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Hydraulic Flow through Engineering Bentonite-Based Containment Barriers

[1]Eric Wooi Kee Loh and [2]Devapriya Chitral Wijeyesekera

[1]*Faculty of Science, Technology, Engineering and Mathematics, INTI International University, Negeri Sembilan, Malaysia*
[2]*Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia*

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Corresponding Author:
Eric Wooi Kee Loh
Faculty of Science, Technology, Engineering and Mathematics, INTI International University, Negeri Sembilan, Malaysia
Email: ericdrloh@gmail.com.my

Abstract: This paper presents the use of software modelling as a tool to study the impact of hydraulic "resistivity" on the contaminant transport through bentonite-based containment barriers. A sensitivity analysis on the predicted data was carried out by varying the boundary conditions as well as the hydraulic resistance to flow through varying contaminant transport parameters. Accordingly, both advective and diffusive flow processes are considered as that which resists the flow. In particular, the effect on the contaminant migration due to desiccation cracking is explored. Laboratory evidence is provided and discussed to show how the initial microstructure of the clay influences the development of subsequent macro structural features such as shrinkage crack patterns. The effect of these cracks and the intensity of cracking on the contaminant migration are modelled and pragmatically discussed. Additionally, the effect on the hydraulic conductivity of bentonite-based barriers, when permeated with non-standard liquids is discussed and a typical analytical output is presented.

Keywords: Bentonite, Containment Barriers, Leachate, Cation Exchange, Advective and Diffusive Flow

Introduction

Barriers built with natural and synthetic materials have been widely used in Geo-environmental Engineering to retard contaminant migration. Amongst others, clay is popularly used as engineered barriers or as an essential component in most synthetic landfill liners to minimise migration of contaminants or for water proofing structures. Waste disposal sites need to adhere to stringent regulations on the disposal of municipal, industrial and hazardous wastes. EU directives recommend low permeability soils, which naturally should contain bentonite, as a sealing material in the construction and rehabilitation of landfills to ensure the protection of groundwater from pollutants. Such clay barriers vary from thin Geosynthetic Clay Liners (GCL; 4.5 to 9 mm thick), to Compacted Clay Liners, (CCL; 0.6 to 2 m thick) to naturally undisturbed clayey barriers up to 30 or 40 m thick.

A full definition of CCL is found in the Landfill Directive; whereas, GCLs are commonly known as factory-manufactured contaminant barriers that consist of a thin layer of either calcium or sodium bentonite core sandwiched between two geotextiles. They are a popular alternative used in waste-containment facilities than CCLs due to their low hydraulic conductivity, ease of installation and perceived resistance to environmental distress (Koerner, 1997). The primary differences between them are the mineralogy and form of bentonite (e.g., powder/granular versus pre-hydrated and extruded with plasticine consistency; sodium versus calcium adsorbed ion, Cation exchange capacity) used in the core of GCL, the type of geotextile (e.g., woven versus nonwoven); or the addition of a geomembrane and the bonding methods (e.g., adhesive bonding, stitch bonding or needle punching).

The hydraulic conductivity of bentonite and clay soil in general, depends on the fraction of free water and the size as well as the tortuosity of the pathways through which the free water flows. A change in the fraction of the pore space filled with bound water results in a corresponding change in fraction of the pore space filled with free water, as well as changes in the flow paths. Thus, factors that affect the fraction of bound water directly affect the hydraulic conductivity of bentonite (Wijeyesekera *et al*., 2012; Shackelford *et al*., 2000; Mesri and Olsen, 1971; McNeal *et al*., 1966). Various studies have shown that the hydraulic conductivity of GCLs can be affected between a factor of 10 and 10,000 when permeated with inorganic permeant solutions (Liu *et al*., 2015; Scalia *et al*., 2014; Shackelford *et al*., 2014; 2000; Hosney and Rowe, 2013; Mazzieri *et al*., 2013; Zhu *et al*., 2013; Benson *et al*., 2010; Brown and Shackelford, 2007; Katsumi *et al*., 2007; Jo *et al*., 2004; 2001; Lee and Shackelford, 2005; Guyonnet *et al*., 2005; Kolstad *et al*., 2004; Egloffstein, 2001; Jo *et al*., 2001; Petrov and Rowe, 1997).

Hydraulic Performance Modelling

The theory and governing equations of flow and transport in porous media has been the subject of extensive research, particularly in the past two decades, in response to problems arising from subsurface contamination (Mategaonkar and Eldho, 2012; Cortazar and Monzon, 2007; El-Fadel *et al*., 1997; US EPA, 1993). Analytical or numerical models have been developed to simulate subsurface leachate flow and transport. Though all these models solve mass, momentum and heat transport equations, the individual model capabilities and solution schemes can differ widely. Inclusion of the detailed discussion on these is beyond the scope of this paper. The four different processes of contaminant migration are:

- Advection; the movement of the contaminant with the seepage of the groundwater
- Dispersion; the apparent mixing and spreading of the contaminant within the flow system
- Adsorption; the process by which chemical dissolved in the groundwater clings to a solid surface which decreasing the concentration of the solute
- Degradation or known as radioactive decay, which will reduce the concentration of radionuclide in both the dissolved and sorbed phases

The cumulative one dimensional effect of these contaminant processes is expressed in the following partial differential equation:

$$D_x \frac{\partial^2 c}{\partial x^2} - \bar{v}_x \frac{\partial c}{\partial x} - \lambda_1 c - \frac{\lambda_2 \rho_d c^*}{\theta} - R = \frac{\partial c}{\partial t} \quad (1)$$

Where:

D_x = Hydrodynamic dispersion in x (L^2T)
$\bar{v}_x$ = Average linear velocity in x (L^2T^{-1})
λ_1 = Dissolved half-life (T^{-1})
λ_2 = Sorbed half-life (T^{-1})
c = Dissolved concentration (L^3M^{-1})
c^* = Sorbed concentration (ML^{-3})
ρ_d = Bulk density (ML^{-3})
θ = Volumetric water content (-)
R = Retardation factor of soption isotherm (-)

This can be extended to the case of two and three-dimensions by simply adding the corresponding terms for hydrodynamic dispersion and advection in the y and z direction.

Case 1: Qualitative Comparison of Barriers Performance

Two identical Compacted Clay (CC) barriers of different hydraulic conductivity were used to representing the defection due to poor construction. Polymerised Bentonite (PB) barriers of difference thickness were used to demonstrate the distinction of single and double layer. These are underlain by a hypothetical 5 m thick geological layer overlying an aquifer. Vertical advective flow seepage results from a leachate head of 0.3 m. Other relevant input information is also given in Table 1. The model considers a steady state condition with constant influent flux. An aqueous phase effective diffusion coefficients, D* of 1×10^{-9}m^2/s was adopted (Bourg *et al*., 2007; García-Gutiérrez *et al*., 2004; Shackelford and Daniel, 1991a; 1991b; Iversen and Jorgensen, 1993). The advective and diffusive equivalency was then investigated separately.

Figure 1 shows an output that result from a purely advective contaminant transport analysis. The result demonstrates the advantage from using a thin layer of PB in terms of preventing advective transport. The completion of the break through took 4.8 years in the case of a single layer of PB_1 (5 mm) and 10.8 years for the case of a double layer of PB_2 (10 mm). In comparison with the CC_1 (poorly constructed) and CC_2 (favourably constructed), the break through time have been reduced to 1.5 and 4.2 years respectively.

Although the thin layer of PB gave desirable results in term of hydraulic conductivity, the break through time of PB (10 mm in thickness) was not comparable to the CC (1000 mm in thickness) in term of the advective-dispersive contaminant transport as evidenced in Figure 2. Nonetheless, the PB generally exhibits a higher adsorption capacity; but, is not enough to compensate the lack of diffusive equivalency in short term. Looking at the long term performance of these two distinct barriers; the primary concern is the relative concentration for the contaminant versus time at the exit boundary is much higher when a CC is used.

Case 2: Cracking Effect of the Bentonite-Based Barriers

Drying process that occurs when bentonite clay barriers are isolated from groundwater is the commonly known mechanism for the engineered clay in the liner to crack during desiccation.

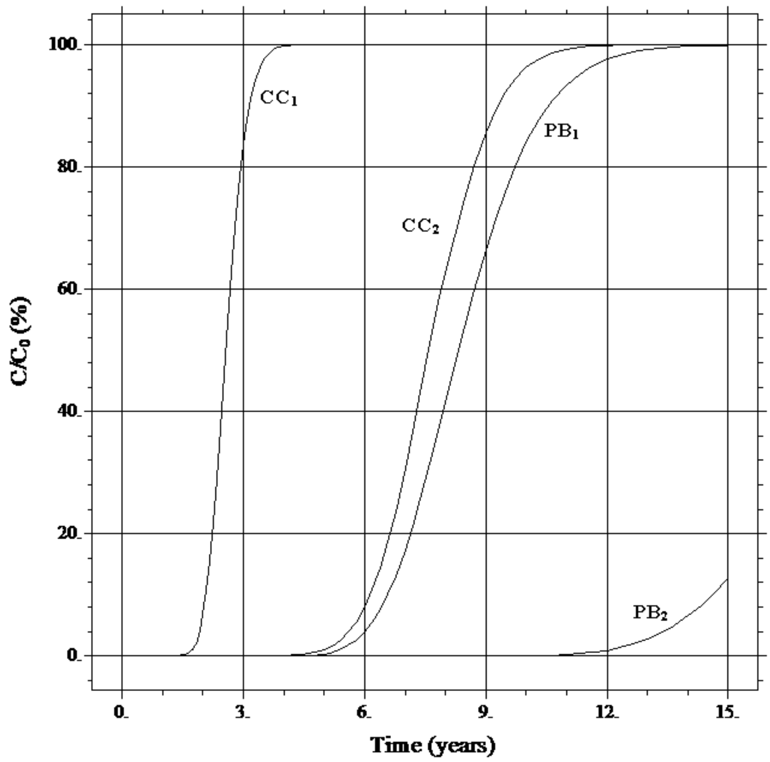

Fig. 1. Purely advective contaminant transport

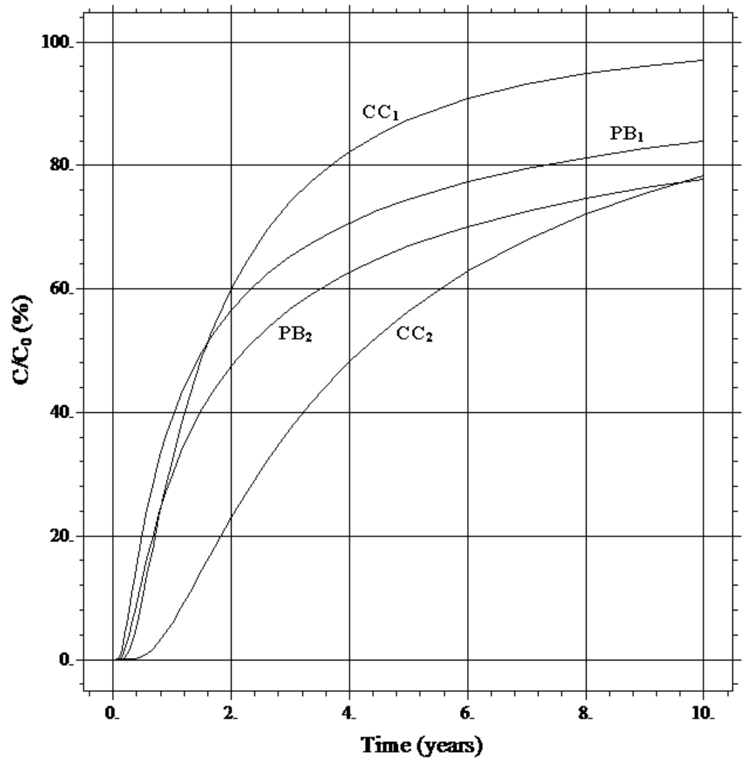

Fig. 2. Advective-dispersive contaminant transports

Table 1. Input parameters and analysis results for model of CC and PB performance

Parameter	CC_1	CC_2	PB_1	PB_2
Thickness (mm)	1000	1000	5	10
Saturated hydraulic conductivity, k_{sat} (m/s)	1×10^{-7}	1×10^{-9}	1×10^{-12}	1×10^{-12}
Diffusion coefficient, D* (m^2/s)	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}
Longitudinal dispersivity, α_L (m^2/years)	0.6	0.6	0.6	0.6
Transverse dispersivity, α_T (m^2/years)	0.06	0.06	0.06	0.06
Leachate head (m)	0.3	0.3	0.3	0.3
Leachate source strength, C_0 (mg/m^3)	100	100	100	100
Case A: Advective Only				
Break through Time (years)	1.5	4.2	4.8	10.8
Time for 50% of concentration (years)	2.5	7.3	8.2	>>15
Case B: Advective-dispersive				
Break through Time (days)	35	68	20	29
Time for 50% of concentration (years)	1.5	4.2	1.5	2.2

Table 2. Input parameters and analysis results for cracking effect

Cracks parameter	A	B	C	D	E	F
Number of cracks, N	0.00	1.0	2.0	4.00	8.000	20.00
Width, a (m)	-0.00	0.2	0.1	0.05	0.025	0.01
Spacing, n (m)	-0.00	0.8	0.4	0.20	0.100	0.04
Break through Time (days)	2.80	2.3	1.4	1.60	1.600	1.80
Arriving Time for 50% of concentration (days)	110.00	75.0	60.0	60.00	60.000	60.00

Freeze thaw effects in the clay, moisture loss due to vapor transpiration from air spaces created by wrinkling of the geomembrane promote the occurrence of cracking. These allow the collection of the evaporated moisture from the underlying clay barriers, causing them to later condense and fall by gravity away from the original source due to diurnal temperature changes. In addition to above, particular attention must also be given to cracking that occur due to the cation exchange within bentonite which normally occurs over a period of approximately 1-3 years (Bradshaw *et al*., 2013; Benson and Meer, 2009; Wijeyesekera, 2003; Egglofstein, 1997).

The bentonite in the linear system generally is found either as air dried granulated/powdered or as prehydrated and extruded form. The loss of its function as a barrier in dry system due to desiccation cracking are incessantly reported by numerous people (He *et al*., 2015; Rowe and Verge, 2013; Wijeyesekera *et al*., 2012; Scalia and Benson, 2011; Egloffstein, 2001; Hewitt and Philip, 1999). A non-uniform distribution of granulated bentonite accentuates the formation of crack patterns.

This is readily recognized to occur in the dry bentonite system. The intensity of cracking varies with the thickness (mass/unit area) as observed by (Wijeyesekera *et al*., 2012). Figure 3 illustrates this observation.

When the dry bentonite adsorbs water for swelling, plastification can occur close to the desiccation cracks. This occurrence is conceivable. Accordingly an increased water flow can occur through the bentonite barries, depending on the extent of the cracking (intensity; spacing, width and length of cracks) and the hydraulic gradient. The geometry and in particular, the width of the cracks in the bentonite layer are decisively dictated by the kind of encapsulation of the bentonite between the cover and a carrier geotextile.

The parameter used in this model simulation are rather conservative, the bentonite barries is assume to have total 20% of volumetric shrinkage and the hydraulic conductivity of the desiccation crack was set to 1×10^{-5} m/s. A crack index as shown below was used to help quantify the cracking in the modeling domain and the modeling domain was tabulated in Table 2:

$$S\% = \frac{Na}{L} \tag{2}$$

Where:
$S\%$ = Shrinkage in percentage
N = Number of cracks
a = Width of cracks
L = 1m

Figure 4 indicated that with cracks, the potential contamination is confined to a time period of a few years; however it will decreases as the intensity of desiccation cracks increases. The higher flow velocities in the fracture cause more rapid and higher concentration of contaminant transport in that region.

Figure 5 depicts the long term effect of increasing the intensity of crack. What is most interesting to note in the graph is that, contaminant migration is susceptible to the intensity of cracking rather than its width. The bentonite barrier are generally very thin; for long term, while higher groundwater velocities within the crack increase the speed of the plume spread, they increase dilution ratio and hence tend to decrease the concentration.

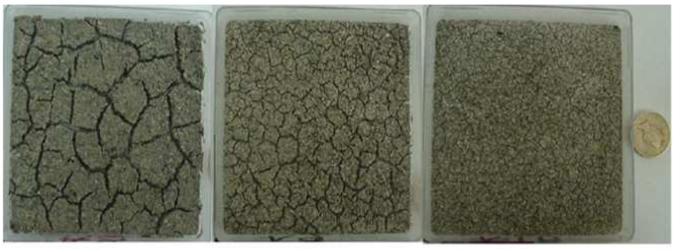

Fig. 3. Desiccation crack patterns-the effect of thinning out of the dry bentonite (Wijeyesekera *et al*., 2012)

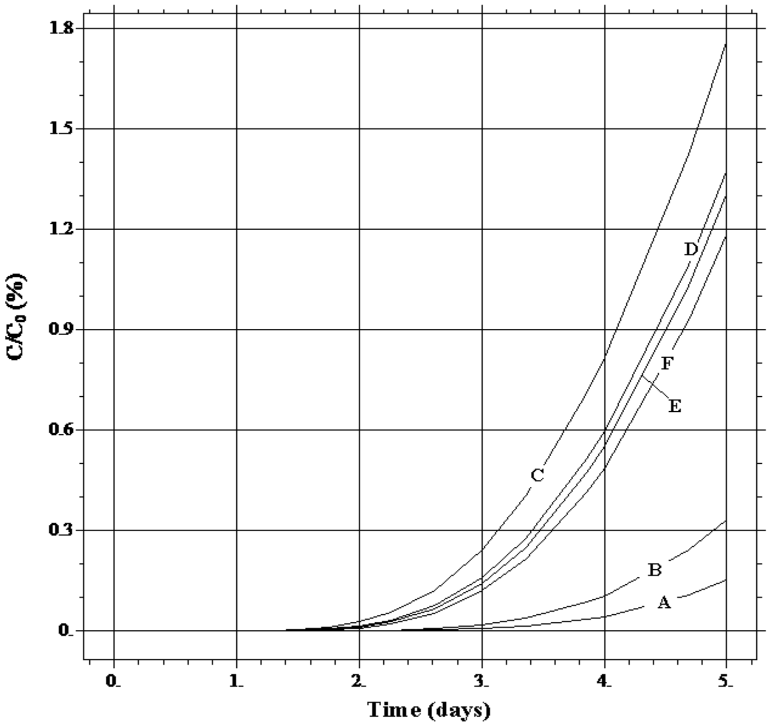

Fig. 4. Short-term effect of different cracking scenario

Case 3: Performance of Bentonite Barrier under Hostile Geo-Chemical Environment

Bentonite barriers are often used to contain liquids other than water and, thus, there has been considerable interest in modelling the performance of system in aqueous permeant solution. Prehydration has been suggested as a means to prevent the hydraulic conductivity of bentonite barriers from being altered by leachate permeation. Prehydration is hydration of the bentonite with a dilute solution (e.g., deionized, distilled, or tap water) by soaking or permeation prior to permeation by a chemical solution (Liu *et al*., 2015; Scalia *et al*., 2014; Shackelford *et al*., 2014; 2000; Mazzieri *et al*., 2013; Zhu *et al*., 2013; Brown and Shackelford, 2007; Katsumi *et al*., 2007; Jo *et al*., 2004; 2001; Kolstad *et al*., 2004; Egloffstein, 2001; Vasko *et al*., 2001; Petrov and Rowe, 1997; Ruhl and Daniel, 1997).

In the author's point of view, prehydration in the field may occur naturally due to migration of water from an underlying subgrade (as a result of capillary effects or vapor-phase diffusion) or may be effected intentionally (e.g., spraying or inundating the bentonite barriers); however, the optimal prehydration state will not always accomplished. Therefore; the focus of this section is on the applications of bentonite barrier when subjected to complex aqueous permeant solution and complete prehydration by permeation with distilled, deionized, or potable water is unlikely to be achieved at site. To facilitate this modelling, long-term hydraulic conductivity of a bentonite permeated with inorganic salt solutions and the diffusion coefficients for inorganic molecules was adopted from (Jo *et al*., 2004; Shackelford and Daniel, 1991a; 1991b) respectively. Other relevant input information is also given in Table 3.

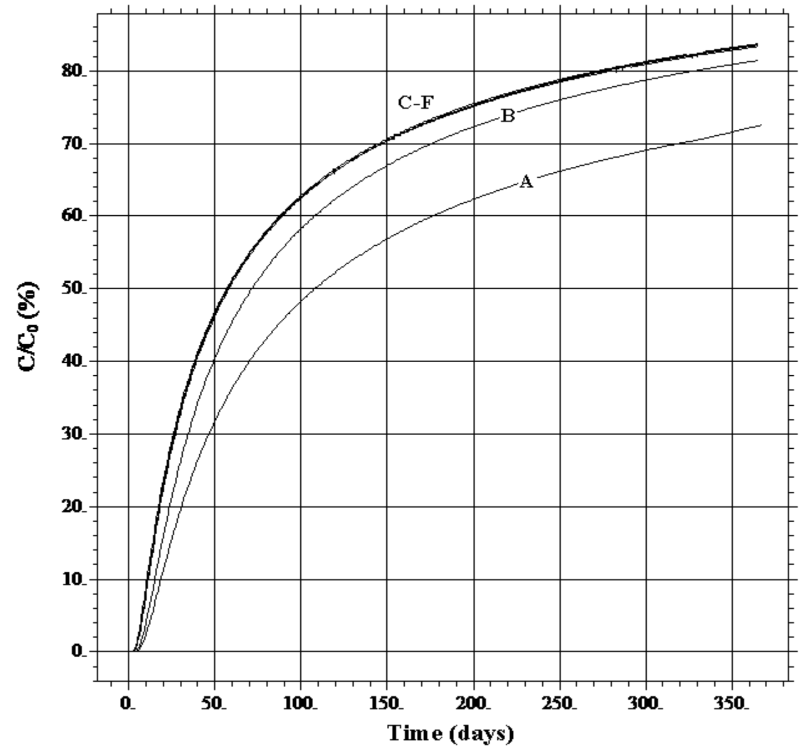

Fig. 5. Long-term effect of different cracking scenario

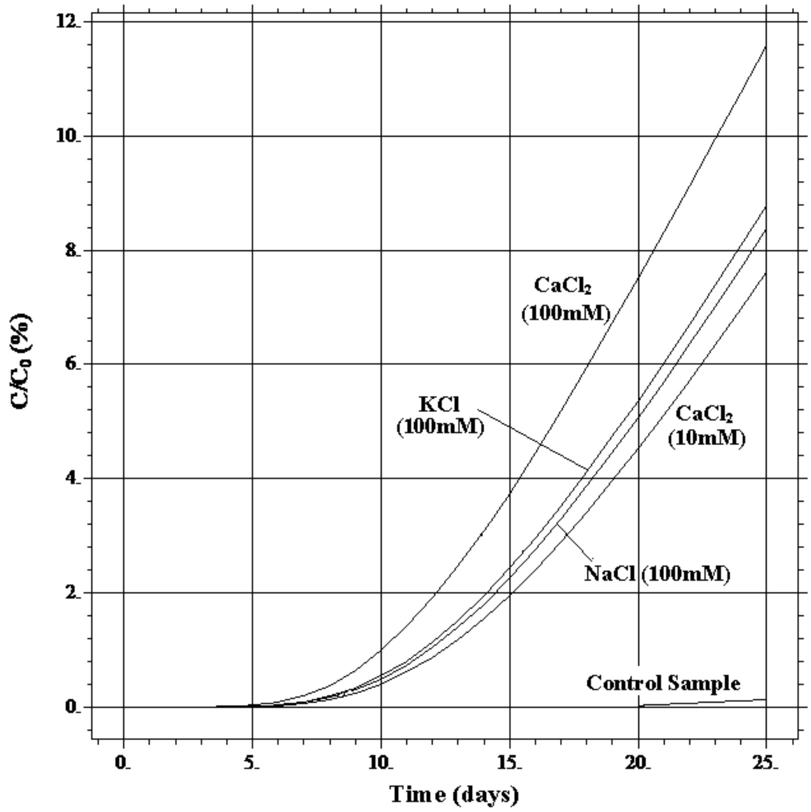

Fig. 6. Short-term effect of different permeant

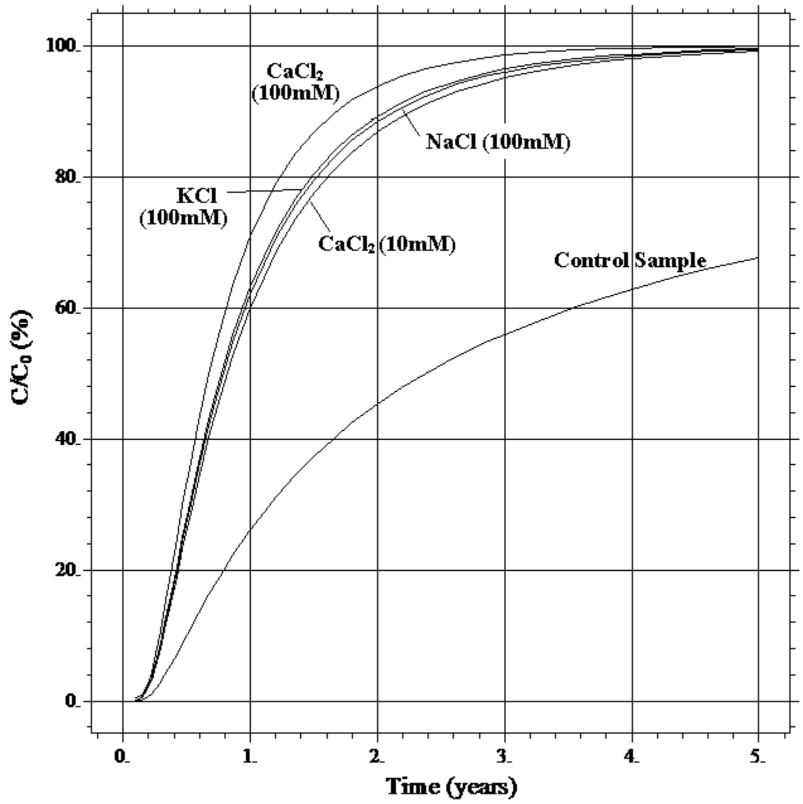

Fig. 7. Long-term effect with different permeant

Table 3. Input parameters and analysis results for bentonite barriers under hostile geo-chemical environment

Case	A	B	C	D	E
Permeant solution	$CaCl_2$	$CaCl_2$	KCl	NaCl	Control
Concentration (mM)	10	100	100	100	Sample
Diffusion coefficient, D* (m^2/s)	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}
Saturated hydraulic conductivity, k_{sat} (m/s)	8.6×10^{-11}	1.1×10^{-6}	5.1×10^{-11}	4.4×10^{-11}	1.0×10^{-12}
Break through Time (days)	5.8	3.5	4.8	5	20
Arriving Time for 50% of concentration (years)	0.84	0.62	0.71	0.73	2.5

Figures 6 and 7 show an output that result from an effect of hydrating liquid on the hydraulic resistivity of bentonite berries. The completion of the break through took 20 days for the control sample. In comparison with the samples permeated by a chemical solution, the break through time have been reduced to circa 3 to 5 folds. This phenomena is most prevail in the strong (100 mM) $CaCl_2$ solution. It is also observed that the relative concentration versus time at the exit geological layer for samples permeated by chemical solution is much higher than the control sample. A more rapid concentration migration of the contaminant was generated within circa 4 to 5 years' time.

Conclusion

Achieving an understanding of the scientific basis to contaminant transport is essential to improve long term prediction of the leachate migration characteristic in engineered landfill design. Based upon the simulated model on hydraulic performance, clarification in model uncertainties as well as unfavorable defection due to poor construction in CC barriers; PB barriers is apparently substitutable for the conventional CC barriers. Factor affecting the performance of PB barriers have been critically presented and the effects have been illustrated through the modelling. Attention must be drawn to the deficiencies experienced in adopting PB barriers particularly when optimal prehydration state is not always accomplished. Design Engineer must not overlooked the desiccation cracking effect due drying process that occurs when barriers is isolated from ground water/subjected to freeze thaw effects/cation exchanged within bentonite. This phenomenal demonstrated a significantly resulted of much higher hydraulic flow through the barriers emphasized.

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Author's Contributions

Authors jointly worked on deriving the results, writing and approved the final manuscript.

Ethics

The authors declare no conflict of interest.

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