

Models for Infusion of Pollutant Species through Engineered Geocomposite Media from Destroyed Polyethylene Membrane

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Abstract

In recent times, it has become crucial to protect soil, surface and groundwater reserves from pollution due to the consequential effects of landfilling operations. In a bid to safeguarding environmental and human health, various technologies have been employed in waste containment over the years. Significantly, geomembranes/ mineral composites liners have been employed. Sequential tests using a small-scale laboratory bespoke column hybrid permeameter device was conducted on the impact of infusion of pollutant species in a geocomposite lining system/ mineral barrier through a circular destroyed polyethylene membrane. The imposition of pressure as a simulation for waste load on the pollutant infusion rate, pollutant transport and the buffering capability of natural-mineral soil profile were studied. Infusion through the geocomposite liner-buffering system (BS) was measured for tests with the destroyed membrane under simulated waste loads of up to 150 kPa. Results and analysis showed significant reduction in infusion rate with increased pressure on the system. This reduction is attributed to the reduced barrier transmissivity, θ and soil liner compressibility alterations in the soil barrier. The infusion rate data for tests with the destroyed membrane in this study were compared with predicted values from equations provided by Forchheimer and Giroud et al. The comparison showed inapplicability to this study and also showed imperfect contact conditions at the membrane/soil interface if assumed in practice. Nevertheless, equations from Giroud for good contact conditions revealed rational infusion rate predictions through the destroyed membrane of the geocomposite media.

Keywords

Buffer, Geocomposites, Infusion, Media, Pollutants

1. Introduction

From decades past till date as recorded by Rowe (2011) the commonest form of waste disposal has involved land application. Waste disposal by landfilling produces gases and leachates/ chemical pollutants whose breakaway or escape from containment facilities must be controlled to restrict or prevent consequential impacts on environmental and human health. As such, to ensure the protection of soil and ground water resources from landfill pollutants, geocomposite liners are often considered. Geomembrane/ mineral composite liners are mostly employed in waste containments and will remain significant components as lining systems in landfill design and construction. However when in-situ, defects or destruction of geomembranes cannot be avoided. In most cases, as reported by Touze-Foltz and Giroud (2003) geomembrane forming part of a geocomposite liner may fail due to defects in-situ or ex-situ from

The vertical hydraulic conductivity, k_z value in stratified soil (hydraulic conductivity of a barrier layer-buffering layer) was calculated and used to determine the infusion rate, Q . Consequently, samples collected from six sectioned cores of the BS were tested and measured for concentration of targeted source chemical pollutants/ ions in the pore water using pulverized pore fluid extraction and silver thiourea methods. The analyses were conducted using the 902 Double Beam Atomic Absorption Spectrophotometry as per Environmental Protection Services Lab Manual (1979).



Figure 2. (a) Wetted geotextile on porous stone to prevent outlet clogging; (b) Lightly rammed BS to simulate loosed subsoil in the chamber



Figure 3. (a) Compacted soil (as CCL) in sample holder; (b) Destroyed membrane with 5 mm centralized puncture overlying the CCL



Figure 4. (a) Leachate in reservoir; (b) Loaded barrier

The natural soil (kaolinitic soil) used in the investigation as CCL and BS was collected around an active landfill in CoJ as shown in Figure 5, and the soil sample was mechanically and chemically tested. Figure 6 shows the soil grain size distribution curve while the water content-dry unit weight relationship was determined by compaction test in accordance with American Society for Testing and Materials- ASTM D-698 (2012).



Figure 5. Pictorial view of soil sampling vicinity

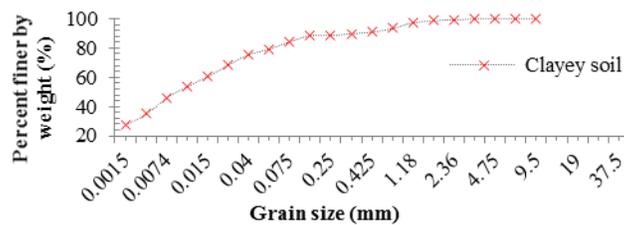


Figure 6. Grain size distribution curve for kaolinitic clay soil

The test yielded optimum water content and maximum dry unit weight of about 15.7 % and 17.4 kN/m³ respectively. The compaction curve is shown in Figure 7. The standard proctor compaction test was done using a light rammer with self-weight of about 0.0244 kN and striking effort of about 595 kN-m/m³. Values for permeability coefficient were measured by falling head test in accordance with ASTM D- 2434 (2006) and lowest permeability, k value of 1.21×10⁻⁸ m/s as seen in Figure 8 was obtained at MDD and OMC.

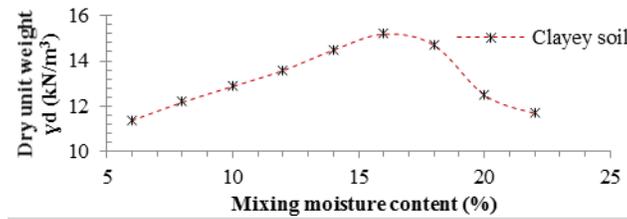


Figure 7. Compaction curve for kaolinitic clay soil

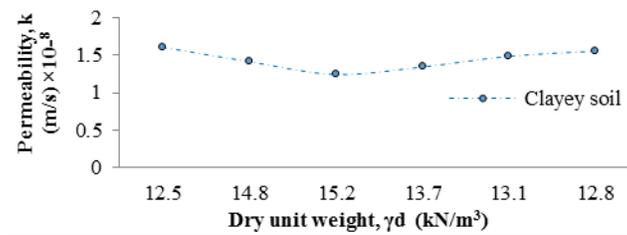


Figure 8. Permeability variation of kaolinitic clay soil

The BS was prepared at relatively low water content and lightly compacted to simulate in-situ conditions of natural soils. Leachate used as permeant for this test was gotten from the landfill leachate pond as shown in Figure 9 designed to collect generated leachate (due to infiltration of storm water and/or interception of the subsurface water with the buried waste). The permeant was taken from a number of points within the leachate pond and pooled together to ensure a proper leachate mixture. The chemical ions were measured by full spectral analysis method on the influent and effluent and compared to South African standard drinking water. The parameters analyzed included the following: Fe and Pb conducted in conformance to Water services Act (108 of 1997); ASTM D-5673 (2010).



Figure 9. Leachate collected from different points in the leachate pool

The initial concentrations (mg/l) of the targeted chemical parameters/ ions from chemical analyses for the leachate are presented in Table 1. A 2 mm thick polyethylene membrane with a 5 mm diameter centralized hole simulated the defect which was improvised due to material constraints. A single complete infusion test lasted a period of up to 90 days.

Table 1. Analysis of leachate sample used for leaching test

Parameter	ASTM Test No.	Concentration of sample (mg/l)	Standard for Drinking Water (mg/l)*
Fe	D 1068	6.0	15
Pb	D 3551	1.2	0.05

*(Water services authorities South Africa, 1997)

3. Results and Discussion of Finding

3.1 Measurement of Infusion Rate through Destructed Circular Hole

A summary of the test features, characteristics, boundaries, duration and materials under which the infusion test for the natural soil was conducted is presented in Table 2. The test herein was for the sample collected around the landfill site in the CoJ. The leachate infusion rate for the sample was measured after which concentration of infused heavy metals through the BS was determined in order to investigate the mechanism of chemical pollutant transport through the geocomposite barrier as well as the buffering efficacy of the natural kaolinitic soil. This was done at the end of the infusion test.

Table 2. Test features and boundaries

Test No.	Barrier Lining System (Natural soil as CCL)	Geosynthetic material	Defect Size, Type and Position
	Dry Unit Weight (kN/m ³)		-
1	16.2	2mm thick polyethylene plastic as Geomembrane	5mm circular hole in the centre
Test No.	Buffering System (Natural soil as CCL)	Pressure, p (kPa)	Test duration (days)
	Dry Unit Weight (kN/m ³)		-
1	12.3	0→25→50→100→150	90

Result for the leachate infusion rate through the geocomposite media is presented in Figure 10. It was observed that steady to quasi steady state was reached in about 20 days into the test for a pressure value = 0 kPa and the infusion rate was monitored and measured for a duration of up to 30 days as shown in Figure 10 before pressure was imposed on the system using the hydraulic loading system, in which case, the infusion rate, Q, was observed to gradually increase to a steady value. Nonetheless, there was a general alteration in the infusion rates as varied pressure levels were imposed on the system.

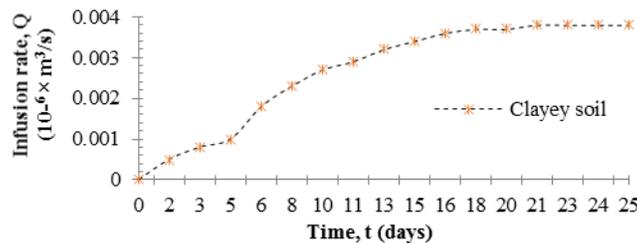


Figure 10. Leachate infusion rate against time at p = 0kPa

Subsequently, the first pressure, p, of 25 kPa was applied to the system. In this case, steady state was reached after about 18 - 20 days and the infusion rate was monitored and measured for another period of 30 days. To further investigate the effect of pressure on the systems infusion rate, the applied pressure was increased from 25→50→100→150 kPa to simulate the waste load imposing the barrier lining systems of a typical landfill. The infusion rates, Q, were measured for each imposed pressure and the duration of the entire test lasted about 90 days. An increasing pressure value on the membrane, revealed the infusion rates to gradually reduce significantly to a steady value. The increase in pressure caused a change in density which led to a decrease in the permeability of the soil barrier. Furthermore, the pressure to the system may have created a fair contact between the membrane and the soil layer thereby reducing the interface transmissivity. This resulted in the reduction of the interface thickness and transmissivity, θ , thereby accounting for the gradual decrease to a steady state of the infusion rate.

3.2 Leachate Infusion Rate through Modelled Prediction

The leachate transport rates through defected geomembrane have several proposed predictive models. Touze-Foltz and Giroud (2003); Foose et al., (2001) divided these models into two groups based on assumed geomembrane/underlain soil contact conditions namely; perfect contact and imperfect contact. The former assumes that there is no

infusion at the geomembrane/ soil interface, while the latter assumes that there is infusion at the interface between the geomembrane and the soil barrier. As stated previously, the variation of infusion rate can be caused by the change of the interface transmissivity, θ , and the permeability, k , of the soil barrier.

The representative models for perfect contact conditions are expressed as follows;

$$Q = 4r_0k_Lh_w \quad (1)$$

$$Q = 2\pi r_0k_Lh_w \quad (2)$$

Where; r_0 = radius of circular defect

k_L = hydraulic conductivity of the underlying soil barrier and

h_w = leachate head on the composite liner.

Model (1) is a proposition by Forchheimer (1930) while (2) was proposed by Giroud and Bonaparte (1986).

As for imperfect interface contact condition, Giroud and Bonaparte (1989) further divided it into good and poor contacts. The proposed empirical model by Giroud (1997) is under the assumption that there is flow at geomembrane/soil interface for a given head distribution and it is expressed as follows;

$$Q = 1.12C_{q0}[1+0.1(h_w/H_L)^{0.95}]r_0^{0.2}k_L^{0.74}h_w^{0.9} \quad (3)$$

Where; C_{q0} = constant of 0.21 for good contact and 1.15 for poor contact

H_L = thickness of the underlying soil barrier.

Other parameters are taken as already defined. The units from (3) are; m in the case of h_w , H_L , r_0 and m/s in the case of k_L and should be used as such. The predicted values in models (1) to (3) as well as the relationship between the measured infusion rates, Q , against applied pressure for the natural soil are presented in Figure 11.

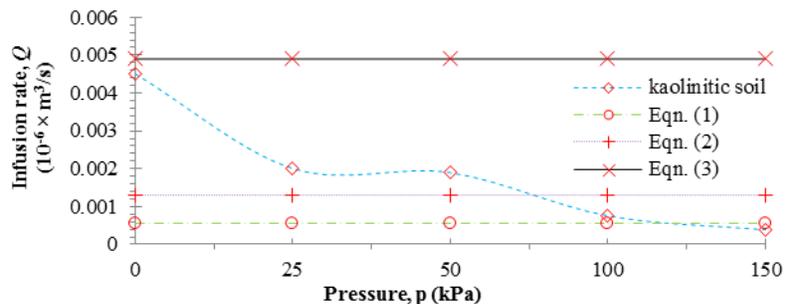


Figure 11. Leachate infusion rate against the respective pressures

The observations made thereof from the comparisons between the predicted values and the measured/ test data can simply be interpreted as follows; that (i) using model (1) and (2) in the case of a perfect contact condition shows inapplicability in practice and to the small-scale test conditions due to the wide variations experienced and that (ii) for a case of a good contact condition model (3) fairly predicts the measured/ test data. It must be noted however, that the influence of applied pressure, p , was not taken into account in the predictive models as compared to the test results in this study.

3.3 Buffering Efficacy and Concentration of Infused Chemical Pollutants in Soil Cores

From the leachate sample analyses and characterization, the leachate was found to have relatively low trace chemical elements including heavy metals. Results from the infusion tests confirmed that these small amounts of trace elements are not transported or infused in any significant manner through the natural soil cores examined. Effluent and relative concentration profiles for the heavy metals; Fe and Pb as nominal selections with respect to the pore volume for the natural soil after reaching steady state is presented in Figure 12. There was no recognized significant difference in the infusion of the heavy metals through the soil. However, results from the BS showed the heavy metals in the natural soil to be mobile. These data indicate that the exchange capacity and the chemical characteristics of the soil are the dominant features controlling the buffering of heavy metals.

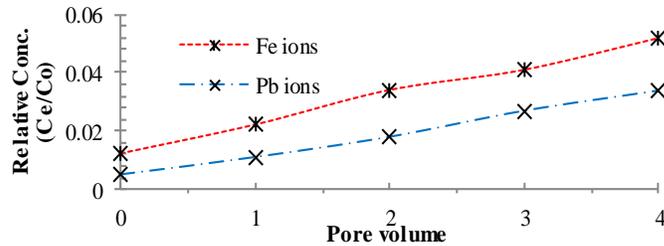


Figure 12. Relative conc. of heavy metals in effluent (Co and Ce = initial and final conc.)

Consequently, the results obtained from the chemical analysis of the pore fluid extracted from six core sections of the BS were consistent with the soil column effluent concentrations. The results showed that significant amounts of heavy metals were retained in the top portions/ sections of the soil as revealed in the concentration-depth profiles shown in Figure 13.

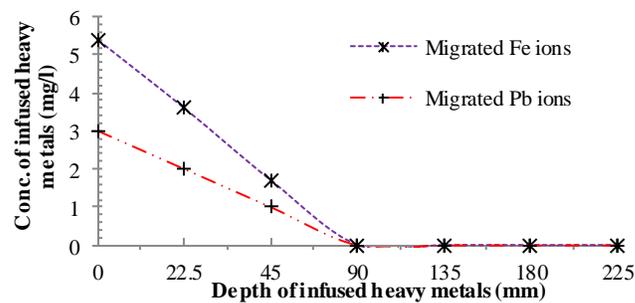


Figure 13. Conc. of infused heavy metal from six core sections of the depth of the BS

The Fe ions appeared to be more mobile than Pb ions found in the leachate, especially in the case where a more acidic environment prevailed. Therefore, the natural soil exhibited good buffering tendencies to the infusion of heavy metals through the BS.

4. Conclusions

A test on geo-composite liner with defected polyethylene membrane under the effect of chemical transport was conducted in a small-scale device called a Modular Consolidometer-Percolation Column Hybrid. Effect of pressure on the leachate flow rate with the transport mechanism and buffering of heavy metals were investigated. From tests and analysis of results, the following conclusions were reached;

- The increase in applied pressure on the liner systems was observed to significantly reduce the leachate flow rate; and from analysis, there was clear indication that the reduction was as a result of the membrane/soil interface transmissivity, θ , reduction and thickness reduction of the soil barrier.
- The assumption of perfect membrane/soil interface contact condition is not applicable to leachate flow through a defected membrane with underlain soil barrier. Giroud empirical equations for good contact condition provided a reasonable prediction for this problem under very low pressure (close to 0 kPa). However, the influence of pressure was not catered for by the predictive equation in their work.
- The measured pore fluid concentration of the transported contaminants, confirmed there was flow through the membrane-soil interface; the concentration of selected chemical ions in sectioned cores of the BS after percolation test revealed the natural soil to have good buffering abilities towards the selected chemical species/ions. However, further study needs to be conducted on the influence of pressure on the interface contact behaviour and modification is required for Giroud empirical equations such that the effect of pressure need be taken into account.

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Biographies

Emmanuel Emem-Obong Agbenyeku is a Doctor of Civil Engineering Science, Postdoctoral Fellow in the Chemical Engineering Technology Department and formerly the Research Coordinator for the Process Energy and Environmental Technology Station (PEETS), University of Johannesburg (UJ), South Africa, specializing in building construction, urban and regional planning, environmental design, geoenvironmental, geological, environmental and waste engineering with considerable on- and off-field environmental forensic skills applied to soil, surface, subsurface and ground water pollution prevention. He has a vast academic research background, as he holds a BTech (Hons) in Building Technology (*suma-cumlaude*), MPhil (*cum-laude*) and DPhil in Civil Engineering Science from the Federal University of Technology, Minna, Niger State, Nigeria and the University of Johannesburg, South Africa respectively. Dr Emmanuel has over 8 years' experience in research and academia most of which came during his national youth service period in Nigeria and full academic research involvements in South Africa, Ghana and Botswana. He has completed projects involving processes of social learning with community groups, which included knowledge co-production and shared learning over extended periods with the aim of building local agency and capacity. Recently, he has explored the use of innovative techniques/ technologies for solving energy problems such as through the construction of biodigesters for the production of biogas for cooking and heating purposes, the design and construction of energy mix solar powered boreholes for the supply of water in rural communities, the education, information and sensitization of rural dwellers on efficient waste management approaches/ practices at source through waste separation methods using colour coded/ labelled bins. He has interests in qualitative, quantitative and mixed method research, ranging from public and environmental works on landfill leachate and acid mine drainage liner/ containment designs, anaerobic biogas digester design, construction and prefabricated installations, waste resource reduction at source, sorting and characterization, valuation and beneficiation, transformation and utilization of waste, to participatory research on the role and impact of waste and alternative material resources on the livelihoods of rural settlers and for low cost-rural housing and development schemes. Dr Emmanuel is a member of a number of interdisciplinary, multi-institutional research teams and is well published journals, conferences and book chapters.

Edison Muzenda is a Full Professor of Chemical and Energy Engineering, Head of the Chemical, Materials and Metallurgical Engineering Department, and Associate Dean Responsible for Research and Postgraduate Studies in the Faculty of Engineering and Technology at the Botswana International University of Science and Technology. He is also presently a Visiting Full Professor of Chemical Engineering at the University of Johannesburg (UJ), South Africa where he was formerly a Full Professor of Chemical Engineering, the Research and Postgraduate Coordinator as well as Head of the Environmental and Process Systems Engineering and Bioenergy Research Groups. More to this, he was also Chair of the Process Energy Environment Technology Station Management Committee at the UJ. He has a well-grounded academic research background, as he holds a BSc Hons and PhD in Chemical Engineering from Zimbabwe and Birmingham, UK respectively. He has over 20 years' experience in academia mostly gained during his time at various institutions including the National University of Science and Technology, Zimbabwe, University of Birmingham, University of Witwatersrand, University of South Africa, UJ and the Botswana International University of Science and Technology. Through the course of his academic preparation and career, he has successfully held several management and leadership positions. He also holds teaching interests and expertise in unit operations, multi-stage separation processes, environmental engineering, chemical engineering thermodynamics, professional engineering skills, research methodology as well as process economics, management and optimization. Professor Edison is a recipient of several awards and scholarships for academic excellence, one of them being recently nominated as an Outstanding Researcher for an African Researcher Booklet by the Department of Science and Technology, South Africa in 2017. However, with respect to greener energy demands and changing times, his research interests shifted to bioenergy engineering, sustainable and social engineering, integrated waste management, air pollution, and separation processes as well as phase equilibrium measurement and computation. In more recent times, his research activities are mainly focused on WASTE to ENERGY projects particularly, biowaste to energy for domestic and vehicular application in collaboration with South African National Energy Development Institute (SANEDI) and City of Johannesburg (CoJ) with strong involvements in waste tyre and plastics utilization for fuels and valuable chemicals in collaboration with Recycling and Economic Development Initiative of South Africa (REDISA). Professor Edison has contributed to over 360 international peer reviewed and refereed scientific articles in the form of journals, conferences books and book chapters. He has also supervised over 30 postgraduate students and more than 260 Honours and BTech research students. He presently serve as reviewer for a number of reputable international conferences and journals, and also a member of several academic and scientific organizations including the Institute of Chemical Engineers, UK, South African Institute of Chemical Engineers and International Society for Development and Sustainability amongst others, while being an Editor for a number of Scientific Journals and Conferences including the South African Journal of Chemical Engineering. He has organized and chaired several international conferences and remains a member of the South African Government Ministerial Advisory Council on Energy and Steering Committee of CoJ – University of Johannesburg Biogas Digester Project amongst other domestic and international involvements.