

Effect of the durability of GCLs on Contaminants transfer through a composite liner exhibiting a hole in the geomembrane: a numerical approach

Hajer Bannour

ISSAT Sousse, University of Sousse Tunisia, hajerbannour@gmail.com

Abstract. This study performs numerical simulations of flow rate and organic contaminant migration through a geosynthetic composite lining system (geomembrane GMB-geosynthetic clay liner GCL) using the GeoStudio program (Ctran/W in conjunction with Seep /W). The GMB is considered defective with a circular hole to account for the coupled phenomena of advection and diffusion. GCLs are considered virgin and suggested for cation exchange and thermal gradient to verify and check the effect of the internal modification and alteration of the GCL by its environment on contaminant transfer. The results are compared with contaminant transport through composite liners with virgin GCL to investigate and study the resistance durability of GCLs to face contaminant transfer transport. After the validation of the proposed model, there was good agreement between the simulated and experimental flow. The result of this study confirms that indeed the typically published diffusion coefficient values for both virgin and aged GCL used in the present study provide good predictions of contaminant migration and effluent concentration over time across the GMB-GCL composite liners

1 Introduction

Composite liners with a geomembrane (GMB) over a geosynthetic clay liner (GCL) or/and an attenuation layer i.e. compacted clay liner (CCL) are a good solution to limit contamination of the surrounding soil and groundwater after decades of research in this field [1-3]. In the absence of defects, the GMB is the main active barrier to contaminant migration. Although the GMB can develop holes during installation and use (short- and long-term). Quality control can prevent the majority of them [4,5]. According to the literature, large holes with a diameter of 10 mm are assumed to have a frequency of 2.5 to 10 holes per hectare [5]. By exposing these defects to leachate, contaminants could be transferred to subsurface and groundwater.

Furthermore, Due to typical field conditions, GCL-GMB composite liners are frequently exposed to chemically aggressive environments, such as those found in landfills. In fact, several studies have confirmed the existence of cation exchange in GCLs under such conditions. Within one to two years, cation exchange dramatically changes the swelling capacity, plasticity, and microstructure of bentonite [4, 6], as well as its beneficial self-healing properties; [7, 8]. Furthermore, increased temperatures and thermal gradients can enhance preferential flow pathways even after GCL rehydration [9-10]. Compared to virgin GCL, these internal and external influences can significantly increase the hydraulic conductivity of GCL by 4 to 5 orders of magnitude depending on site conditions [11]. In spite of that, no significant increase in advective flow rate has been observed (less than one order of magnitude) [12].

It is indicated that the advective flow through a defect in the GMB is governed by the interface transmissivity between the GMB and the GCL [2,13, 15]. The "Wetted area" refers to the area covered by the interface flow. Afterward, the liquid migrates into and through the underlying medium. In addition to this advective transport, a concentration gradient across the liner leads to a diffusive transport. The combination of advective and diffusive transport mechanisms makes it possible to correctly predict the transport of leachate contaminants in the presence of a hole in the GMB through the composite liner.

The leachate contained organic and inorganic contaminants. In all, approximately six hundred different organic and inorganic compounds were found in the landfills, with varying compositions and concentrations [14]. Compounds found in landfills can be grouped into the following categories (in descending order of detections): phenolic compounds, aromatic hydrocarbons (like volatile organic compounds), heterocyclic compounds, carboxylic acids, phthalates, anilines, aliphatic acids, phenoxy acids, organophosphorus compounds, terpenoids, and triazines.

Studies of inorganic compounds such as sodium and chloride, and some metals (Al, As, Cd, Cu, Fe, K, Mg, Mn, Ni, Sr, Zn) have been well documented with successful experimental and numerical analyses using GCLs and composite liners [2, 15], [16-18].

Also, several cases have been interested on studying the diffusion of organic compounds through virgin and aged GCLs. This is because even at low concentrations, organic compounds such as phenolic compounds are toxic to humans and the environment [19]. Thus, when released to the subsurface, organic compounds can have a negative impact on groundwater quality and human health [1, 20, 21].

Then, a thorough review of organic compound migration has to be conducted, with an emphasis on phenolic compounds, in order to prevent widespread groundwater contamination in the vicinity of landfills for an extended period of time. The biggest challenge is the inaccessible holes that are created when tens to hundreds of feet are placed over the composite liner, so it remains difficult to predict the extent of contamination from these organic compounds. Modeling of organic contaminant transport is possible and requires the input of diffusion coefficients.

[19, 21] investigated how organic components (phenolic and VOCs : aromatic hydrocarbons) diffused into virgin and aged specimens under conditions of complete cation exchange. As a result of cation exchange, the diffusion coefficient of GCLs increased when compared to virgin GCLs.

Indeed, For phenolic compounds in GCL specimens submitted to cation exchange, diffusion coefficients range from 8.1×10^{-11} to 6.4×10^{-10} m²/s [19]. However no diffusion tests have been undertaken by considering the combination of cation exchange and thermal gradient (leading to higher increase of the hydraulic conductivity of the GCL by several orders of magnitude).

The goal of this work is twofold: The first is to numerically simulate contamination transport through composite liners with circular holes in the GMB using the GEOSTUDIO module. Advection and diffusion of organic phenolic are considered coupled by this code using SEEP /W with CTRAN. The second objective is to evaluate the effects of aging of the GCL by cation exchange on contaminant transport by determining the relative concentrations over time through the liner. The obtained results are compared with composite liners made of virgin GCL to investigate their durability. For this purpose, the simulations presented in this study are

divided into two parts: The first part is a validation study of the use of the model and software in the case of a circular hole in the GMB. The simulations were compared with existing experimental and numerical results on NaCl transport from the literature.

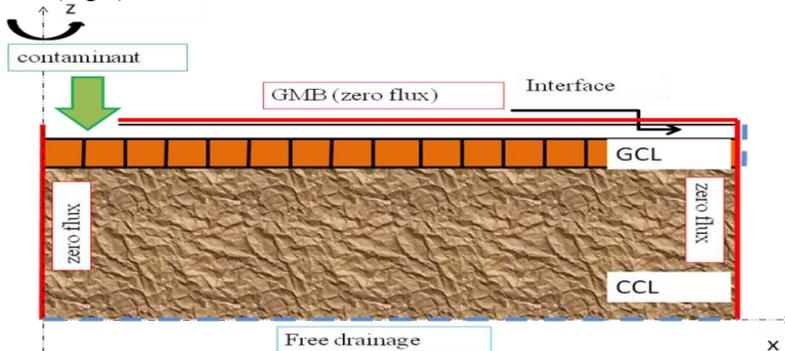
A second part of this study consists of performing simulations of phenolic organic contaminant in the same configuration considering the aging of GCLs and comparing the results with the case of virgin GCL. The durability of the GCL is evaluated for the advection-diffusion performance.

2 Numerical program and simulated features

The purpose of this study is to simulate the flow rate and the contaminant transport through a single hole in the geomembrane.

2.1 General features of the composite liner and boundary conditions

The 2D axisymmetric model studied is shown in Fig.1. It consists of a composite liner composed of a damaged GMB stacked on a 0.01 m thick GCL resting on a 0.3 m thick silty sand. This scheme is similar to the composite liners used in experiments with transmissivity cells [2], but not inverted. Thus, the GMB with the hole is on top, while the GCL below it covers the silty sand referred in Figure 1 as a compacted clay liner (CCL). A variable grid was used to refine the mesh near the hole. The interface between the GMB and the GCL is modeled as a thin layer 0.001 m thick, and the hydraulic conductivity was adjusted to obtain the required transmissivity [3]. A free-flowing boundary condition was used for the lower boundary and a non-flowing boundary condition was used for the GMB. The GMB has a hole of 10 mm diameter. The hole was modeled as a boundary condition for a hydraulic head of 0.3 m. A boundary condition for the initial concentration C_0 was set at the nodes of the hole to simulate the diffusion of impurities. Elsewhere in the model, the initial concentration is zero. A zero flux boundary condition was set for the intact GMB, the side boundaries, and the symmetry axis (Fig.1).



CCL: compacted clay liner

Fig. 1. Feature of the composite liner

2.2 The numerical program

In order to improve consistency of the results, we first replicated numerically the flow rate and contaminant transport using NaCl leakage and diffusion through a GMB-GCL composite liner with a single hole [2]. The second step involves using diffusion coefficients for organic

compounds to simulate their transport (relative concentrations and mass fluxes into the aquifer) and comparing the behavior of the composite liner using virgin and aged GCL. In Table 1, we describe the different case studies undertaken in this study. In cases 1_V, 2_V, 3_V, and 4_V, validations are performed based on experimental results of Rowe and Abdelatty's study in 2013 related to flow rates and contaminant transports. Cases 1_V and 2_V are related to tap water permeation for a hydraulic head equal to 0.3 and 1 m respectively and cases 3_V and 4_V are related to NaCl permeation for a hydraulic head equal to 0.3 and 1 m respectively; Cases 5, 6 and 7 are simulations of diffusion and organic contaminants transport considering a virgin GCL, an aged GCL after cation exchange (CEC) and an aged GCLs after cation exchange and thermal gradient (CEC+T).

Table 1. Numerical program used in this study

Case	Case 1 V*	Case 2 V*	Case 3 V*	Case 4 V*	Case 5	Case 6	Case 7
Saturated hydraulic conductivity of the soil liner K_{soil} [m/s]	1×10^{-06}	1×10^{-06}	1×10^{-06}	1×10^{-06}	8×10^{-09}	8×10^{-09}	8×10^{-09}
Saturated hydraulic conductivity of the GCL K_{GCL} [m/s]	4.6×10^{-11}	4.6×10^{-11}	$4.1/2.5/1 \times 10^{-10}$	$4.1/2.5/1 \times 10^{-10}$	1.55×10^{-11}	1.31×10^{-10}	5.55×10^{-06}
Hydraulic head [m]	0.3	1	0.3	1	0.3	0.3	0.3
Experimental flow rate Q [m^3/s]	1.5×10^{-11}	5.1×10^{-11}	1.55×10^{-11}	5.25×10^{-11}	1.2×10^{-11}		1.5×10^{-10}
Back calculated interface transmissivity θ [m^2/s] (R&A,2012)**	2.2×10^{-11}	2.4×10^{-11}	1.07×10^{-11}	1.15×10^{-11}	-		-
Back calculated interface transmissivity θ [m^2/s] (This study)	1.5×10^{-11}	2.5×10^{-11}	9.0×10^{-12}	1.6×10^{-11}	1.80×10^{-11}	1.80×10^{-11}	2.0×10^{-10}
Effective diffusion coefficient of the soil liner D_{soil} [m^2/s]	6×10^{-10} (Chloride)	6×10^{-10} (Chloride)	$2-8 \times 10^{-10}$ (Chloride)	$2-8 \times 10^{-10}$ (Chloride)	0.67- 1.73×10^{-11}	1.1- 8.5×10^{-10}	0.8- 6.4×10^{-10}
Effective diffusion coefficient of the GCL D_{GCL} [m^2/s]			$1-4 \times 10^{-10}$ (Chloride)	$1-4 \times 10^{-10}$ (Chloride)	0.5- 1.3×10^{-10}	0.8- 6.4×10^{-10}	0.8- 6.4×10^{-10}

V*: validation case; (R&A, 2012)**: Rowe and Abdelatty (2012)

2.3 Model validation

Numerical models were validated using experimental data presented in [2]. The first step of the validation was to recreate numerically the flow rate for the two hydraulic heads (0.3 and 1 m) and for the two fluid permeations (water and NaCl). According to experimental data, the second step is to estimate the transmissivity using the same calculation method [15]. With 0.3 and 1 m hydraulic heads, the best transmissivities were found to be 1.5×10^{-11} and 2.5×10^{-11} m^2/s with a mean of 2×10^{-11} m^2/s . This value is the same as the one obtained by [19] when using sodium bentonite as part of the GCL and is very close to the 2.3×10^{-11} m^2/s back calculated interface transmissivity obtained by numerical modelling performed by [15].

When permeated with 0.14 mol/l NaCl solution. Experimental results indicate that the hydraulic conductivity of the GCL decreased along its length and divided into three zones: $k_1 = 4.2 \times 10^{-10}$ m/s ($0 < x_1 < 0.1m$); $k_2 = 2.5 \times 10^{-10}$ m/s ($0.1 < x_2 < 0.15m$); $k_3 = 1 \times 10^{-10}$ m/s ($0.15 < x_3 < 0.3m$). In this case, the back calculation of interface transmissivity followed the same methodology. As expected, the interface transmissivity decreased under 0.3 and 1 m hydraulic head (according to observed flow rates of 1.55×10^{-11} m^3/s and 5.25×10^{-11} m^3/s), with a mean value of 1.25×10^{-11} m^2/s . These findings are consistent with observations made by [2, 15], [22, 23] who concluded that the transmissivity is a detrimental parameter affecting the flow rate rather than the change in the nature or/ and the hydraulic conductivity of the GCL.

The inferred interface transmissivity and the diffusion coefficient data available for the silty sand and the GCLs are used to simulate the advection-dispersion analysis. Figure 2 shows the simulated relative contaminant concentration C/C_0 for 0.3 m hydraulic head after 900 days of permeation with NaCl solution compared to experimental results from [2]. Contaminant concentrations were extracted from an observation well located at $x_1 = 0.1$ m and $x_5=0.3$ m, which correspond to the receptor zone called respectively A1 and A5 in [2]'s experimental work. It can be noticed that simulated contaminant curves reproduce the theoretical and experimental evolution for advection-diffusion contaminant transport and illustrate how the diffusion coefficient and hydraulic head could affect concentrations and contaminants behaviour by advection-diffusion. In reference to Figures 2 (a) and (b) (hydraulic head equals 0.3m) it could be concluded that the best fit between observed values and simulated concentrations were for case 6 related to diffusion coefficients of 6×10^{-10} and 1×10^{-10} m²/s, respectively for the soil and the GCL [15]. In addition, we noticed that relative contaminant concentrations always remained very low ($C/C_0 < 0.05$) and never reached the maximum imposed at the source. As a result of this simulation, the composite liner proved to be efficient. In the validation study, the results obtained with Geostudio are in good agreement with previous experimental results in relation with the theoretical behavior of contaminant transfer. In the next session, other scenarios and different contaminants will be simulated.

Table 2. Diffusion coefficients of soil and GCL used in the contaminant transport analysis [15].

Case	Diffusion coefficient D_e (m ² /s) for soil	Diffusion coefficient D_e (m ² /s) for GCL
Case 1	2.0×10^{-10}	1.0×10^{-10}
Case 2	8.0×10^{-10}	1.0×10^{-10}
Case 3	2.0×10^{-10}	4.0×10^{-10}
Case 4	8.0×10^{-10}	4.0×10^{-10}
Case 5	6.0×10^{-10}	2.0×10^{-10}
Case 6	6.0×10^{-10}	1.0×10^{-10}

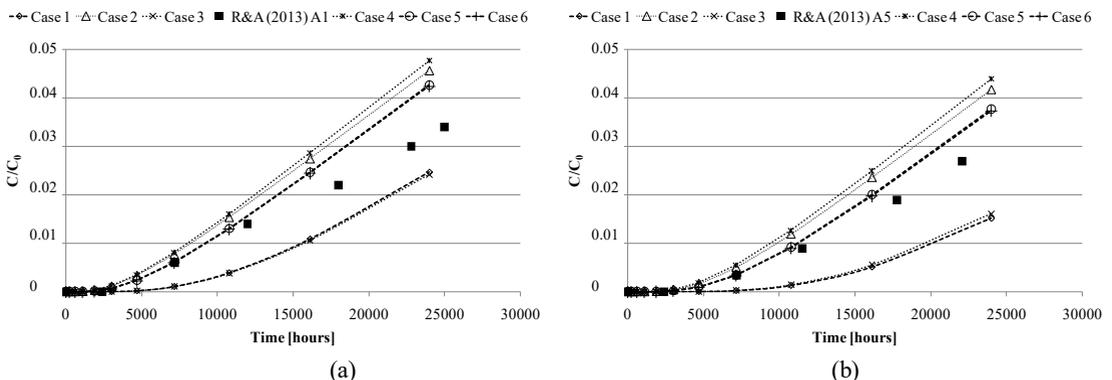


Fig.2 Comparison between observed and numerical values: (a) x_1 (A1); (b) x_5 (A5) (R&A (2013): Rowe and Abdelatty (2013))

2.4 Results and discussion

Three case studies were analyzed; case 5 examines flow rate and contamination migration of phenolic compounds through composite liners with a virgin GCL, case 6 illustrates the same numerical modelling using a GCL undergoing cation exchange, and finally, case 7 presents results with a GCL experiencing cation exchange and thermal gradient. According to [19],

diffusion coefficients of phenolic compounds through virgin GCLs varied from 5×10^{-11} to $1.3 \times 10^{-10} \text{ m}^2/\text{s}$. For GCLs experiencing cation exchange, diffusion coefficients of phenolic compounds varied from 8×10^{-11} to $6.4 \times 10^{-10} \text{ m}^2/\text{s}$ (see Table 1). Also, this range of diffusion coefficients was considered for GCLs after cation exchange and thermal gradient, and considered to be the lowest range in the literature. Based on experimental flow rates, the same parametric procedure was used for selecting interface transmissivity. A study performed by [12] looked at flow rates for virgin and aged GCLs in conjunction with a GMB with a 4 mm hole. Results of this study are presented in table 1. Case 5, referring to virgin GCL presents a hydraulic conductivity equal to $1.55 \times 10^{-11} \text{ m/s}$, after cation exchange [19] noticed that the hydraulic conductivity increased by a factor of 8.5 to reach $1.31 \times 10^{-10} \text{ m/s}$. A virgin GCL presenting the same characteristics has been already tested as a part of a composite liner for determining the flow rate. [2, 23] reported that the increase in hydraulic conductivity of up to one order of magnitude due to the change of the GCL of bentonite from sodium to calcium due to cation exchange had no effect on the steady state flow rate (advective transfers). Therefore, the same interface transmissivity can be adopted for both cases (5 and 6).

When the hydraulic conductivity increases from 1.55×10^{-11} to $5.55 \times 10^{-10} \text{ m/s}$, the back calculated transmissivity increases by one order of magnitude from 2.0×10^{-11} to $2.0 \times 10^{-10} \text{ m}^2/\text{s}$ for observed flow rates of respectively 1.35×10^{-11} and $1.5 \times 10^{-10} \text{ m}^3/\text{s}$. Thus, it can be said [15] that when the hydraulic conductivity increases by five orders of magnitude, the effect of the change in transmissivity overrides the effect of the change in hydraulic conductivity. [19] provided diffusion coefficients for virgin and GCL after cation exchange. We can apply our validated model for contaminant transfer by advection diffusion analysis.

On Figure 3, we show the evolution of the Relative concentration C/C_0 over time (for phenolic effluents and for a hydraulic conductivity equal to 0.3 m). Case (a) shows a numerical comparison of Relative concentration C/C_0 over time over a hole in the GMB overlying a virgin GCL and a GCL performing cation exchange. The numerical comparison in case (b) shows relative concentration C/C_0 over time over a hole in the GMB overlying a virgin GCL and a GCL performing cation exchange and thermal gradient. It is overlaid by a 0.3 m CCL layer where the relative concentration C/C_0 has been extracted at its base for $x_1 = 0.1 \text{ m}$. In the graph 1 (a), virgin GCL1 refers to the lowest diffusion coefficient of phenolic component for virgin GCLs adopted from [19] ($D = 5 \times 10^{-11} \text{ m}^2/\text{s}$); virgin GCL2 refers to the highest diffusion coefficient of phenolic component for virgin GCLs adopted from [19] $1.3 \times 10^{-10} \text{ m}^2/\text{s}$. According to Figure 3 (a) and (b), aged GCL CEC refers to the case where the GCL is only performing cation exchange and aged GCL CEC+T refers to the case where the GCL is also performing thermal gradient. Specifically, case 1 refers to the lowest diffusion coefficient of phenolic component for aged GCLs adopted from [19] ($D = 8 \times 10^{-11} \text{ m}^2/\text{s}$); while case 2 refers to the highest diffusion coefficient of phenolic component for aged GCLs adopted from [19] $D = 4.6 \times 10^{-10} \text{ m}^2/\text{s}$.

After 25 000 hours of simulation (more than 2.5 years), it was found that the increase in the hydraulic conductivity leading to an increase in the diffusion coefficients from a range of [$0.5 \times 10^{-10} \text{ m}^2/\text{s}$, $1.3 \times 10^{-10} \text{ m}^2/\text{s}$] to [$0.8 \times 10^{-10} \text{ m}^2/\text{s}$, $6.4 \times 10^{-10} \text{ m}^2/\text{s}$] increases the simulated relative concentration evolution over time from [0.01;0.04] to [0.06;0.16] for GCL performing cation exchange according to Figure 3 (a) and to complete contaminant migration ($C/C_0=1$) for GCL performing cation exchange and thermal gradient Figure 3(b). Even if cases CEC and CEC+T present the same diffusion coefficients, case (b) clearly shows the highest increase in relative concentration through the composite liner with a complete contaminant migration occurring approximately after 1 year of exposure to contaminant. Indeed, the relative concentration of phenolic component showed an increase from 3.5 to 6.5 times for GCL performing cation exchange and from 21 to 100 times for GCL performing cation exchange and thermal gradient. As a result, when GCLs are exposed to thermal gradients and cation

exchange, contaminant transfer is dominated by advection and interface transmissivity rather than diffusion.

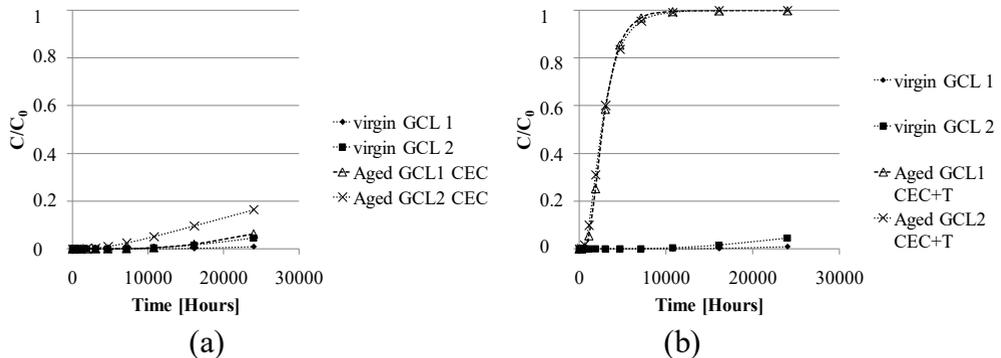


Fig.3 Relative concentration C/C_0 over time for phenolic effluent and for $h = 0.3$ m at the base of the CCL for $x_1 = 0.1$ m; (a) comparison between the case of virgin GCLs and aged GCLs performing cation exchange (CEC) and (b) comparison between the case of virgin GCLs and aged GCLs performing cation exchange and thermal gradient (CEC+T)

3 Conclusion

To In order to evaluate the level of protection provided by composite liners under typical site conditions (holes in the GMB and physical alteration of GCLs), it is necessary to assess how much contamination is transported through composite liners, i.e. the amount of contamination from the leachate. In this study, organic contaminants are chosen as they pose an environmental risk and their migration through a composite liner and adjacent compacted clay liner subsoil can be predicted using published diffusion coefficients. To analyze the transfer of phenolic organic contaminants through a GMB-GCL-CCL composite liner with a 4 mm hole in the GMB, a numerical model was adapted. This study compared between virgin and aged GCLs as regards contaminant migration. The results showed that contaminant migration through the composite liner increases under typical site conditions due to cation exchange and thermal gradient. Therefore, when GCLs are exposed to thermal gradients and cation exchange, contaminants are transferred mainly through advection and interface transmissivity rather than diffusion.

As a result, the diffusion coefficient of GCLs helped predict contaminant migration through composite liners. In order to emphasize these results, other contaminants and other site conditions must be considered.

4 References

1. R.K. Rowe, *Long-term performance of contaminant barrier systems*, Geotech. **55** (2005)
2. R.K. Rowe, K.M. Abdelatty, (2013). *Leakage and contaminant transport through a single hole in the geomembrane component of a composite liner*. J. of Geotech. and Geoenv. Eng., **139** (2013)
3. N. Touze-Foltz, H. Bannour, C. Barral, G. Stoltz, *A review of the performance of geosynthetics for environmental protection*. Geotex. and Geom, **44** (2016)
4. N.Touze-Foltz, J. Lupo, M. Barroso, *Geoenvironmental applications of geosynthetics. Keynote lecture, Eurogeo 4*, (2008)

5. R.K. Rowe (2017). *Karl Terzaghi Lecture: Protecting the Environment with Geosynthetics: Successes and Challenges* (2017)
6. A. Bouazza, T. Vangpaisal, S. Jefferis, *Effect of wet–dry cycles and cation exchange on gas permeability of geosynthetic clay liners*, J.of Geotech. and Geoenv. Eng., **132** (2006)
7. S.R. Meer, C.H.Benson, *Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers*. Journal J.of Geotech. and Geoenv. Eng., **133** (2007)
8. P. Fleisher, M. Heilbaum, *Excavation of GCL lining (GBR-C) in navigation canals and dykes after several years of service*. Eurogeo4 (2008)
9. L.C. Lin, C.H. Benson, *Effect of Wet-Dry Cycling on Swelling and Hydraulic Conductivity of GCLs*, J. of Geotech. and Geoenv.Eng., ASCE. **12** (2000)
10. C.H. Benson, H. Craig, S.R. Meer, *Relative abundance of monovalent and divalent cations and the impact of desiccation on geosynthetic clay liners*, J.of Geotech. and Geoenv. Eng **135** (2009)
11. R.K. ROWE, *Geosynthetics and the minimization of contaminant migration through barrier systems beneath solid waste*. 6th int. conf. on geosynth. (1997)
12. H. Bannour, C. Barral, N. Touze-Foltz, *Altered geosynthetic clay liners: effect on the hydraulic performance of composite liners*, Euro. J. of Env. and Civil Eng., **19** (2015)
13. K.W. Brown, J. C.Thomas, R. L., Lytton, P. Jayawickrama, , S. Bhart, *Quantification of Leakage Rates Through Holes in Landfill Liners*, US Env. Prot. A. Report, (1987)
14. M. Van Praagh, N. Torneman, M. Johansson, Ingelstedt Frendberg, L., E. Heander, A. E. Johansson, *Emerging organic contaminants in leachate – review and risk assessment. Sardinia 2011*, International Waste Management and Landfill Symposium S, 8 (2011)
15. R.K. Rowe, K. Abdelatty, *Modeling contaminant transport through composite liner with a hole in the geomembrane*, Can. Geotech. J. **49** (2012)
16. C. B. Lake, R. K. Rowe, *Diffusion of sodium and chloride through geosynthetic clay liners*, Geotex. and Geom., **18** (2000)
17. C. B. Lake, G. Cardenas, V. Goreham, G.A. *Aluminium migration through a geosynthetic clay liner*, Geosynth. Int., **14** (2007)
18. K. Lange, R.K. Rowe, H. Jamieson, *Diffusion of metals in geosynthetic clay liners*, Geosynth. Int., **16** (2009)
19. M.J.A. Mendes, N. Touze-Foltz, M. Gardoni, M. Ahari, L. Mazeas, *Quantification of diffusion of phenolic compounds in virgin GCL and in GCL after contact with a synthetic leachate*, Geotex. and Geom. **38** (2013)
20. C. B. Lake, R. K. Rowe, *Volatile organic compound diffusion and sorption coefficients for a needle-punched GCL* Geosynth. Int., **11** (2004)
21. S., Rosin-Paumier, N. Touze-Foltz, L. Mazeas, A. Guenne, *Quantification of volatile organic compounds diffusion for virgin geosynthetic clay liners and for a GCL after contact with a synthetic leachate*, J. Geotech. Geoenv. Eng. **137** (2011)
22. R. K. Rowe, *Geosynthetics and the minimization of contaminant migration through barrier systems beneath solid waste*, (1998)
23. M. J. A., Mendes, N. Touze-Foltz, E. M. Palmeira, P. Pierson, (2010). Influence of structural and material properties of GCLs on interface flow in composite liners due to geomembrane defects. *Geosynth. Int.*, **17** (2010)