Reduction of Anionic Chemical Contaminant Infusion through Engineered Clayey Medium

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Abstract

Waste containment has always involved the use of land which sees the disposal of enormous quantities of waste in landfills. This waste disposal approach creates gases and other toxic substances whose escape from containment facilities poses severe threats to environmental and human health. Most breakaways of toxic elements from landfills are often associated with leachate infusion through failed barrier components/ containment materials to levels with consequential impacts. As such, it is pertinent that barrier lining systems are designed and constructed with integrity to ensure the protection of soil, water resources and other natural reserves, as well as prevent the pollution of surrounding environment. These challenges paved way for the study to investigate landfill leachate infusion through a circular failed geocomposite liner using a laboratory fabricated permeation testing apparatus. Pressures which simulated actual landfill waste loads were applied to the lining system and the buffering capacity of a natural zeolitic mineral layer was investigated by measuring the leachate infusion rate and anionic (Cl and HCO_3) contaminant infusion through the geocomposite liner-buffering strata (BS). 25 - 150 kPa of simulated landfill waste loads were imposed on the system at intervals. The study was also done as a revalidation mechanism to previous studies. The outcomes revealed significant reduction in infusion rate over the varied pressure. The infusion reduction is attributed to the reduced liner transmissivity, θ and compressed soil layer. However, the natural zeolitic soil displayed poor buffering of Cl ions but showed a fair result in the case of HCO_3 ions. Data for infusion rates were compared with empirical values from existing models by Forchheimer and Giroud. The comparisons indicated inapplicability to this study and to real life scenarios if conditions of perfect contact at the polyethylene/soil interface were assumed. Nevertheless, Giroud's model for good contact condition considerably predicted infusion rate through a failed medium.

Keywords
Anions, Buffer, Contaminants, Infusion, Media

1. Introduction

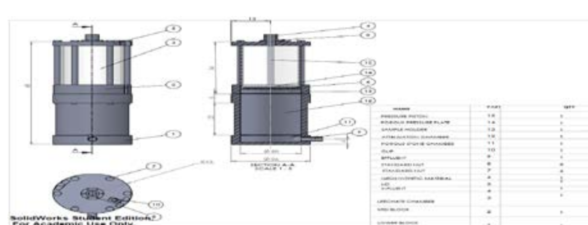
The disposal of waste involves the use of land and this trend has been in existence for many decades. Disposal of waste in landfills as recorded by Rowe (2011) generates gases and leachates/ contaminants whose escape from engineered containment facilities must be constantly monitored and controlled to prevent or eliminate severe impact on surrounding environments. Therefore, to ensure that soil and groundwater resources are protected from landfill leachates, geocomposite systems are mostly utilized. Polyethylene (PE)/ mineral composite liners are often used in engineered containment facilities and for the longest time possible, will continue to be adapted, especially by developing countries as significant components of landfill lining systems. More so, it is well established that in-situ and ex-situ PE failures can at best be minimized but cannot be prevented. As such, PE forming a vital part of a geocomposite liner may fail due to defects on or out of site, either from fabrication, installation, aging or a combination of factors (Touze-Foltz and Giroud, 2003). Hence, determining leachate infusion through a failed PE overlying a zeolitic mineral liner is pertinent in the design and construction of landfills. Furthermore, the establishment of such landfilling facilities around valuable water sources are in some instances inevitable. Therefore, in such cases, the proper and effective separation of waste bodies from groundwater and other useful resources need be executed with high construction integrity such that pollution and other consequential human and environmental health impacts are avoided (Department of Water Affairs and Forestry, 2005). This is may be achievable when compacted clay liners (CCLs) are employed as part of the lining system to control the infusion of leachate through failed liners i.e., PE, Geomembranes (GM) or Geosynthetic Clay Liner (GCL). Considering a fast growing and developing country like South Africa, in which Gauteng province and City of Johannesburg (CoJ) alone generates approximately half of the nation's daily waste with lesser available waste deposition sites (landfills) over time as reported by Environmental Impact Assessment Regulations-EIAR (2005) and the enormously increasing tonnages of disposed waste each day becoming a huge concern, with improper waste dumping leading to health, environmental and aesthetic problems, simply implies that there is a dire situation at hand which requires an urgent solution. The potential contamination of vital soil, surface, subsurface and groundwater resources by landfilling operations is often an issue of concern, thus, the need for the study. Additionally, there are several predictive models proposed for similar problems of leachate infusion through failed landfill systems, nonetheless, Foose et al., (2001); Touze-Foltz and Giroud (2003) stated that predicted values differ by wide margins for different cases, boundaries and operating conditions. The effects of waste loads on leachate infusion through a failed PE of a zeolitic mineral geocomposite, the infusion pattern through the geocomposite of the natural zeolitic material as CCL and its buffering capability to anionic contaminant influx have not been sufficiently documented. Thus, series of tests using a fabricated laboratory device to investigate the leachate infusion through a circular failed PE with underlain a natural zeolitic mineral layer as CCL and BS was conducted towards determining the effects of pressure applied to the system on the infusion rate, mechanism of infusion and the buffering capability of the natural soil/ anionic chemical contaminant (HCO_3 and Cl) infusion reduction through an engineered clayey medium.

2. Materials and Method

2.1 Experimental Approach

A soil liner- 24 mm thick and 5 mm diameter puncture in the center of a 2 mm thick PE plastic simulated a failed system having a 225 mm thick BS which comprised the test setup. The fabricated device, a modular consolidometer-percolation column hybrid with 160 mm diameter is joined to a steel loading frame capable of applying over 1000 kPa pressure to the system. Figure 1 shows a pictorial and schematic view of the device consisting of three parts: (i) the bottom part called the buffering chamber; containing the natural soil serving as the natural earth and BS below the geocomposite liner as shown in Figure 2 (ii) the mid-block called the sample holder; contained the designed geocomposite liner (natural soil as CCL and failed PE) placed over the buffering chamber as shown in Figure 3 and (iii) the upper part above the geocomposite liner; functioned as the leachate chamber as displayed in Figure 4. The leachate chamber was marked to hold a constant head of 250 mm through-out the test duration. Although the device was not designed to hold a constant head, it was manually topped to a constant head at every time there was a drop in level. Soil layers were prepared inside the bottom chamber, the mid-block/ sample holder and the failed PE was placed over the soil liner. A moistened geotextile was placed over a porous stone to serve as filters, preventing moving fines from clogging the outlet of the system. After the components were assembled, O-rings, gasket corks and silicon sealants were used to prevent leakages and maintain air-tight seals between the top, mid and bottom sections of the device. The loading frame was set up, the leachate added and the desired pressure was applied.

(a) Pictorial view



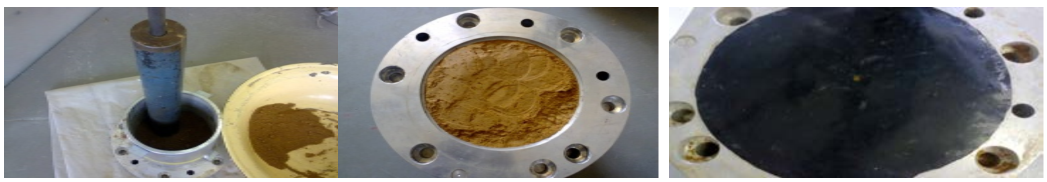
(b) Schematic view

Figure 1. Fabricated modular consolidometer-percolation column hybrid device

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. Subsequently, samples collected from six sectioned cores of the BS tested by pulverized pore fluid extraction and silver thiourea methods. Concentrations of target source contaminants/ions in the pore water were measured. The analyses were conducted using the 902 Double Beam Atomic Absorption Spectrophotometry as per Environmental Protection Services Laboratory Manual.

(a) (b)

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



(a) (b)

Figure 3. (a) Compacted soil (as CCL) in liner holder; (b) Failed PE with 5 mm centred puncture overlain the CCL

(a) (b)

Figure 4. (a) Leachate in chamber; (b) Liner under hydraulic loading pressure

The natural zeolitic soil used as CCL and BS was collected around a landfill in the CoJ, South Africa as presented in Figure 5 and was mechanically and chemically tested. Figure 6 shows the soil grain size distribution curve, while optimum water content (OWC)-maximum dry unit weight (MDUW) relationship was determined by compaction test in accordance with with American Society for Testing and Materials- ASTM D-698 (2012).

Figure 5. Pictorial view of soil sampling vicinity

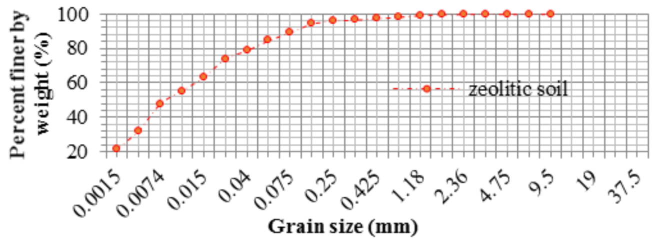


Figure 6. Grain size distribution curve for zeolitic clayey soil

The test yielded OWC and MDUW of about 15.5% and 17.1kN/m^3 respectively and Figure 7 shows the compaction curve. The standard proctor compaction test was done by a light rammer with self-weight of about 0.0244kN and striking effort of about 595kN-m/m^3. Values for permeability coefficient were measured by falling head test in accordance with ASTM D- 2434 (2006) and lowest permeability, k value obtained at MDUW and OWC was 1.19×10^{-8} m/s as presented Figure 8.

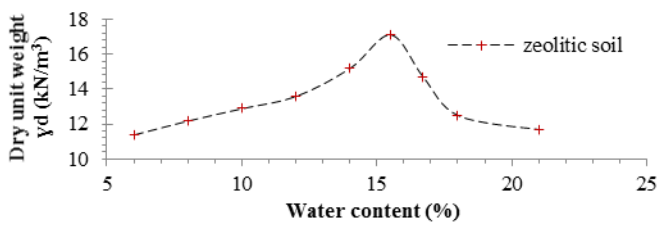


Figure 7. Compaction curve for zeolitic clayey soil

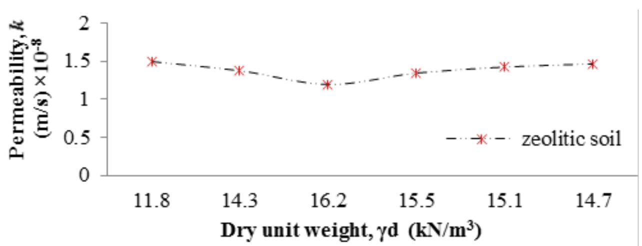


Figure 8. Permeability variation of zeolitic clayey soil

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 programme was manually collected from a landfill leachate pond designed to retain generated leachate due to infiltration of storm water and/or interception of the subsurface water with the buried waste as shown in Figure 9. The leachate was scooped from a number of points within the pond and pooled together to ensure a homogenized mixture. The chemical ions were measured by full spectral analysis method on the influent and effluent and were compared to South African standard of drinking water. HCO_3 and Cl ions were analyzed in to conformance to Water Services Act (108 of 1997); ASTM D-5673 (2010).

Figure 9. Leachate collected from different points in the pond

Initial concentrations (mg/l) of the targeted chemical contaminant ions from chemical analyses of the leachate are given in Table 1. The 2 mm thick failed PE membrane with 5 mm diameter centre hole that simulated the failure was used due to material constraints and the duration of the infusion test lasted for roughly 100 days.

Table 1. Analysis of leachate used for infusion test

Parameter	ASTM Test No.	Concentration of sample (mg/l)	Standard for Drinking Water (mg/l)*
HCO_3	D 1253	273	-
Cl	D 513	140	230

*(Water services authorities South Africa, 1997)

3. Results and Discussion of Finding

3.1 Measurement of Infusion Rate through Circular Failed Polyethylene Membrane

The infusion test was for the sample collected around the landfill site in the CoJ. The seepage rate was determined and the concentration of transported anions through the BS was determined to investigate the mechanism of contaminant infusion through the geocomposite liner as well as the buffering ability of the natural zeolitic soil which was conducted on termination of the infusion test. Summaries of the test features, test duration and materials under which the infusion test was conducted are presented in Table 2.

Table 2. Test features and material boundaries

Parameters	Properties
MDUW (kN/m^3) of mineral liner (CCL)	17.1
MDUW (kN/m^3) of Buffering strata (BS)	12.8
Geosynthetics	2 mm thick PE
Puncture size, type and position	5 mm circular centralized defect
Pressure (kPa)	0→25→50→100→150
Test duration	About 100 days

The results of leachate infusion rate through the geocomposite liner is shown in Figure 10. It is evident that steady to quasi steady state was reached in roughly 20 days into the test for 0 kPa pressure and the infusion rate was monitored and measured for up to 25 days prior the application of the first pressure of 25 kPa to the system. The infusion rate, *Q*, was seen to gradually increase to a steady value as well as changes observed in the infusion rates on subsequent incremental application of pressure.

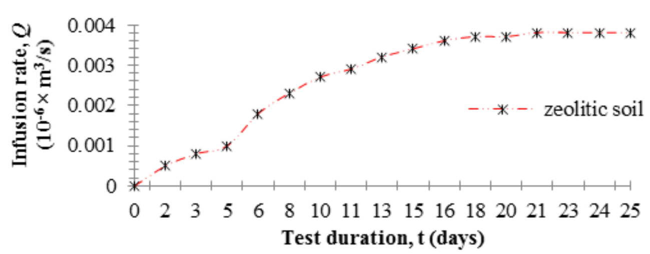


Figure 10. Leachate infusion rate against time at p = 0 kPa

The first pressure, p, of 25 kPa was applied to the system and steady state was reached in roughly 20 days, however, the infusion rate was further monitored and measured over a duration of 30 days. More so, investigate the influence of pressure on the infusion rate of the system, pressure was increased from 25→50→100→150 kPa to simulate waste loads imposing typical landfill liners. The infusion rates, *Q*, were measured for each applied pressure and the duration of the entire test lasted about 100 days. Increase in the applied pressure on the PE revealed the infusion rates to gradually reduce considerably to a steady state. Consequently, the increase in pressure triggered a change in density which led to a decrease in the permeability of the soil liner. Additionally, the pressure applied to the system may have created a fair contact between the PE and the mineral soil liner thereby, decreasing the interface thickness and as such, reduced the interface transmissivity. This may therefore, have resulted in the gradual reduction to a steady state of the infusion rate.

3.2 Predicting Leachate Infusion Rate from an Empirical View

The leachate infusion rates through failed PE have several proposed empirical models. These models were divided into two groups by Touze-Foltz and Giroud (2003) and Foose et al., (2001) based on assumed PE-underlain soil contact conditions namely; perfect contact and imperfect contact. The former assumes that there is no infusion at the PE-soil interface, while the latter assumes that there is infusion at the interface between the PE 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 barrier due to densification of the soil liner. The representative models for perfect contact conditions are given 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) was proposed by Forchheimer (1930) while (2) was a proposition 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 infusion at PE-soil interface for a given head distribution expressed as follows;

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

Where; C_{qo} = 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 model (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) - (3) as well as the relationship between the measured infusion rates, Q, against applied pressure for the natural zeolitic soil is shown in Figure 11.

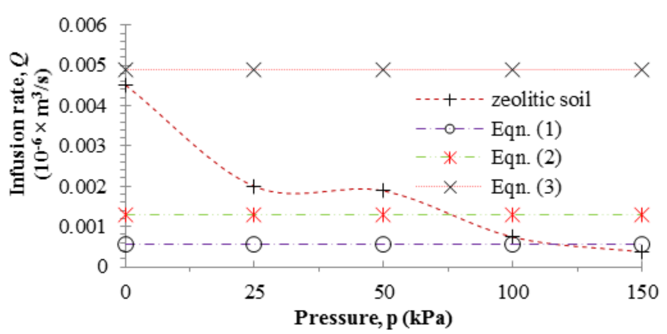


Figure 11. Leachate infusion rate against the various applied pressure

The observations made 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 in the case of a field investigation and that (ii) for a case of a good contact condition, model (3) fairly predicts the measured/ test data. However, it is emphasized that the influence of applied pressure, p, was not taken into cognizance in the predictive models as compared to the test results in this study.

3.3 Buffering of Infused Anionic Chemical Contaminants

The analyses and characterization of the leachate sample generally showed relatively low trace elements, including anions. The behaviour of chloride ions was studied mainly to separate the effects of dispersion and chemical processes operating in the soil system. Results from the infusion tests confirmed that these small amounts of trace elements do not travel in a significant manner through the natural BS examined. Effluent and relative concentration profiles for the Cl ions with respect to the pore volume of the natural zeolitic soil subsequent to reaching steady state is shown in Figure 12. The observed buffer is generally not a function of the type or amount of clay minerals present in the zeolitic material. Hence, there was no appreciable difference in anionic infusion through the soil.

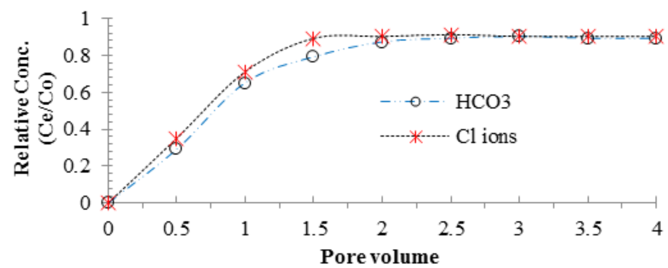


Figure 12. Relative conc. of anions in effluent (Co and Ce = initial and final conc.)

Results from the BS showed low accumulation and retention of the Cl ion, as revealed in distribution profile depths. Minute HCO_3 was however, detected in the extracted pore fluid subsequent to leachate infusion as presented in Figure 13. This can be attributed mainly to physical dispersion in the soil column system, with perhaps a small amount of interaction at the anions exchange sites on the respective soil edges or due to other chemical reactions. The exchange between chloride ions and other ions with negative charges, which are part of the lattice is not feasible because the chloride ion is about two and half times the size of the oxygen ion, i.e., it is too large to replace or co-ordinate with oxygen and hydroxyl ions.

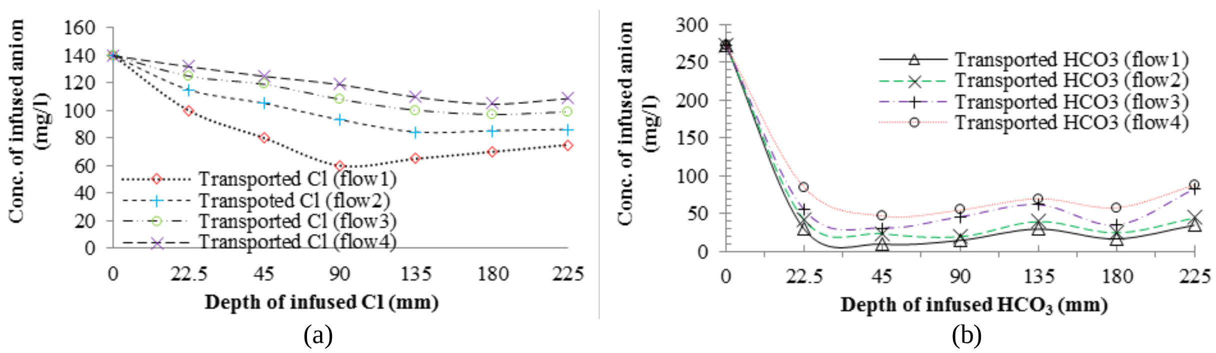


Figure 13. (a) Infused profiles of Cl ions through the BS; (b) Infused profiles of HCO_3 ions through the BS

The buffering of chloride ion that was observed was relatively low and it is not surprising because: (a) Cl is considered to be a mobile and non-interacting anion which make it a conservative contaminant and (b) chloride ions are generally considered to be non-specific ions, which implies they exist only in the outer coating of the double layer as recorded by Sposito (1979). Therefore, the natural zeolitic soil exhibited poor buffering characteristics towards Cl ions but had a reasonably fair outcome in the case of HCO_3 ions.

4. Conclusions

Tests on geocomposites with failed PE under the influence of leachate infusion were conducted in a fabricated laboratory column device. Pressure effects on the leachate infusion rate, infusion mechanism and buffering of anionic contaminant species were investigated. From the analyses of results the following conclusions were reached:

- The increase in applied pressure on the liner significantly reduced the leachate infusion rate; and from analysis, there was evident that the reduction was as a result of the decreased PE-soil interface transmissivity, θ, and the soil liner densification.
- The assumption of perfect PE-soil interface contact condition is not applicable to leachate infusion through a failed system with underlying mineral layer. Nonetheless, Giroud's empirical model for good contact condition provided a rational prediction for this problem under pressure of 0 kPa. However, the influence of pressure was not considered by the model as contrary to the case of this study.

- The measured pore fluid concentration of the infused ions, confirmed there was flow through the PE-soil interface; the concentration of the selected nominal anion in the sectioned cores of the BS subsequent to the compatibility test revealed the natural zeolitic soil to have poor buffering behaviour towards Cl ions but had fairly buffered the HCO_3. Additionally, it is recommended that further studies be conducted on the infusion of other trace chemical contaminants/ ions through the tested zeolitic material in this study as well as through other locally available clayey media.

In a nutshell, the chloride infusion curves through the zeolitic soil showed the characteristics of the non-reactive ions, which were not readily altered by chemical and biological processes. This revealed that Cl ions infused faster through the BS than in the case of the HCO_3 ions. This study has demonstrated that the tested soil type used in the experimental works to contain the generated leachate from solid waste disposal can be sparingly used to contain the different selected contaminant species investigated. The results gathered in this study further suggests that under favourable soil conditions, landfill leachates containing low anionic trace levels will not pose a substantial threat to the subsurface environment. Although, it is emphasized that the buffering efficacy of the zeolitic tested soil is not infinite. Hence, from observations and analyses of results, care must be taken not to dispose heavy concentrated inorganic waste in the landfill site where the soil samples were collected.

Acknowledgements
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Biographies
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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. He has explored the use of innovative 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 practices at source through waste separation methods. 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 in journals, conferences and book chapters.

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