HYDRAULIC, CHEMICAL AND BIOLOGICAL COUPLING ON HEAVY METALS TRANSPORT THROUGH LANDFILLS LINERS

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ABSTRACT

Soil layers in landfill liners are usually considered non-reactive, and the biological activity in the barrier is neglected for the calculation of the liner life span. The purpose of this research is to highlight the relative importance of hydraulic conductivity, chemical retardation and biological clogging on the transport of heavy metals through landfill liners. Mass transport was computed considering semi-empirical equations to determine contaminant leakage through geomembranes' imperfections, and Darcy´s law and advection–diffusion equation were used to evaluate the transport through soil liners. Hydraulic conductivity values were modified considering its reduction due to biological effects, and different retardation factors were considered to evaluate heavy metal adsorption on soil particles. The effect of compacted soil barrier thickness in specific discharge and breakthrough time was evaluated. Obtained results showed that the use of a geomembrane results in higher breakthrough time for composite liners when the prevailing transport mechanism is advection. Results also indicated the importance of considering bioclogging on the coupled hydraulic and chemical flow that determine the breakthrough time.

Keywords: Geosynthetic; landfill liner; bioclogging; leachate; hydraulic conductivity; heavy metals

INTRODUCTION

Typical liners and covers for landfill and wastewater ponds are constructed using in-site natural compacted soil when it has appropriate geotechnical characteristics. Addition of bentonite and geosynthetics materials to local soils is a common practice to enhance hydraulic or mechanical behavior of liners (Koerner, 2012). Among the desired soil properties for liners the most important are soil strength and stability, hydraulic conductivity and contaminant retention

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capacity (Musso et al., 2014; Sharma and Reddy, 2004).

Soil hydraulic conductivity depends on soil and fluid properties and flow conditions. Among the most important factors it is possible to mention soil mineralogy, soil fabric, void ratio, degree of saturation, density and viscosity of permeating fluids and hydraulic gradient. Spatial variability of soil properties (e.g. porosity) and variability in leachate properties (e.g. ionic strength) can control the hydraulic conductivity of a compacted clay liner (CCL) (Montoro and Francisca 2010; Rienzner and Gandolfi, 2014; Musso et al., 2016).

Most regulations specify a maximum hydraulic conductivity (*k*) and a minimum CCL thickness for landfill liners. In general, *k* should be lower than 1 x 10^{-9} m/s in order to minimize leachate migration and CCL thickness ranges from 0.6 m to 3.6 m depending on waste type and local regulations (Benson and Daniel, 1994a).

Deviations between hydraulic conductivities determined under controlled laboratory conditions respect to in-situ data are frequently associated to three facts: (a) different soil structure achieved during compaction, (b) the difficulty of obtaining homogeneous mixtures in the field, and (c) the assumption that long term leachate-soils interaction can be considered as negligible (Beaven et al., 2008).

Particle-fluid interactions and biological reactions are of key importance for the hydraulic behavior of CCL (Francisca and Glatstein, 2010). As a consequence, barriers can eventually suffer physical and chemical changes that affect CCL hydraulic conductivity (e.g. mineral dissolution, swelling and shrinkage, contraction and cracking) (Wang et al., 2013). The high load of nutrients and microorganisms in the leachate can also reduce CCL porosity due to microorganism growth inside pores (bioclogging) and affect contaminant removal from leachate (e.g. associated to bioremediation) (Li et al., 2013). Different authors presented experimental results showing that the hydraulic conductivity of soil mixtures decreases over time by factors of 10^2 (Glatstein and Francisca, 2014; Seifert and Engesgaard, 2007), 10^3 (Seki et al., 1998), or even 10^5 (Van Gulck and Rowe, 2004), when permeated with nutrients. These authors confirmed the presence of bacteria and yeast in the leachate and determined that the increase/decrease of biomass in the pore space can explain the observed decrease/increase in hydraulic conductivity.

Leakage through a liner system is governed by different mechanisms depending on liner system configuration. Advection is the main transport mechanism for CCL, while diffusion prevails in geomembrane liners (GM), very low hydraulic conductivity liners as in geosynthetic clay liners (GCLs) and composite liners (e.g. GM-CCL) (Sharma and Reddy, 2004). However, the main transport mechanism through GM's imperfections is also advection if the GM presents defects, holes or wrinkles (Giroud and Bonaparte, 1989b; Rowe, 2012). Empirical equations are the most used models to estimate the leakage through liners (Touze–Foltz and Giroud, 2005; Rowe et al., 2012). Therefore, leakage through composite liners depends on CCL hydraulic conductivity, contact conditions between GM and CCL, GM – CCL interface transmissivity, and size, number and geometry of GM imperfections (Foose et al., 2001).

In addition to soil and leachate properties that determine the specific discharge through landfill liners, the contaminant retention capacity is of great relevance for the quantification of mass transport. The most important mechanism affecting contaminant transport within the liner is adsorption (Ruiz et al., 2012). Presence of additives and polymers, clay mineralogy, pre-hydration conditions and bioclogging mechanisms also play fundamental roles in determining the hydraulic conductivity and chemical retention capacity of clays used for the construction of landfill liners (Razakamanantsoa et al., 2012; Rosin-Paumier and Touze-Foltz, 2012; Seifert and Engesgaard, 2012).

Most regulations allow alternative liners design regarding the materials employed, the number and type of layers involved, and the mechanism that prevails for liquid and contaminant retention. However, the equivalency between the recommended and the alternative design has to be assessed by determining the equivalency in terms of the contaminant impact occurring in the receptor aquifer (Rowe and Branchman, 2004).

The purpose of this research is to quantify the relative importance of hydraulic, chemical and biological effects on leakage and mass transport through composite liners. Numerical modeling represents landfill barriers made of compacted silt-bentonite and a geomembrane permeated with heavy metals. The results obtained show that these mechanisms take place all together controlling the specific discharge and contaminant percolation time through barriers.

LEAKAGE MODELING THROUGH LINERS

Leakage through liners and associated transport of contaminant were computed for single and composite liner systems in landfills frequently used in Argentina and other developing countries in South America. Single liners considered in this work are compacted clay liners (CCL) that may have different thickness depending on involved mass transport mechanisms and operational conditions. Composite liners (GM-CCL) are considered here as a two layers' system with a geomembrane (GM) placed above a CCL.

Hydraulic conductivities of typical CCL were adopted from Glatstein and Francisca (2014). Then, the amount of liquid and contaminant that can percolate through different clay liners was numerically determined as it is explained in the following subsections.

Liquid flux

Leakage through CCL liners was determined by Darcy's law as follows:

$$v = \frac{Q}{A} = k_s \frac{dh}{dl} \quad (1)$$

Where v = specific discharge also known as Darcy´s velocity, Q = volumetric discharge, A = surface area, k_s = saturated hydraulic conductivity of the soil layer and dh/dl = hydraulic gradient.

Leakage through composite liners (GM-CCL) with defects identified as holes in direct contact with the CCL was computed by following the procedure developed by Giroud (1997):

$$Q_h = n_d C_{ql0}\left[1 + 0.1\left(\frac{h}{t_s}\right)^{0.95}\right] a^{0.1} h^{0.9} k_s^{0.74} \quad (2)$$

Where, n_d = number of GM defects, C_{ql0} = contact quality factor between GM and CCL, h = hydraulic head over the GM, t_s = thickness of the CCL and a = surface area of the defect. Different models can be used with this purpose, however Rowe (1998) determined that difference between models has low relevance for most practical purposes.

For design considerations it is typically recommended to consider a leachate head of 0.3 m (EPA 1993), and 5 defects/ha with a defect area of 290 mm² (Giroud and Bonaparte 1989a; Giroud, 1997; Nosko and Touze Foltz, 2000 and Touze Foltz and Barroso, 2006).

The presence of wrinkles is also commonly found in bottom liners. To account for the effect of one hole in a GM coincident with a wrinkle on the leakage through composite liners (GM-CCL), the model developed by Rowe (1998) was implemented as follows:

$$Q_w = 2L[k_s z + (k_s t_s Tr)^{0.5}](h + t_s)/t_s \quad (3)$$

Where, L = length of the connected wrinkle, z = half-width of the wrinkle, and Tr = transmissivity of the GM–CCL interface. All of these parameters were implemented as suggested by Rowe (2012) assuming no interaction between adjacent wrinkles. There are different alternatives to consider the effect of wrinkles depending on the contact condition and type of defect (Touze-Foltz et al., 1999). However, equation (3) was preferred in this work given that it shows good agreement with the observed behavior in real liners (Rowe, 2012). Rowe et al., (2004) recommends to consider a hole in coincidence with a wrinkle of length = 100 m and width = 20 cm, and poor contact.

Equations (1) to (3) can be used to determine the time at which the liquid percolates through the bottom liner (Benson and Daniel, 1994a), but neglect interaction between contaminant and barrier geomaterials.

Hydraulic conductivity of the CCL

Variations of hydraulic conductivity of CCL during permeation were reported by many authors in the past decades. This phenomenon can be attributed to physical, chemical and biological clogging as well as to particle-fluid interactions (Thullner et al., 2002; Mohamedzein, 2016).

In the present work, the influence of time on hydraulic conductivity is considered by means of an empirical equation that allows fitting the observed long term reduction in k reported by Glatstein and Francisca (2014):

$$k_t = k_\infty + \frac{(k_0 - k_\infty)}{1 + \left(\frac{t}{t\alpha}\right)^{t\alpha}} \quad (4)$$

Where k_t = hydraulic conductivity at time t, k_0 and k_∞ = initial and final hydraulic conductivity, and $t\alpha$ = fitting parameter that indicates the time when k shows a significant decrease.

The most common construction material for landfill liners is the local soil that in most cases needs to be stabilized with bentonite to fulfill the required hydraulic conductivity specified in most of regulations. All modeling performed in this work considers a CCL made of compacted silt-bentonite mixtures, using data reported by Glatstein and Francisca (2014) as reference values.

Silt considered here has Aeolian origin and is known as loess. This type of soil can be found in many places around the world including South America, North America, Asia and Europe. This soil has fine particles, middle hydraulic conductivity, low plasticity, open microstructure, high void ratio and mechanical behavior highly dependent on moisture content (Francisca 2007). Silt used by Glatstein and Francisca (2014) was mainly composed by quartz, feldspar, and calcite and also include a clay fraction where the most abundant mineral was illite. The most significant properties of this soil were: specific surface Ss= 2500 m^2/kg, plasticity index PI = 2.8%, and the cation exchange capacity CEC = 3.2 meq/kg. In the case of the bentonite, the most abundant mineral was sodium montmorillonite, and the most relevant soil properties were: Ss = 731,000 m^2/kg, PI = 240% and cation exchange capacity = 934 meq/kg.

Figure 1 shows the change in hydraulic conductivity with the permeation time for silt-bentonite mixtures according to data reported by Glatstein and Francisca (2014). Results shown in Figure 1 highlight the reduction in hydraulic con-

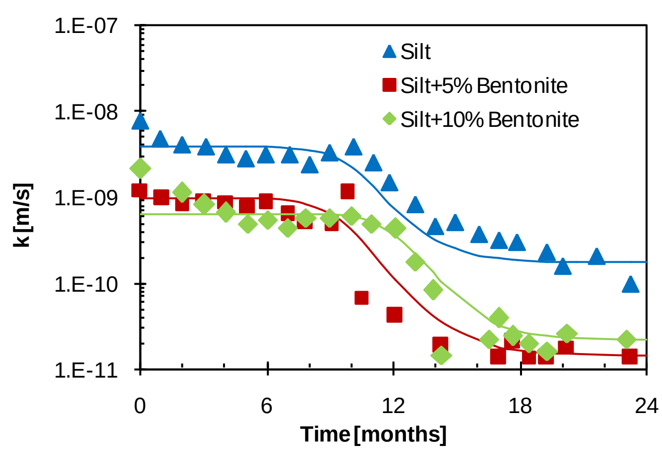

FIGURE 1
Influence of time on the hydraulic conductivity of compacted silt-bentonite mixtures permeated with leachate according to equation (4). Data from Glatstein and Francisca (2014).

ductivity due to the effect of biological clogging. These authors recommend using equation (4) to compute the expected specific discharge and mass transport for long term scenarios. Table 1 shows the model parameters used in this research to compute long term hydraulic conductivities, obtained by means of a least square fitting technique. The solid lines represent the expected variation of hydraulic conductivity according to equation (4). Comparison between the data measured by Glatstein and Francisca (2014) with the modeling performed in this work shows good agreements for each individual series, which allows us to use equation (4) to compute the short and long time liquid flux.

Chemical flux

Mass transport of dissolved ions in porous media is controlled by advection, chemical diffusion, mechanical dispersion and physical/chemical reactions (e.g. adsorption, precipitation). Equation (5) is the differential equation that describes the change in concentration with time and distance for mass transport within a reactive porous media (Fetter, 1999).

$$\frac{\delta C}{\delta t} = D_L{}^* \frac{\delta^2 C}{\delta x^2} - v_x \frac{\delta C}{\delta x} \pm \frac{B_d}{\theta} \frac{\delta C^*}{\delta t} \quad (5)$$

Where v_x = average seepage velocity, C = contaminant concentration, D_L* = longitudinal hydrodynamic dispersion coefficient, B_d = bulk density of the porous media (e.g. CCL), θ = volumetric water content and C^* = adsorbed mass of solute per mass of solids. The average effective velocity can be obtained from the Darcy´s velocity (v) and soil porosity (n) as follows:

$$v_x = \frac{v}{n} \quad (6)$$

The third term on the right of the equation (5) represents the change in concentration with time given by the adsorption of the contaminant on the soil particles, which delays the contaminant percolation through landfill liners. The amount of contaminant adsorbed on particles surface can be related to the equilibrium contaminant concentration by sorption isotherms (linear, Freundlich or Langmuir models, among others).

Contaminants considered here include heavy metals frequently found in landfill leachate. Similar trends are expected for other ionic compounds when no other removal mechanisms or chemical reactions develop. Then, for most practical purposes the influence of the variability of the mass diffusion coefficient has negligible effect on mass transport in comparison with the influence of any other soil and GM properties including the presence of defects.

Mass transport through liners was computed by the equation derived by Ogata and Banks (1961), which is the solution of Equation (5) for 1 dimensional mass transport, as follows:

$$\frac{C_{(x,t)}}{C_0} = \frac{1}{2}\left[erfc\left(\frac{x\,R - v_x t}{2\sqrt{D_l{}^* tR}}\right) + \exp\left(\frac{v_x t}{D_l^*}\right) erf\left(\frac{x\,R + v_x t}{2\sqrt{D_l{}^* tR}}\right)\right] \quad (7)$$

Where $C_{(x,t)}$ = concentration at any distance and time within the soil liner, C_0 = concentration in the inlet flow, and R= retardation factor defined as the time needed by the center of mass of a contaminant plume to pass through a soil liner, respect to the expected time for non-reactive transport (diffusion + advection only). Then, R = 1 when the porous media is non-reactive and adsorption cannot develop. Adsorption mechanisms were considered by modifying the retardation factor R from 1 to 10 which is within the range considered by the different scenarios evaluated by Chai and Miura (2002), and within the same order of magnitude of those considered by Malusis and Shackelford (2004) and Kandris and Pantazidou (2012). Higher retardation factors were reported in literature but the direct measurement of retardation factor for each metal and adsorbed material should be determined.

Heavy metals transport through composite liners is mainly related to the presence of imperfections. Therefore, concentration at the bottom of the liner depends on the amount of leakage and on chemical reactions. Chemical reactions depend on particle-leachate interactions; then, the volume of soil wetted because of leakage through an imperfection in the GM is of key importance. There are some analytical equations to determine the radius of the wetted area in the CCL below the GM.

The model derived by Rowe (1998) and modified by Touze-Foltz et al., (1999) (Eq. 7) was used to compute the radius of a wetted area, R_w as follows:

TABLE 1

Fitting parameters of equation (4), and coefficient of determination (R^2), to predict the long term hydraulic conductivity of silt-bentonite mixtures reported by Glatstein and Francisca (2014).

Material	k_0 (m/s)	k_f (m/s)	t_α (month)	R^2
Silt	3.90E-09	1.74E-10	10	0.85
Silt+5%Bentonite	9.73E-10	1.41E-11	10	0.94
Silt+10% Bentonite	6.35E-10	2.15E-11	12	0.86

$$AI_0(\alpha R_w) + BK_0(\alpha R_w) - t_s = 0 \qquad (8)$$

Where

$$\alpha = \sqrt{\frac{k_s}{Trt_s}} \qquad (9)$$

$$A = \frac{(h+t_s)K_1(\alpha R_w)}{K_1(\alpha R_w)I_0(\alpha r_0)+K_0(\alpha r_0)I_1(\alpha R_w)} \qquad (10)$$

$$B = \frac{(h+t_s)I_1(\alpha R_w)}{K_1(\alpha R_w)I_0(\alpha r_0)+K_0(\alpha r_0)I_1(\alpha R_w)} \qquad (11)$$

r_0 = radius of the imperfection, K_0 and I_0 and K_1 and I_1 = modified Bessel functions of zero and first order respectively, and Tr= interface transmissivity is given by

$$\log Tr = a + b \log k_s \qquad (12)$$

Where a and b are coefficients that depend on the contact quality between the GM and the CCL (a = -1.3564 and b= 0.7155 for good contact and a = -0.5618 and b = 0.7155 for poor contact conditions, Touze Foltz et al., 1999). Note that units in equations 8 to 12 should be used following the International System.

CCL and GM systems were compared by analyzing the breakthrough time required to reach a concentration below the barrier equals to the 50% of the initial concentration in the leachate on top of the barrier (C/C_0=0.5) (Rowe and Brachman, 2004). Note that the breakthrough time results affected by the retardation factor in equation (7) when adsorption has a significant effect on mass transport.

Relative concentrations (C/C_0) were determined from equation (7). For the case of CCL, the contaminant average effective velocity (v_x) was computed from equation (6), while for GM it was implemented as follows:

$$v_x = \frac{Q_h}{n_d A_w} \qquad (13)$$

Where A_w = wetted area below an imperfection that is determined from the radius R_w obtained from equation (8), Q_h = volumetric discharge from equation (2) and n_d = number of GM defects.

Assuming continuity, we propose in this work an average effective velocity v_x for the case of holes in contact with or adjacent to wrinkles, as:

$$v_x = \frac{Q_w}{A_{ww}} \qquad (14)$$

Where Q_w = volumetric discharge from a hole coincident with a wrinkle from equation (3), and A_{ww} = wetted area below a wrinkle that is determined from the wetted radius of a wrinkle R_{ww} obtained from equation (8), as:

$$A_{ww} = 2R_{ww}L \qquad (15)$$

In this case, the half-width of the wrinkle, z, was used as the radius of the imperfection (r_0) in equation (8). Volumetric discharges and wetted areas of holes non coincident with wrinkles where found negligible for this scenario.

OBTAINED RESULTS

Figure 2 shows the influence of soil thickness (t_s) on the expected specific discharge (q) of two different liner systems, a CCL and a GM–CCL using in both cases silt+10% bentonite. These trends were obtained by considering hydraulic conductivity values shown in Figure 1, leachate head = 0.3 m, defect area = 290 mm^2, number of defects= 5/ha, without wrinkles and good contact between GM and CCL, and with wrinkles and poor contact between GM and CCL, wrinkle length = 100 m, wrinkle width = 20 cm. Figure 2a shows the expected specific leakage in ideal liner systems

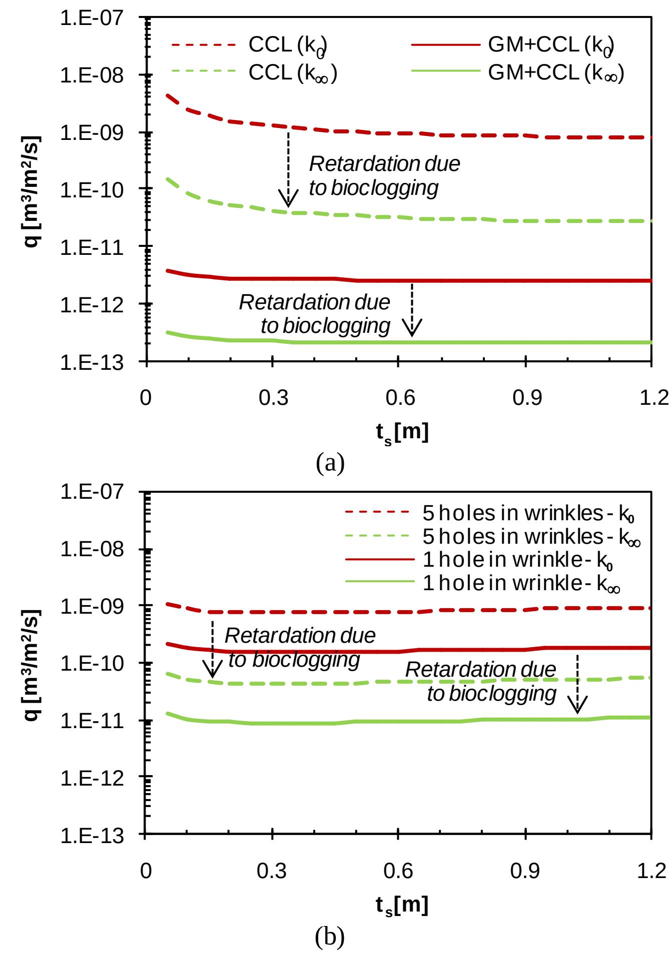

FIGURE 2

Influence of barrier thickness and bioclogging on the specific discharge: a) GM with circular defects; b) GM with holes and wrinkles.

while Figure 2b reveals the effect of holes and wrinkles on q. The specific discharge was determined from equation (1) for the CCL and equation (2) considering 5 imperfections per hectare and good contact conditions for the GM-CCL (Giroud and Bonaparte, 1989a) (Fig. 2a). The effect of wrinkles was evaluated from equation (3) by considering the same number of holes but poor contact conditions for holes that are adjacent to or in contact with wrinkles as suggested by Rowe (2012) (Fig. 2b). The figure also shows the change in the amount of leakage through the liner by considering the initial and final hydraulic conductivities presented in Table 1 for each liner system. The obtained results indicate that CCL discharge is independent of the CCL thickness after 0.4 m, while CCL thickness has negligible influence on GM-CCL discharge. Also, the presence of holes and wrinkles significantly increase the amount of leakage thought the liner being the number of holes in coincidence or adjacent to wrinkles the parameter that controls the expected specific discharge. Note that results presented in Figures 1 and 2 assume that reduction of bioclogging effects are negligible and that presence of antibiotic or antifungal solutions is avoided to preserve the long term reduction in k.

In addition to the discharge rate, the relative concentration of the percolating leachate plays also a fundamental role. The controlling transport mechanism for CCL is diffusion+advection, while advection through the GM imperfections is for GM-CCL. Figure 3 shows the contaminant relative concentration change with time determined by equation (7), and neglecting the effect of adsorption (retardation factor R=1). Two different behaviors are expected for each liner when hydraulic conductivity is assumed equal to the initial and final values reported in Table 1. It is important to highlight that small differences in k promote a marked retardation on the contaminant front increasing the breakthrough time. Also, by considering the decrease of hydraulic conductivity due to bioclogging mechanisms, the breakthrough time is increased from 7 to 13 times its original value.

The use of composite liners has been increasing since the past decade due to the complementation between properties and advantages of CCL and GM (Koerner, 2012). The performance of different liner systems can be compared by means of the breakthrough time indicated by arrows in Figure 3. Note that results shown in Figures 2 and 3 highlight the importance of retardation and bioclogging on leachate and contaminant fluxes while the most significant design barrier property is the breakthrough time shown in Figure 4. Even that the lower long term hydraulic conductivity is not used for the design of liners, the presence of bacteria and evidences of bioclogging would help to increase the time needed for the contaminant to moves from the top to the bottom of the liner.

Figure 4 shows the influence of hydraulic conductivity on the breakthrough time for CCL and GM-CCL systems, defined as the time at which the concentration equals fifty percent of the initial concentration. Obtained results are for leachate head = 0.3 m, diffusion coefficient = 10^{-9} m^2/s, effective porosity = 0.4, thickness of CCL = 0.6 m, GMh = geomembrane with 5 holes/ha, defect area = 290 mm^2 and good contact between GM and CCL, GMw = geomembrane

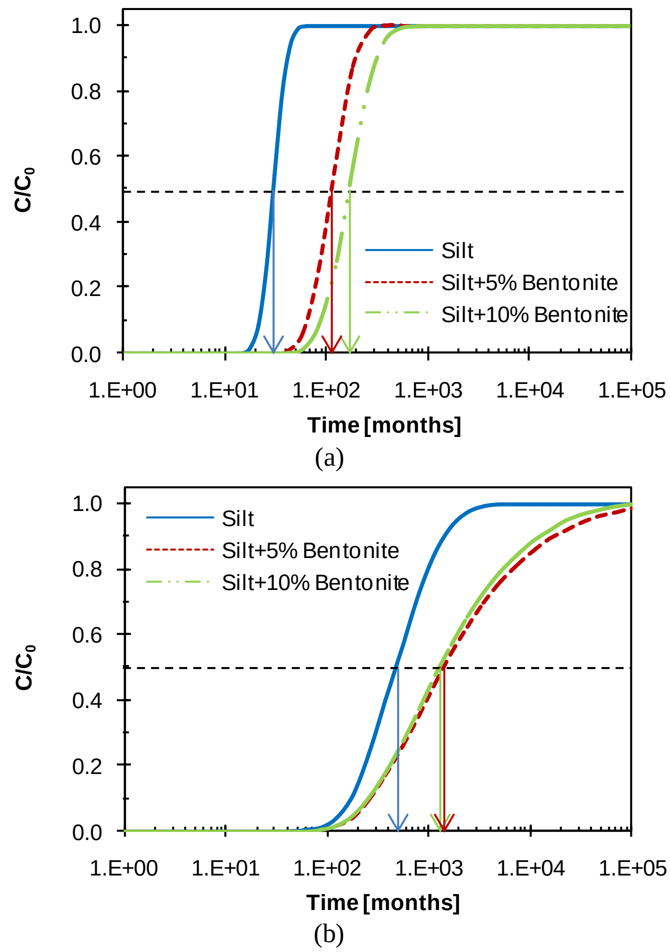

FIGURE 3

Influence of time on the expected concentrations in the liquid after passing through an inert barrier by considering: a) $k = k_0$; b) $k = k_f$.

with 5 holes/ha, 1 hole coincident with a wrinkle, and poor contact between GM and CCL, wrinkle length = 100 m, wrinkle width = 20 cm (Rowe 2004), and retardation factor R=1 (Figure 4a) and R=10 (Figure 4b). The effect of biocclogging is reflected by varying the hydraulic conductivity of the CCL as experimentally determined by Glatstein and Francisca (2014) (Figure 1). Two systems are compared, the first one is a 0.6 m thick CCL, which represents the minimum requirements in several developing countries, and the second one is a 0.6 m thick CCL with the inclusion of a GM, representing most common international regulations (EPA, 1993; Sharma and Reddy, 2004). Under the assumption of no adsorption (R=1) and no change in hydraulic conductivity (k=k_0), the breakthrough time for these two systems is 55 and 151 months, respectively (Fig. 4a), considering the hydraulic conductivity required by regulations (k= 10^{-9} m/s).

Disregarding sorption processes (R=1), for soils with k lower than 10^{-10} m/s, the retention time is approximately the same (600 months) for either CCL or GM-CCL. This result indicates that mass transport and breakthrough time are only controlled by diffusion when hydraulic conductivity is lower

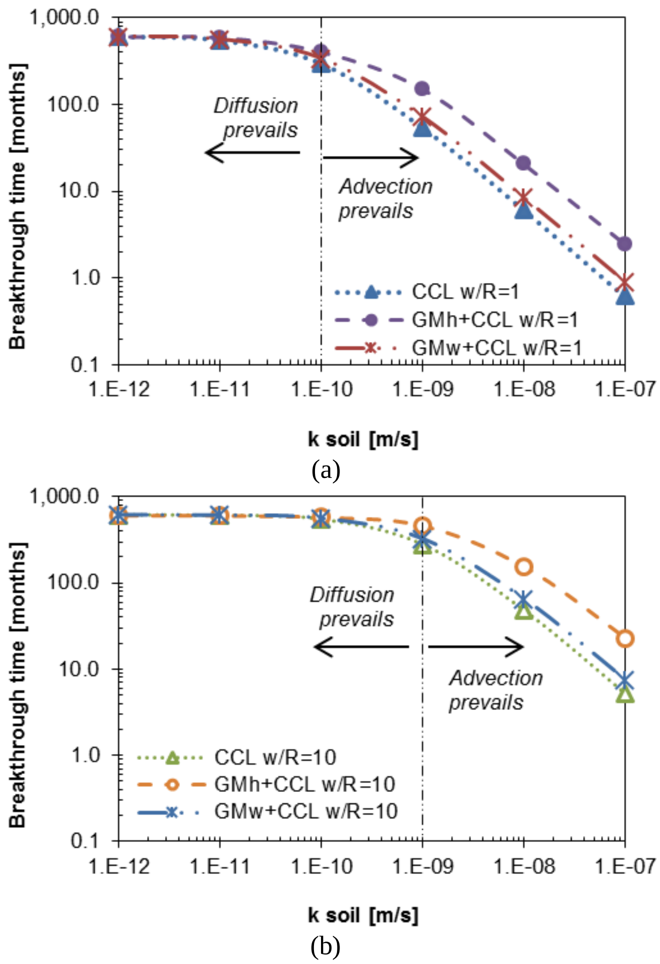

FIGURE 4

Simultaneous influence of hydraulic conductivity on the breakthrough time for CCL and GM-CCL, (a) disregarding retardation (R=1), and (b) considering R=10.

than 10^{-10} m/s (Fig. 4a). Under these conditions, whether or not the liner includes a GM, the breakthrough time reaches approximately 610 months. These results may be appropriate for different field applications when solute flux is only controlled by diffusion as previously indicated by Rabideau and Khandelwal (1998).

Considering a commonly accepted retardation factor *R*=10 for bentonite, the breakthrough time rises to 278 and 465 months for CCL and GM-CCL, respectively. In addition, the presence of the GM clearly contributes not only to reduce the specific discharge (Fig. 2) but also significantly increases the breakthrough time. Therefore, the amount of mass that passes through the liner reduces significantly.

It is important to highlight that breakthrough times in the case of holes in coincidence or adjacent to wrinkles resulted significantly lower than those expected for holes in the GM in direct contact with the CCL regardless the retardation factor (Figs. 4a and 4b). These results can be explained by the larger wetted area below wrinkles than below holes. Then, considering that the breakthrough time reduces when holes and wrinkles coexist (Fig. 4) and at the same time this significantly increase the specific discharge (Fig. 2), the amount of mass that passes through the liner system is mainly controlled by wrinkles.

Analysis shown in Figure 4 can be used for the comparison of different liner systems and their performance to restrict the displacement of contaminants. From these comparisons, alternative barriers to those recommended by current regulations (e.g. US EPA 1993) with similar capability of restricting mass transport can be determined.

Obtained results show that the breakthrough time for a GM-CCL with a thickness equal to 0.6 m, hydraulic conductivity $k \cong 10^{-9}$ m/s (achieved with silt + 5% bentonite) and R=1 (neglecting adsorption contribution) are quite similar to those expected for a single CCL with a thickness equal to 1.3 m and the same hydraulic conductivity and retardation factor. The same breakthrough time is obtained for a GM-CCL system 0.32 m thick when adsorption mechanisms with R=10 are taken into account. In addition, if the reduction of hydraulic conductivity due to bioclogging is also considered, this thickness can be further reduced to 0.30 m for the same expected breakthrough time as schematically shown in Figure 5. However, note that the main goal is not reducing the barrier thickness but to increase the safety and breakthrough time for barriers. This can be possible if barriers are not considered as inert materials. Even retardation and bioclogging effects are well known since several decades ago, these phenomena are not yet considered to evaluate the performance of landfill liners.

However, CCL thicknesses lower than 0.3 m are not recommended according to the results reported by Benson and Daniel (1994b) to minimize the effect of variability on the equivalent hydraulic conductivity of the barrier. By maintaining the minimum recommended thickness, the safety of the barrier to restrict leachate migration and mass transport increases (Fig. 5). Therefore, a CCL 0.45 m thick made of three lifts 0.15 each one may have a better perfor-

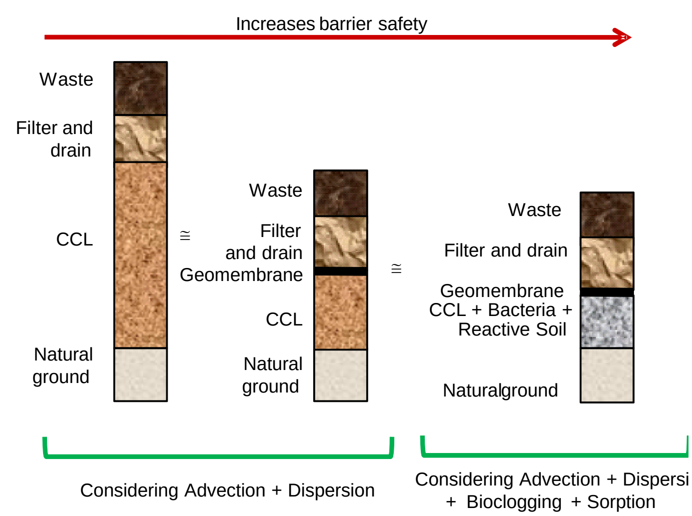

FIGURE 5

Changes in barrier height and safety by considering new aspects on the design.

mance containing leachate and contaminants than a thicker CCL due to adsorption and bioclogging mechanisms.

CONCLUSIONS

This work analyzes the influence of bioclogging on mass transport through composite liners. Different numerical models are developed in order include the effect of hydraulic conductivity reduction due to bacteria growth within the liner pores and it effect on the breakthrough time for heavy metals in reactive and non-reactive liners. The main conclusions can be summarized as follows:

- The amount of inorganic contaminants that passes through bottom liners and the breakthrough time are significantly affected by the presence and characteristics of holes and wrinkles.
- The breakthrough time increases significantly due to microorganism growth inside soil pores. Adsorption mechanisms also induce the same effect given that the retardation factor also slower the chemical flux within the liner.
- Long term decreases in k below 10^{-10} m/s will not influence significantly on the life span of the barrier, since diffusion becomes the dominant mechanism in the transport process.
- Reduction of k due to bioclogging and the increase of breakthrough time due to bioclogging and adsorption of metals on the CCL significantly contribute to minimize the negative effect of holes and wrinkles on mass transport though liners.
- The correct combination of engineering design considering chemical and microbiological reactions that take place within the liner provide new opportunities to improve landfill liners behavior. These new factors can be considered in future designs of liner systems, as well as in decision making processes.

ACKNOWLEDGEMENTS

This work was partially supported by FONCyT (PICT-2014-3101), CONICET (PIP 11220150100298CO) and SECYT-UNC. Authors thank the support received from FCEFyN-UNC and ISEA-UNC during this research.

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