. 2005, Jo et al. 2005).

Results of tests performed on virgin non prehydrated GCLs in the laboratory with calcium chloride solutions are summarized in Figure 6 (Gleason et al. 1997, Norotte et al. 2004, Katsumi et al. 2007, Katsumi et al. 2008a, Katsumi et al. 2008b).

The highest hydraulic conductivities were obtained with concentrated $CaCl_2$ solutions (>0.2 M). Nevertheless many of these studies have shown that GCLs maintain low hydraulic conductivity in the range of 10^{-11} to 10^{-9} m/s when permeated with lowest calcium concentration solutions which are close to the frequent calcium concentration in the pore water of soils (range between 0.001 M and 0.004 M) (Egloffstein 2001).

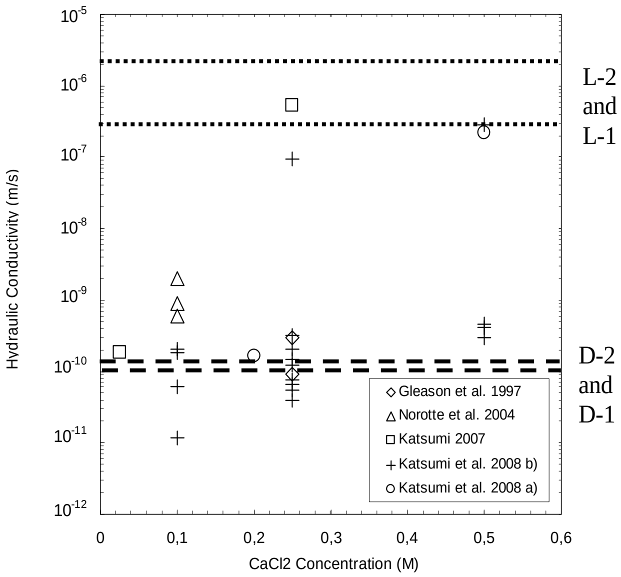

Figure 6. Hydraulic conductivity of GCLs percolated with $CaCl_2$ solutions.

Table 3. Summary of properties of soils.

Site		Initial water content (%)	CEC (meq/100g)	Exchange Cations (cmol/kg) Na	K	Ca	Mg
L-1	Surface layer	19	28.0	6.54	0.60	19.79	1.15
	Subgrade	21	32.7	5.43	0.60	16.79	0.72
L-2	Surface layer	18	38.0	5.31	0.00	22.36	0.64
	Subgrade	18	31.4	8.49	0.51	13.98	0.67
D	Surface layer	5	24.3	5.87	0.31	5.63	0.29
	Subgrade	17	17.5	5.72	0.33	3.13	0.29

The $CaCl_2$ maximal concentrations existing in the real landfill and dam overlying and underlying soils range between 0.0005 M and 0.0037 M (Table 3). For the same range of concentrations GCLs which were ion-exchanged in the laboratory by $CaCl_2$ solutions and exhumed GCLs are compared. The comparison shows that the low hydraulic conductivity values obtained in D-1 and D-2 GCL samples are in good agreement with the laboratory results.

The difference between results obtained for GCL samples L-1 and L-2 exhumed from the landfill ($k>10^{-7}$ m/s) and the GCL samples D-1 and D-2 exhumed from the dam ($k<10^{-10}$ m/s) can not be explained only by the cation exchange occurred in the bentonites but by a combination of various criteria: cation exchange and desiccation-hydration cycles experienced by the GCLs. Indeed the GCL placed in the landfill cover had a greater life service (8 years) which lead to a greater exposure to climatic condition compared to the GCL installed in the dam which was only subjected to three dry seasons.

4.2 *Comparison with other recent field studies*

Only a few recent field studies report on the behavior of GCLs in covers in a detailed way as the one described in this paper.

Benson et al. (2007) studied needle-punched GCL samples exhumed from the cover of a landfill located in Wisconsin after 2 and 4 years of service. GCLs initially contained Na bentonite and were covered by 0.76 m of a vegetated surface layer. The hydraulic conductivities of the GCLs were 4.2×10^{-10} and 9.4×10^{-8} m/s for the GCLs exhumed after 2 years of service and 1.4×10^{-8} and 8.1×10^{-7} m/s for the GCLs exhumed after 4 years of service. Replacement of the native Na cations in the exchange complex by Ca and Mg combined with dehydration of the bentonite appeared to be the key factors causing the large increase in hydraulic conductivity. The overlying and underlying soils appear to be the source of Ca and Mg cations that exchanged with Na.

Meer and Benson (2007) detailed the investigation of needlepunched GCLs exhumed from three landfills in Wisconsin and in Georgia after 4.6, 4.1 and 5.6 years of service. All GCLs contained Na bentonite and were covered by 0.75 m and 0.80 m of vegetated surface layer depending on the site. Most of the Na initially in the bentonite had been replaced by Ca and Mg in the exhumed GCLs and the bentonites had swell indices typical of Ca bentonite (~10 mL/2g). Hydraulic conductivities of the exhumed GCLs varied over a wide range (5.2×10^{-11} to 1.3×10^{-6} m/s) and were strongly related to the gravimetric water content at the time of sampling: GCL samples with a gravimetric water content less than 80% had high hydraulic conductivities (10^{-8} to 10^{-6} m/s)(Fig. 7) whereas GCLs with gravimetric water contents greater than 100% had lower hydraulic conductivity (10^{-11} to 10^{-9} m/s). According to Meer and Benson the abrupt change in hydraulic conductivity shown in Figure 7 suggests that GCL desiccation to lower water content has a more dramatic effect on hydraulic conductivity.

Hydraulic conductivities exhibited no relationship with mole fraction of exchangeable Na because the Na mole fraction was low on all of the exhumed GCLs but the data could be segregated into two groups regardless of the Na mole fraction: GCLs with higher hydraulic conductivity ($>10^{-7}$ m/s) and GCLs with lower hydraulic conductivity ($<10^{-9}$ m/s) (Fig. 8). The lower hydraulic conductivities were similar to those obtained from hydraulic conductivity tests performed on GCLs in the laboratory with dilute calcium chloride solutions (10 mM) by Egloffstein (2001) and Jo (2005); whereas the very high hydraulic conductivities obtained were caused by other factors in conjunction with ion exchange.

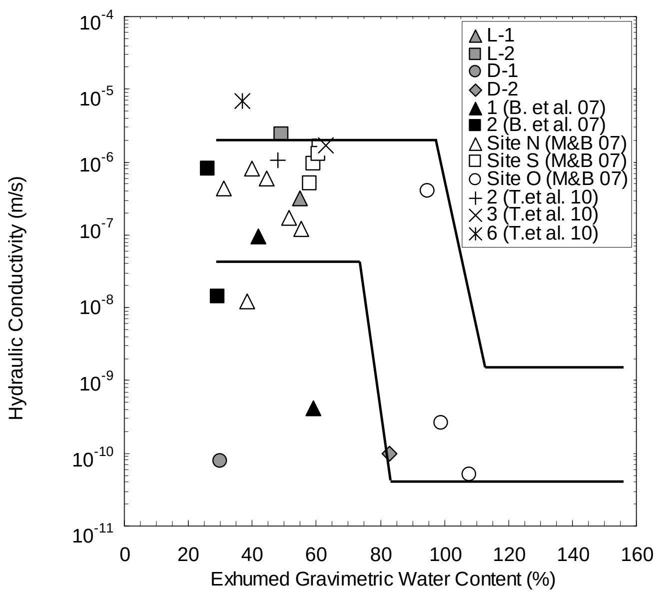

Figure 7. Hydraulic conductivity of exhumed GCLs versus gravimetric water content at the time of exhumation.

Touze et al. (2010b) presented the results obtained on needlepunched GCL samples exhumed from a cover of a landfill site in France after 3 and 6 years of service. GCLs contained calcium activated bentonite. The thickness of the cover soil was found to be approximately 0.2 and 0.5 m respectively and contained a large amount of calcium carbonate. The bentonite in the GCL showed a full exchange of sodium to calcium; the GCL samples did not exhibit any swelling capacity and the hydraulic conductivity measured ranged between 1.07×10^{-6} and 6.91×10^{-6} m/s. The GCL was no longer performing its lining function in relation with significant root intrusion in the GCL, desiccation-hydration cycles and cation exchange.

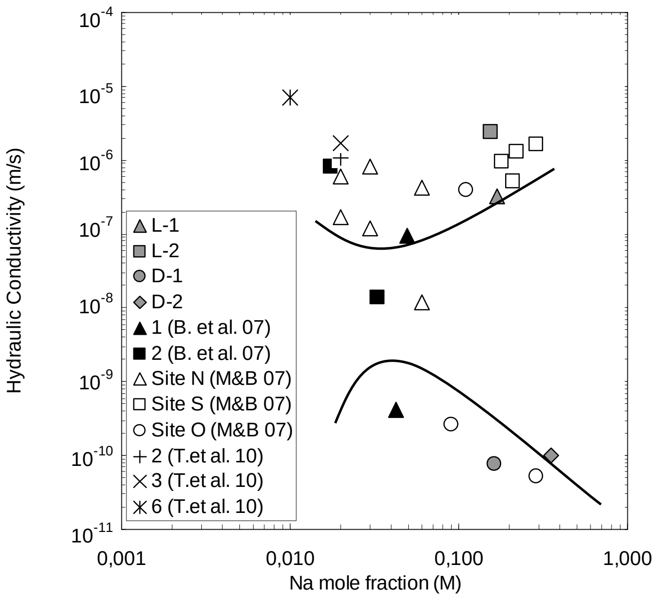

Figure 8. Hydraulic conductivity of exhumed GCLs versus Na mole fraction in the exchange complex of the bentonite.

Except for some points, hydraulic conductivity values as a function of the gravimetric water content of the bentonite at the time of sampling for all exhumed GCL samples are in good agreement with the tendencies observed by Meer and Benson (2007) (Fig. 7); low hydraulic conductivity is obtained when the water content of GCL exceeds 80%. GCL sample D-1 and 6 (Touze-Foltz et al. 2010) have very low gravimetric water contents at the time of sampling due to the very low cover soil thickness (0.2 m for both sites) but higher hydraulic conductivities obtained for the GCL samples 6 (Touze-Foltz et al. 2010) could be explained by the long service life of the GCLs (6 years) which led to a greater exposure to desiccation-hydration cycles. A large difference in hydraulic conductivities between the GCL samples 1 (Benson et al. 2007) is also noticed in Fig. 7. Indeed, one GCL sample had a very low hydraulic conductivity ($k = 4.2\times10^{-10}$ m/s) whereas the second sample had a hydraulic conductivity close to 10^{-7} m/s; but no reason for this difference could be determined from data collected by Benson et al. (2007).

As described by Meer and Benson (2007) even if there is no apparent relationship between hydraulic conductivity and Na mole fraction, the data collected from the various studies can be segregated into two groups regardless of the Na mole fraction (Fig. 8), except for two data points. Even if all the GCL samples exhumed from the landfill cover and the dam exhibit a low content in sodium ions (Na mole fraction range from 0.15 to 0.35), the hydraulic conductivities obtained for the GCL samples D-1 and D-2 exhumed from the dam match with the low conductivity value group whereas the hydraulic conductivities obtained for the GCL samples exhumed from the landfill L-1 and L-2 belong to the high value group. The difference between the hydraulic conductivities of the GCL samples D-1, D-2 and L-1, L-2 can be linked to the very different service lives of the GCLs (3 years for D-1, D-2 and 8 years for L-1, L-2); the full exchange of sodium ions and an insufficient cover soil thickness which could not prevent the GCL from desiccation combined with a long time exposure to climatic conditions led to the formation of irreversible cracks in the bentonite.

5 CONCLUSION

GCL samples were exhumed from a landfill cover and from a dam after 8 and 3 years of service and tested for water content, swell index, saturated hydraulic conductivity and exchangeable cations. The GCLs were located under a shallow soil cover with a thickness in the range 0.2 to 0.5 m; samples of the overlying and underlying soils were also collected and tested for water content and exchangeable cations.

The bentonite in the GCL showed an exchange of sodium to calcium evidenced by swell indices and quantification of the concentration in various cations in the bentonite. The difference between hydraulic conductivity results obtained for GCL samples exhumed from the landfill ($k>10^{-7}$ m/s) and the dam ($k<10^{-10}$ m/s) cannot be explained only by the cation exchange occurred in the bentonites but by a combination of cation exchange and desiccation-hydration cycles experienced by the GCLs.

Indeed, the comparison of the exhumed GCLs and GCLs which were ion-exchanged by $CaCl_2$ solutions showed that GCLs maintain low hydraulic conductivity in the (range of 10^{-11} to 10^{-9} m/s) when permeated with lowest calcium concentration solutions (<0.004 M) which are the maximal calcium concentration found in the pore water of overlying and underlying soils collected in the landfill and in the dam.

The results from this study are consistent with previous recent results from the literature which indicate that cation exchange combined with hydration-desiccation cycles can adversely affect GCL in its function of hydraulic barrier.

6 ACKNOWLEDGMENTS

The urban area community of Le Havre (CODAH) permitted sampling and testing of the GCLs exhumed from the dam. Assistance provided by the CODAH is gratefully acknowledged.

7 REFERENCES

ASTM D5890**.** 2011. Standard Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners, *American Society for testing and Materials (ASTM)*, West Conshohocken, Pennsylvania, USA.

Benson, C., Thorstad, P., Jo, H, Rock, S. 2007. Hydraulic performance of geosynthetic clay liners in a landfill final cover. *Journal of Geotechnical and Geoenvironmental Engineering* 133(7): 814-827.

Bouazza, A. 2002. Geosynthetic clay liners. *Geotextiles and Geomembranes* 20: 3-17.

Egloffstein, T. 2001. Natural bentonites-Influence of the ion exchange and partial desiccation on permeability and self-healing capacity of bentonites used in GCLs. *Geotextiles and Geomembranes* 19:427-444.

Gleason, M., Daniel, D., Eykolt, G. 1997. Calcium and sodium bentonite for hydraulic containment applications. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(5): 438-445.

Guyonnet, D., Gaucher, E., Gaboriau, H., Pons, C.-H. Clinard, C., Norotte, V., Didier, G.2005. Geosynthetic clay liner interaction with leachate: correlation between permeability, microstructure, and surface chemistry. *Journal of Geotechnical and Geoenvironmental Engineering* 131(6): 740-749.

Heibaum, M., Fleischer, P. 2010. Geosynthetic clay liners (GBR-C) for hydraulic structures. *3rd International Symposium on Geosythetic Clay Liners*, Würzburg, Germany, 15-16 September 2010.

Jo, H., Katsumi, T., Benson, C., Edil, T. 2001. Hydraulic conductivity and swelling of nonprehydrated GCLs permeated with single-species salt solutions. *Journal of Geotechnical and Geoenvironmental Engineering* 127(7) : 557-567.

Jo, H., Benson, C., Shakelford, C., Lee, J-M., Edil, T. 2005. Long term hydraulic conductivity of a geosythetic clay liner permeated with inorganic salt solutions. *Journal of Geotechnical and Geoenvironmental Engineering* 131(4) : 405-417.

Katsumi, T., Ishimori, H., Ogawa, A., Yoshikawa, K., Hanamoto, K., Fukagawa, R. 2007. Hydraulic conductivity of nonprehydrated geosynthetic clay liners permeated with inorganic solutions and waste leachates. *Soils and Foundations* 47 (1): 79-96.

Katsumi, T., Ishimori, H., Onikata, M., S., Fukagawa, R. 2008a. Long term barrier performance of modified bentonite materials against sodium and calcium permeant solutions. *Geotextiles and Geomembranes* 26:14-30.

Katsumi, T., Ishimori, H., Ogawa, A., Maruyama, S., Fukagawa, R. 2008b. Effect of water content distribution on hydraulic conductivity of prehydrated GCLs against calcium chloride solutions. *Soils and Foundations* 48 (3): 407-417.

Lee, J., Shackelford, C., Benson, C., Jo, H., Edil, T. 2005. Correlating index properties and hydraulic conductivity of geosynthetic clay liners. *Journal of Geotechnical and Geoenvironmental Engineering* 131(11): 1319-1329.

Lin, L., Benson, C. 2000. Effect of Wet-Dry Cycling on Swelling and Hydraulic Conductivity of GCLs. *Journal of Geotechnical and Geoenvironmental Engineering* 126(1): 40-49.

Meer, S., Benson, C. 2007. Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers. *Journal of Geotechnical and Geoenvironmental Engineering* 133(5): 550-563.

NF P 84-705.2008. Geosynthetic barriers – Determination of swelling, flow and permeability characteristics of geosynthetic clay liners (GCL) using an oedopermeameter - Characterisation test and performance test, *Association Française de Normalisation (AFNOR)*, Paris, France (in English).

NF X 31-130. 1999. Soil quality – Chemical methods – Determination of cationic exchange capacity (CEC) and extractibles cations, *Association Française de Normalisation (AFNOR)*, Paris, France (in French).

Norotte, V., Didier, G., Guyonnet, D., Gaucher, E. 2004. Evolution of GCL hydraulic performance during contact with landfill leachate. *Advances in Geosynthetic Clay Liner Technology: 2ndSymposium*, ASTM STP 1456, R.E. Mackey and K. von Maubeuge, Eds, ASTM International, West Conshohocken, PA.

Touze-Foltz, N., Lupo, J., Barroso, M. 2010a. Geoenvironmental applications of geosynthetics. *4thEuropean Geosynthetics Conference (EuroGeo 4), Keynote* paper, Edinburgh, Scotland, United Kingdom, 7-10 September 2008.

Touze-Foltz, N., Croissant, D., Rosin-Paumier, S., Pirrion, T., Ouvry, J-F. 2010b. Performance of a GCL in a landfill cover after six years in service. *3rd International Symposium on Geosythetic Clay Liners*, Würzburg, Germany, 15-16 September 2010.

Vasko, S.M., Jo, H.Y., Benson, C.H., Edil, T.B., Katsumi, T. 2001. Hydraulic conductivity of partially prehydrated geosynthetic clay liners permeated with aqueous calcium chloride solutions. *Geosynthetics Conference 2001*, IFAI, St Paul, MN.

Werth, K., Heerten, G., Pries, J-K., Klompmaker, J. 2010. 20 years experience with GCLs in dams and dykes. *3rd International Symposium on Geosythetic Clay Liners*, Würzburg, Germany, 15-16 September 2010.

XP P84-703. 2002. Bentonitic geosynthetics - Determination of the swelling capacity of clay in bentonitic geosynthetics, *Association Française de Normalisation (AFNOR)*, Paris, France (in French).

Zanzinger, H., Touze-Foltz, N. 2009. Clay geosyhtetic barriers performance in landfill covers. *GIGSA GeoAfrica 2009 Conference*, Cape Town, 2-5 September 2009.