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Attenuation Potency of Mineral Liner to Cationic Migration

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Abstract

In waste containment, it has become imperative that regimes of soil, surface and groundwater reserves are duly protected from contamination from leachate generation and migration in landfills. However, in developing countries such as South Africa, the construction of engineered facilities may be costly and the prevention of contaminants may become significantly reliant on the geology of the waste disposal site. More so, membranes forming part of geocomposite systems for waste containment may fail at any point in time leading to consequential environmental and human health impacts. Hence this study conducted series of laboratory tests of a failed membrane in a geocomposite liner under leachate migration through a circular defect using a bespoke hybrid column permeameter device. A zeolitic mineral liner; 24 mm thick, polythene plastic (PP); 2 mm thick having a 5 mm centralized inflicted puncture were used to simulate the circular failure in the membrane with a 225 mm thick mineral layer as attenuation strata (AS) making up the experimental setup. The bespoke device of 60 mm diameter was coupled to a hydraulic pressure frame capable of imposing over 800 kPa pressure to the liner. Permeant through the liner system was evaluated in ranges of 0 – 150 kPa. The study measured migration rates for conditions of good and perfect interface contacts. The study found the conditions of good contact to be valid but unachievable for conditions of perfect contact. However, tests results revealed significant reduction in migration rates with increased pressure, p, on the system. This is plausibly due to reduced system transmissivity, θ, and densification of the zeolitic liner. Subsequent to compatibility tests, there was substantial evidence that cation concentrations migrated through the failed membrane-mineral liner. Nonetheless, a fairly reasonable attenuation potency of the zeolitic mineral layer as AS to migrating cations was recorded.

Keywords: Attenuation; Cations; Contaminants; Migration; Zeolite

1. Introduction

Civilization, industrialization, and globalization have resulted in increased human activities towards meeting and satisfying dire needs and challenges of the most recent decades. This has warranted varied industrial and domestic

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activities leading to massive generation of solid wastes with environmental and human health impacts. Hence, it has become pertinent that these by-products of human activities are appropriately contained in engineered waste disposal facilities [1]. Conversely, recycling is considered the first and best option of dealing with waste before landfilling and other waste management options are opted for on account of waste handling difficulties, cost or available technologies in present times [2]. It is well known that land disposal has come a long way as a method of getting rid of various generated waste, and still is the commonest form of waste disposal generally, and it is the most publicly accepted which will remain for a long time to come. Landfills are known to produce gases and leachates whose breakaway and eventual migration into surrounding soil, surface and groundwater could have severe human and environmental health effects. Consequently, leachate migration as argued by [3] should be highly restricted to the lowest minimum if not totally stopped. Nonetheless, rain, runoffs and waste containing high moisture in landfills trigger the degradation and generation of leachate contaminants by microbial actions. As such, protecting regimes of soil and groundwater reserves against leachate pollution should remain of significant interest to landfill engineering and good waste management practices. However, in developed countries, waste lining/ liner systems are well utilized in guarding against contaminant migration to levels with consequential impacts. Whereas in developing countries, where the construction of engineered facilities may be expensive, the prevention of contaminant migration may be highly dependent on the geological formation of the disposal site [4]. On the one hand, membrane which forms part of a geocomposite liner may fail or be defected from fabrication, installation or due to ultraviolet radiation in its service life. On the other hand, constructing disposal facilities around vital water reserves may be unavoidable and therefore, it must be done with integrity to ensure protection of soil and groundwater regions from waste bodies [5]. This can be achieved by employing mineral clay liners/ compacted clay liners (CCL) as components of geocomposite lining systems to prevent migrating contaminants from reaching ground levels posing detrimental impacts in cases of membrane failures e.g., failures of Geomembrane (GM) or Geosynthetic Clay Liner (GCL). As such, membrane-soil liners are recommended worldwide and are actively utilized in waste containment which forms a major component for multiple systems in engineered landfills. As recorded by [3] the employment of geosynthetics is also recognized in designs for better services and is rapidly expanding as engineers and manufacturers develop improved materials and new analysis routines towards proper waste containment in landfills. The daily generation and disposal of more than 41,000 tons of solid waste in South Africa has attracted attention, particularly, in the Gauteng province and City of Johannesburg (CoJ) where cumulatively, over 25,000 tons of waste is dumped daily [6]. This imposes enormous waste load on the lining system, and considering that over 75% of Municipal Solid Waste (MSW) in South Africa ends up in landfills, the liners are thus subjected to pressure from waste piles from which failures of membranes in-situ may be inevitable [7]. Pollution of soil and groundwater resources is part of the many effects of landfilling which requires to be addressed along with the health, environmental and aesthetic challenges often associated with waste disposal. These concerns gave this study the impetus to investigate the impact of pressure on migration rate, cation migration mechanism in zeolitic soil liner used as CCL, as well as its attenuation capabilities considering that there is still much to be documented on this subject matter towards adding to the body of knowledge as well as proffering solution. Landfill surveys from this study, showed an estimated 150 kPa of waste imposing the liners. Consequently, the study investigated pressure effects on leachate migration through a failed polythene plastic (PP) liner underlain by a zeolitic mineral soil liner as CCL and attenuation strata (AS). Results of pressure effects on migration rates, cation migration and the attenuation tendencies of zeolitic mineral clay liner are therefore reported in this study.

Nomenclature

Leachate	water escaping from a landfill site which, if not collected, contaminates the natural water sources
Contamination	the action or state of making or being made impure by polluting or poisoning
Migration	refers to the movement and filtering of fluids or contaminants through porous media

2. Experimental process

In this study, zeolitic soil was harvested in Johannesburg, South Africa, from an active landfill site slightly distant from the actual dump area to ensure a certain degree of purity and used as CCL and AS. The natural mineralzeolitic clayey sample as shown in Fig. 1 was collected and then mechanically and chemically tested to determine applicable engineering and compositional properties.

Fig. 1. Zeolitic soil sampling area

The grain size distribution curve and the compaction curve which expresses the relationship between optimum moisture content (OMC) and maximum dry unit weight (MDUW) of the soil determined by compaction test in conformance with [8] are presented in Figs. 2(a) and (b) respectively. The standard proctor compaction test was done with a light self-weighted rammer of about 0.0244 kN and striking effort of about 595 kN-m/m^3. The tests yielded OMC of 15.5 % and MDUW of 17.1 kN/m^3 for the zeolitic soil. The results for permeability coefficient determined in accordance with [9] were measured by falling head test as the bespoke column hybrid permeameter device was not designed to hold a constant head. The AS was prepared with relatively low water content throughout the testing stages and was lightly compacted in order to simulate the in-situ conditions of natural soils. The relationship between the permeability and dry unit weight of the natural soil is presented in Fig. 2(c).

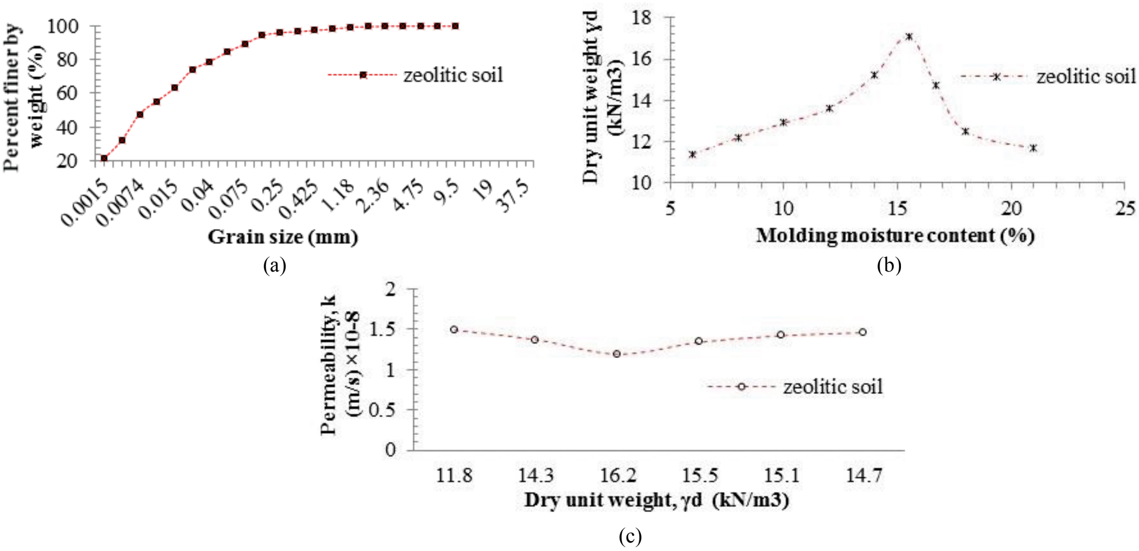


Fig. 2. (a) Zeolitic soil grain size distribution curve; (b) Zeolitic soil compaction curve; (c) Zeolitic soil permeability variation

The permeant used in the study was scooped from the leachate basin at the landfill site. The basin was designed to hold generated leachate formed by degradation of waste, infiltrated storm water and/or intercepted surface water in contact with the waste body. The leachate was sampled from different points within the basin as shown in Fig. 3 and vigorously stirred to ensure a homogenized leachate composition. From the chemical analyses of the sampled leachate, Table 1 presents the initial concentrations (mg/l) of the targeted contaminant species. The cationic contaminants were of interest to the study due to their ion exchange behaviours when migrating through charged clay surfaces used as attenuators, as well as to validate and establish closure on the obtained results based on their comparisons to related works by the authors [10, 4, 7, 11, 12].

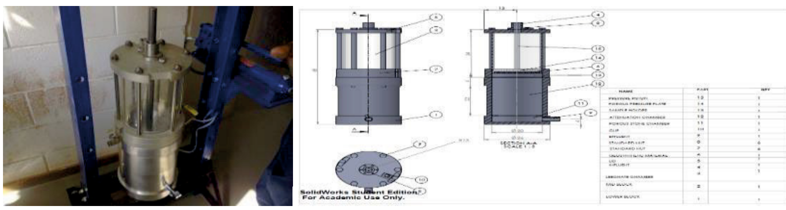
Fig. 3. Permeant/ leachate sampling from leachate pond in-situ

Table 1. Leachate analysis for soil compatibility/ soil-leachate interaction test

Parameter	ASTM Test	Conc. (mg/l)	Drinking water standard (mg/l)*
Mg	D 511	25	145
Ca	-	170	200
K	D 4192	18	-
Na	D 4191	130	250

Source: *(Water services authorities South Africa, 1997)

The full spectral analysis method was used to measure the cation content on both the leachate influent and effluent which was compared to the South African standard of drinking water in consonance with [13, 14]. In consideration of the complexity and nature of the contaminant species capable of being formed from the decomposition of solid waste in landfills, the scarcely available spectral testing materials made it possible to only detail a few compositional features, properties and characteristics of the nominal products. As such, cation tests for migration and attenuation of nominal selected ions in the cores of the AS from the leachate was conducted. In general, the selection of the cation species was based on two main drivers: (i) the availability and concentration of the ions present in the leachate generated at the landfill and; (ii) the potential hazardous impact expected in a case of contaminant escape or breakaway to subsurface regions. Hence, the parameters analyzed were the dominant intruding cations at the landfill i.e., the alkali metals (Group IA) and the alkaline earth metals (Group IIA) e.g., Na and K, Ca and Mg respectively. The bespoke column hybrid permeameter device had the leachate reservoir marked to hold a constant head of 250 mm throughout the testing duration. A pictorial and schematic view of the bespoke device is presented in Fig. 4. The device comprises of three sections: (i) the bottom part called the attenuation chamber; which contained the zeolitic natural soil strata acting as the natural earth/AS underneath the geocomposite system as shown in Fig. 5. (ii) the mid-block called the sample holder; which contained the designed geocomposite liner (natural soil as CCL and failed PP membrane) overlain the attenuation chamber as shown in Fig. 6, and (iii) the upper part above the geocomposite liner; which functioned as the leachate chamber as presented in Fig. 7.

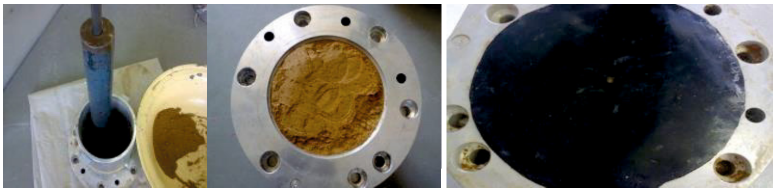


(a) (b)

Fig. 4. (a) Pictorial view of the bespoke column device; (b) Schematic view of the bespoke column device

(a) (b)

Fig. 5. (a) Hydrated geotextile on porous stone to prevent outlet clogging; (b) Lightly rammered AS to simulate loosed subsoil



(a) (b)

Fig. 6. (a) Compacted soil as CCL in sample holder; (b) Failed/ defected PP with 5 mm inflicted centred puncture overlain the CCL

The soil layers were prepared in the bottom chamber and the mid-block/ sample holder with failed PP membrane overlying the soil layer. O-rings, gasket corks and silicon sealants were used to ensure an airtight and leakage free assemblage of the device. The hydraulic frame was set up (for tests which required loading), the leachate was then added and the desired load was imposed. The vertical hydraulic conductivity, k_z value, in stratified soil (hydraulic conductivity of a liner-AS) was calculated and used to determine the permeation rate, Q.

(a)

(b)

Fig. 7. (a) Leachate in chamber (b) Soil-leachate interaction/ migration test under simulated waste load up to 150 kPa

In the first test conducted no external load was imposed on the system. Subsequently, samples collected from six sectioned cores of the AS were tested and measured for concentration of target source ions in the pore water using pulverized pore fluid extraction method and silver thiourea method. The analyses were done by using the 902 Double Beam Atomic Absorption Spectrophotometry as specified by Laboratory Manual EPS, 2011.

3. Results and discussion of finding

3.1. Leachate migration test

Besides the series of confirmatory tests conducted during the study, one major compatibility test was eventually adopted. A clear summary of the test structure employed in the study is presented in Table 2. The conditions, durations, components, and material characteristic properties under which the testing procedures were conducted are duly recorded. Results of the observed leachate-soil interaction/ compatibility test from the leachate migration behaviours through the failed liner under loading and non-loading impacts are also reported.

Table 2. Test structure employed in the study

Parameters	Properties
MDUW (kN/m^3) of compacted clay liner (CCL)	17.1
MDUW (kN/m^3) of attenuation strata (AS)	12.8
Geosynthetics	2 mm thick PP
Puncture size, type and position	5 mm failure/ inflicted centralized defect
Pressure (kPa)	$0 \rightarrow 25 \rightarrow 50 \rightarrow 100 \rightarrow 150$
Test duration	$\leq$ 100 days

Series of tests to ascertain the cation concentrations and migration through the AS was conducted. The mechanism of cationic contaminant migration through the liner and the attenuation behaviour of the zeolitic soil to the cations were also investigated with measurements and analysis carried out at the end of every run. The results of the migration rates through the lining system are graphically presented in Figs. 8(a) to (e). In the test structure, hydrated geotextile was placed over the porous stone to act as filter in preventing fines from clogging the outlet of the chamber. The results of the effluents from revealed steady increase over the test periods. It was observed that steady to quasi steady state was reached in approximately 20 days of the tests and the migration rates were measured up to 25 days. The migration rate, Q, for $p = 0$ kPa was seen to slowly increase to a steady value as shown in Fig. 8(a). Subsequently, on introduction of load to the system as shown in Figs. 8(b) to (e), the migration rates were observed to reduce. From the first pressure, p, of 25 kPa imposed on the system, steady state was reached after roughly 18-20 days as shown in Fig. 8(b) and the migration rate was monitored and measured for a duration up to 23 days.

For further investigations on the effect of pressure on the system's migration rate, the imposed load was increased from 25→50→100→150 kPa respectively. This was done to closely simulate the waste load imposing the lining system of the landfill sites visited during the study. The measured relationship between the migration rates, Q, against the test duration, t, for loads of 50 - 150 kPa are shown in Figs. 8(c) to (e). An increasing pressure on the membrane showed the migration rates to gradually reduce to a steady value.

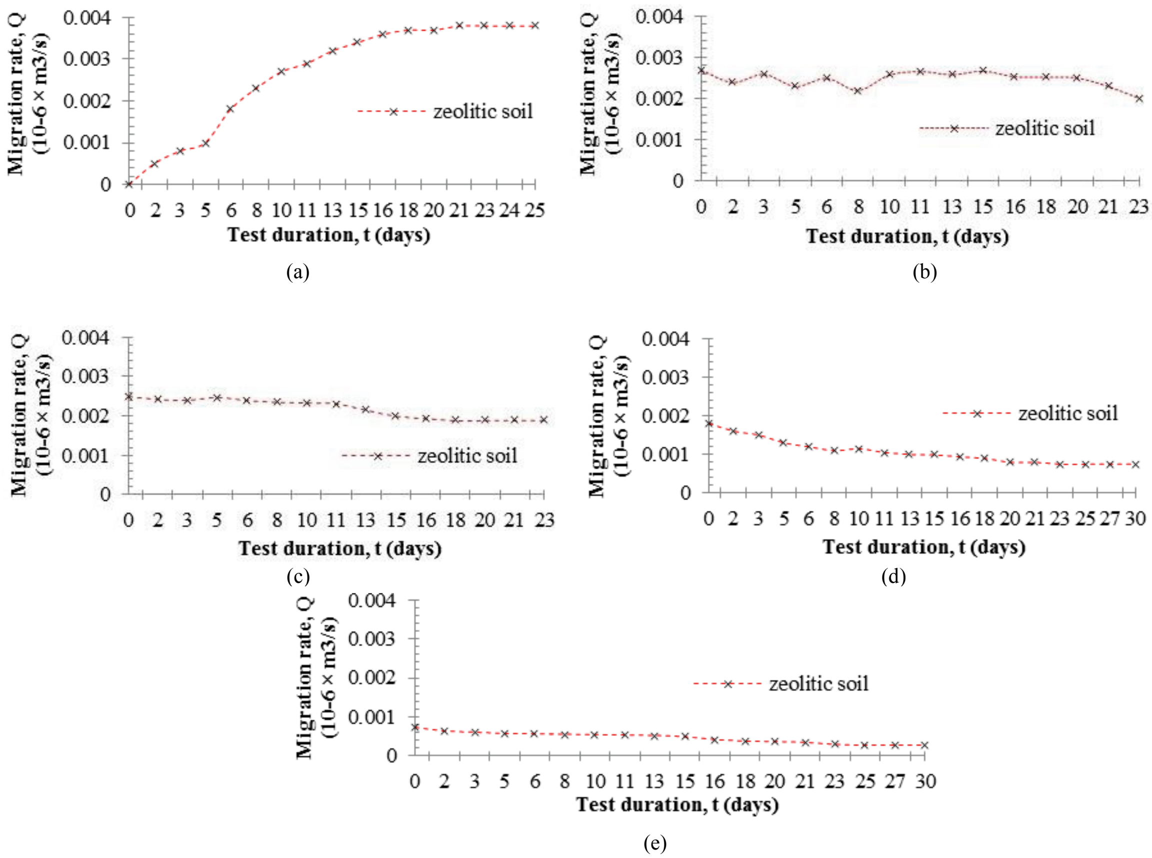


Fig. 8. (a); (b); (c); (d) and (e) Migration rate Vs test duration for $p = 0$, 25, 50, 100, and 150 kPa respectively

Similarly, the relationship between the measured migration rates, Q, against the pressure, p is presented in Fig. 9.

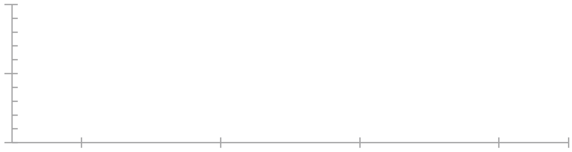


Fig. 9. Migration rate Vs pressure variations

The changing loads induced a change in density which caused a decrease in the permeability of the soil liner. Also, the applied pressure created a fair contact between the PP membrane and the soil liner thereby reducing the interface transmissivity; which led to the reduction of the interface thickness and transmissivity, θ, plausibly explaining the gradual decrease of the migration rates, Q to a steady state.

3.2. Zeolitic attenuation potency to cationic migration

The leachate formed by the degradation of buried solid waste at sanitary landfills is often associated with appearance of substantial concentration of major cations. These cations in certain concentrations could pose threats to groundwater quality. Nonetheless, analysis of the pore fluid chemistry of the studied zeolitic soil sections showed the pore fluid to be rich in Na ions while other cations such as K, Ca and Mg were present only in low concentrations. The cations present in the leachate solution are assumed to have originated from the putrefaction of the dumped refuse as well as the dissolution of minerals in the soil top cover at the landfill. Results from the migration compatibility test confirmed a degree of attenuation to the selected cations; which were contained in the leachate as they migrated through the AS of the zeolitic soil. This implied that the selected cations, in a mineral water system do not migrate in any peculiar manner through the cores of the natural zeolitic AS. The major cations were plausibly attenuated mainly by cation exchange replaceability due to isomorphic substitution since clay particles usually possess negative charges. The counter ions (for negatively charged surfaces, i.e., cations or positive ions) are attracted and accumulated close to the charged surfaces. As such, there was no significant migration of the selected cations through the soil cores as they were mostly retained at the surface of the AS. Other processes which could also be responsible for the attenuation of cations are; electrostatic adsorption (physical sorption) and/or incorporation into the structure lattice (chemisorption). The effluent relative concentration for the cations with respect to the pore volume for the permeated zeolitic soil after reaching steady state is presented in Fig. 10.

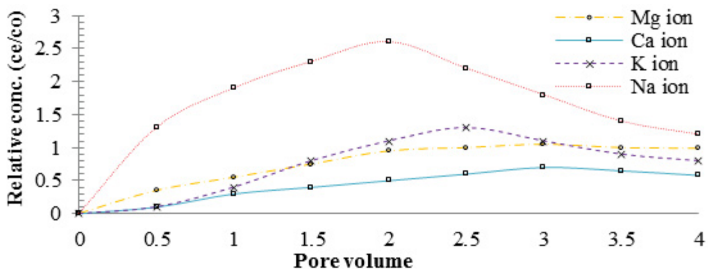
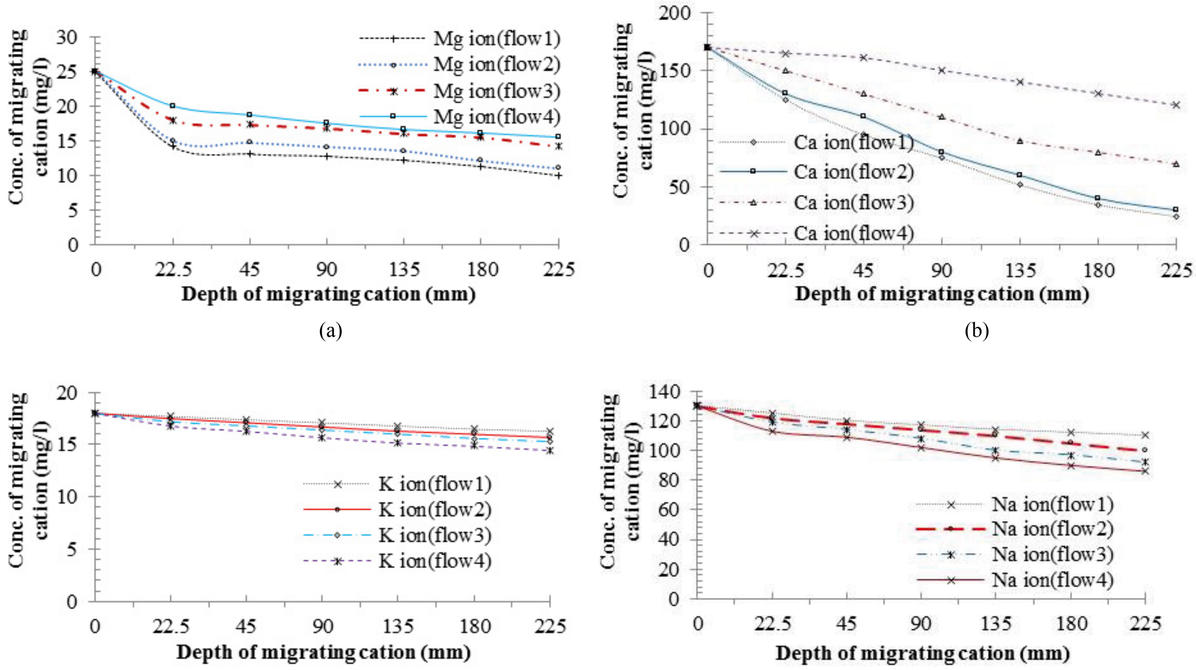


Fig. 10. Cation relative conc. (Co and Ce = initial and final conc.)

The amount of reduction observed in the concentration of a given element as it migrates through the soil core was reflected by the; (i) shift of the breakthrough curve towards higher pore volume passages and (ii) extent to which relative concentration remained below unity i.e. ($Ce/Co \neq 1$). However, in this study, negative attenuation or elution of Na^{+} from the zeolitic tested soil was observed after pore volume passages of permeates. The migration depth profiles for the respective selected cations through the natural zeolitic soil are thus shown in Figs. 11(a) to (d).



(a) (b) (c) (d)

Fig. 11. (a); (b); (c) and (d) Migration profiles of Mg, Ca, K and Na ions through the AS respectively

The relative concentration value greater than 1.0 is an indication that Na^+ eluted from the system at higher concentration than those of the effluent leachate. In the migration compatibility tests, collected leachate cationic contaminants migrated the zeolitic soil cores with and without loading effects. Generally, the natural zeolitic soil exhibited fair to good attenuation potencies toward the migrating cationic contaminants through the AS. Furthermore, soil ion exchange sites are capable of exchanging certain ions within soils as ions in leachates migrate through the soil cores. This ability is also seen in various natural systems such as living cells, proteins, cellulose and resins. The synthetic resins are primarily used for purifying water, but also for various applications including elemental separations. In the Na^+ elusion process, the migrating leachate is softened as it migrates through the cores containing Na^+ cations but binds Ca^{2+} and Mg^{2+} more strongly than Na^+. The cores take up Ca^{2+} and Mg^{2+} and releases Na^+ thereby making for a 'softer' effluent. It was therefore noted that the reasonable attenuation observed for the measured selected cation species were due to factors such as; (i) properties of the soil (ii) characteristics of the solution transport system and (iii) reactions of the specific contaminants that determine the shape of the breakthrough curve of the migrating cation species. Normally, only a few of these characteristics are primarily responsible for the rate of migration that determines the final shape and the breakthrough point. Therefore, the study examined the effects of soil cation exchange capacity on the cations species buffering properties. Additionally, cation exchange resulted in the storage of some cations on the exchange sites on the mineral surfaces and the release of other cations to the pore fluid solution as shown in the breakthrough curves for the respective cationic contaminant species presented in Figs. 11(a) to (d). The quantities of cations exchange along the flow path were estimated by determining: (a) the cation-exchange capacity of the clay soil matrix in the leaching system and (b) the chemical equilibrium between the input cations and the exchangeable ones. The alterations in the net storage of cations on exchange sites in the attenuation system were also estimated using standard mass balance and massaction relations, as well as selectivity coefficients. This was done to investigate the reasonable ability of the tested zeolitic clay mineral liner as attenuator towards migrating cationic contaminants often formed from the degradation of waste in dump sites.

4. Conclusions

The study herein investigated a geocomposite liner under leachate migration from a failed PP using a bespoke laboratory device. Loading effects on migration rates, migration and attenuation of cationic contaminants (Mg, Ca, K and Na) were studied. From results and analysis, the following conclusions were reached:

- The increase in load on the lining system triggered significant reduction in migration rates; which implied that the reduction was due to reduced membrane-soil interface transmissivity, θ, and liner densification.
- The tests with failed PP indicated interface flow between the membrane and soil liner; which signified that a perfect membrane-soil liner contact was not achieved.
- The results from the migration compatibility/ leachate-soil interaction test and analysis of pore fluid concentration of the migrated cations confirmed the flow through the membrane-soil interface.
- The concentration of cation contaminants in the sectioned cores of the AS after the migration test revealed the natural zeolitic soil to have fair to good attenuation capacity towards the contaminants; showing that significant amounts of the selected cations were retained in the surface portion of the AS of the zeolitic soil.
- The Na^+ was eluted from the system at high concentrations; which indicated the possibility that sodium was replaced with calcium and magnesium in the exchangeable sites of the zeolitic profile/ charged soil surface. However, further study is recommended on the buffering of other contaminant species not addressed in this study using zeolitic mineral liners.

In a nut shell, the attenuation of cation contaminants mainly occur by cation exchange replaceability triggered by isomorphic substitution of negative charges in clay particle surfaces. This study has therefore demonstrated that the zeolitic soil used in the experimental works to contain the generated landfill leachate can reasonably attenuate the selected contaminant species. Notwithstanding, the data obtained have demonstrated that the tested soil can release potential contaminants under migration of leachate as in the case of the eluted sodium ion. As such, it is recorded that the attenuation potency of the zeolitic soil is not infinite. Hence, care must be ensured in the design and construction of engineered landfill lining systems as the migration of cationic contaminants to vital regions can have consequential impacts by deteriorating groundwater quality and pose threats to human and environmental health.

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