Buffering efficacy and interaction of minerals in clayey soil with contaminants from landfilling and mining activities: A bird-eye view

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Abstract-The drastic growth in global population, energy resource use, industrial and infrastructure development have led to enormous problems in global conditions and contending environmental challenges. In recent years, South Africa has intensified research on industrialisation and associated environmental problems regarding waste generation, ecosystem matters, human and environmental health risk assessment, and waste management systems. The study has made it clear that geo-environments in and around landfills, and mines are severely contaminated by toxic substances not limited to heavy metals and organic compounds. The all-encompassing introductory presentation in this paper based on a bird-eye view- review approach, pinpoints the present state from site reconnaissance, and impact of landfilling and mining operations in areas with such activities. This study however, has paved way for subsequent technically intense investigations on assessing the buffering efficacy of natural soils from affected sites. This include examining the interaction of pollutants with the soil minerals in succeeding papers towards curtailing soil, surface, subsurface and ground water contamination which invariably affect human and environmental health.

INTRODUCTION

Motivation

In recent years as reported by Agbenyeku et al., (2014a) there have been immense growth in global population, industrial development, energy resource use and civil infrastructure development. Growth in one sector often generates problems in other areas and under present global conditions, environmental challenges have caused crucial issues in most parts of the world (Agbenyeku et al., 2014b). Over the years, research on industrialisation and associated environmental problems i.e., waste generation, matters on ecosystem, human health risk assessment and waste management systems have intensified (Lakshmi and Hilary, 2000). It has therefore been revealed that the geo-environments in surrounding areas of landfills, mines, farmlands and old factory sites are constantly being polluted by toxic substances such as; heavy metals and organic compounds. Such environmental pollutions have triggered interdisciplinary approaches towards fostering sustainable solutions. Figure 1 shows a conceptual illustration of a geo-environmental contamination from a landfill caused by the permeation of leachate into the immediate environment.

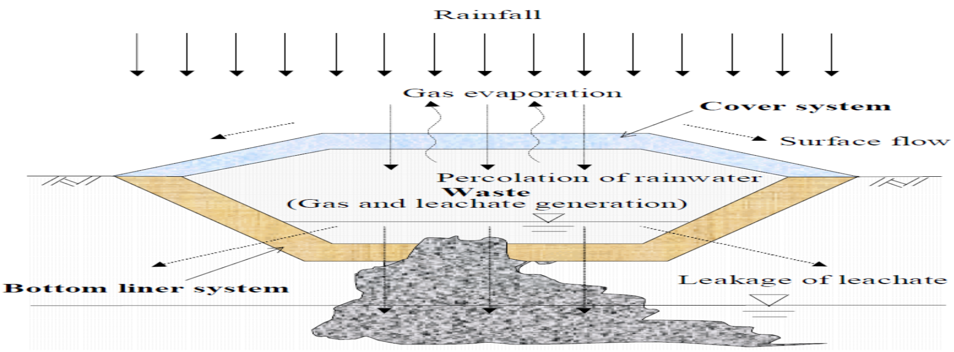


Figure 1: Conceptual representation of the discharge of toxic leachate substances from a landfill triggered by the permeation of storm water/rainfall (adapted from Kamon et al., 2001)

Percolation of rain and/or surface water into waste bodies lead to the accumulation of generated leachate on liners and increases the risk of leachate seepage into surrounding environments. As such, Kamon et al., (2001) suggested the proper handling of generated leachate towards environmental protection in affected sites such that, the surrounding geo-environmental resources i.e., soil, surface, subsurface, and groundwater are kept safe. Typically, waste containment facilities are essential to safeguard the geo-environment from being polluted by the migration of waste generated leachate. An effective design of waste containment facilities does not only imply the installation of bottom liner systems, reducing generated leachate but also involves the utilisation of cover systems, prevention of rain and surface water from infiltrating waste layers thereby minimising the formation of leachate.

Efforts however, to develop technologies for contaminated-site characterisation, subsurface barriers for contaminants (waste containment), clean-up systems for contaminated ground and assessment of the fate and transport of contaminants are on the rise. As public agencies, private firms, global organisations and academe have embarked on projects aimed at seeking solutions to waste management and subsurface contamination problems. It has therefore, become clear that the science and engineering involved are very diverse and require the adoption of cross-disciplinary and multidisciplinary measures (Bouazza et al., 2002). Primarily, needs have stemmed to adequately address the importance to the assessment of contaminant generation, subsurface contamination and development of relevant control systems drawn from a variety of applied science and engineering fields. Hence, all elements related to environmental problems of ground, surfaces and subsurfaces are relevant towards investigating the implications on the environment, the health and safety of inhabitants, as well as, building up control measures. It therefore encompasses the application of science and engineering principles to the analysis of the fate of contaminants on and in the ground; transport of moisture, contaminants and energy through geomedia, design and implementation of schemes for treating, modifying, reusing, or containing wastes on and in the ground (Lakshmi and Hilary, 2000).

The protection of groundwater and surface water is now a major consideration in the design of waste containment facilities in many countries, including South Africa. Geosynthetics play an important role in the protective task because of their versatility, cost-effectiveness, ease of installation and good property depiction both mechanically and hydraulically (Bouazza et al., 2002). Geosynthetics is the collective term applied to thin and flexible sheets of synthetic polymer material incorporated in or about a containment structure to enhance its performance. The American Society for Testing and Materials (ASTM) defined geosynthetics in D 4439 as follows: "A planar product manufactured from polymeric material used with soil, rock, earth or other related material as an integral part of a man-made project, structure or system." Functions that geosynthetics can perform include hydraulic barriers, filtration/separation, reinforcement and in-plane drainage. Furthermore, they can offer a technical advantage in relation to traditional lining systems or other containment barriers. Geomembranes/soil composite liners are widely used in the construction of landfills and tailings dams. Geomembrane is a very low-permeability synthetic membrane liner or barrier used with any soil related material so as to control fluid migration in man-made projects, structures or systems (ASTM D 4439). Containment systems include both geosynthetics/geomembrane and earthen/soil material components (e.g., compacted clays for liners, granular media for drainage layers and various soils which serve as protective and vegetative layers) typically for landfills and mine tailings dams (Agbenyeku et al., 2015a; Rowe, 2001; Manassero et al., 2000; Zornberg and Christopher, 1999). Hence, the pertinence of investigating the buffering efficacy and interaction of minerals in clayey soil with contaminants from landfilling and mining activities cannot be overemphasized.

Defined Problem

Environmental Impact Assessment Regulation EIAR, (2005) on municipal solid waste (MSW) disposal in South Africa have revealed that over time, land-use have remained the primary method of managing MSW which have continually been illegally disposed or dumped at unsuitable sites. The disposal of more than 41,000 tons of solid waste in South Africa each day, with Gauteng province and the City of Johannesburg (CoJ) disposing of more than 17,000 and 4,000 tons respectively have rapidly become a major challenge (Agbenyeku et al., 20014b). This method of waste disposal often leads to serious health, environmental and aesthetic problems (Agbenyeku and Akinseye, 2015). The associated environmental and health risks posed by the improper or illegal disposal and containment of solid waste is generally known and much have been recorded in related works. For instance, contaminant species and/or toxic elements present in leachate generated from deposited MSW can contaminate soil/land, surface and groundwater reserves (Agbenyeku and Akinseye, 2015; Agbenyeku et al., 2015a; 2015b; 2014a; 2014b; 2013a; 2013b; Coetzee et al., 2007; Coetzee et al., 2005a). Nevertheless, much more is needed to be documented and extensively discussed particularly, in areas of contaminant buffering by minerals in clay/clayey soils. The insistent attraction, growth and investments in the exploitation of South Africa's mineral resources have led to a drastic increase in generated mine waste (EIAR, 2005). Mining activities are associated with environmental contamination such as acid mine drainage (AMD). AMD is highly acidic water usually containing high concentrations of metals, sulphides and salts as a consequence of mining operations. With the major sources of AMD to include; drainage from underground mine shafts, runoff and discharge from open pits and mine waste dumps, tailings and ore stockpiles, making up closely 88% of all waste produced in South Africa, it becomes clearer why AMD has become a major national concern (Department of Minerals and Energy Resources DMER, 2008b; Coetzee et al., 2008b). Recent assessments have shown that South Africa's mining history has generated vast economic benefit and still plays a significant role in ensuring the country's stance in the global market.

Notwithstanding, large-scale closure of mining operations since the 1970s within the Witwatersrand mining regions or basins and the subsequent termination of the extraction of underground water from mines have become important national interests (DMER, 2008b). As is the case in other parts of the world, the Council for Geoscience (2005a) recorded that the activities of the mining sector in South Africa have resulted in severe environmental consequences, notably in respect to poor environmental and water management and, in the case of the gold mines of the Witwatersrand AMD. Given the magnitude and dynamics of the South African mining industry, it must be accepted that the challenges of mine water management cannot be shouldered by either government or the mining sector alone (Coetzee et al., 2008a). The termination of underground mine water extraction leads to the mine voids becoming flooded. This phenomenon was highlighted in September 2002, when acidic mine water started flowing from an abandoned shaft in the Mogale City/Randfontein area of the Western Basin as a result of the flooding of the mines in this basin to a level where water could flow out onto the surface (Coetzee et al., 2008b). This surface flow or decant of mine water can generally affect environmental and human health as the water, in accordance with well-known and researched chemical and geochemical reactions between the mine rock strata, wastes and oxygen, readily becomes acidic which is basically characterised by elevated concentrations of salts, heavy metals and radionuclides posing consequential impacts (DMER, 2008b; Coetzee et al., 2008b; 2005b; Council of Geoscience, 2008; 2005a; 2004a; 2004b; 2004c). Although the occurrence of AMD issues are encountered in most gold mining areas in South Africa, including the Klerksdorp/Orkney/Stilfontein/Hartebeesfontein (KOSH), Free State, Far West Rand and Evander gold mining areas, the coal mining areas of Mpumalanga and KwaZulu-Natal and the O'OKiep Copper District, attention is mostly given to areas where the risk demands the most urgent and immediate action first (Department of Water Affairs and Forestry DWA, 2006; 2008; 2009; 2010; DMER, 2008a; 2008b; 2008c; 2008d; 2008e).

As earlier recalled, the flooding of the mine voids and/or AMD decant gives rise to a number of general environmental and human health concerns: AMD produced from sulphide-bearing mine waste usually has the potential to pollute potable groundwater and surface water sources, AMD extensively contaminates surface streams and could incur devastating ecological impacts, rising water levels could flood urban areas and result in geotechnical impacts that may jeopardise the integrity of urban infrastructure, rising water levels in the mine voids may lead to an increase in seismic activity thereby presenting grave safety risks to deep underground mining ventures and some risk to safety and property on the surface in the vicinity of the mines, rising mine water levels have the potential to flow towards and pollute adjacent groundwater resources, flooding may result in inter-mine water migration and may threaten neighbouring operational mines hence, limiting access to economic reefs (Department of Water Affairs and Forestry DWA, 2006; 2008; 2009; 2010; DMER, 2008a; 2008b; 2008c; 2008d; 2008e). Conventionally, wastes in South Africa have long been disposed in ways that appeared cheapest and least repulsive to the public which often involved land application. However, with recent enormous industrial and environmental changes, the ability of land to contain the vastly generated wastes and myriad contaminants with no apparent consequence have drastically diminished (DWA, 2005). The implications of the contamination of soil and water resources due to MSW landfill leachate and AMD on the environment, health state of inhabitants, destruction of ecosystems and non-renewable natural resources are severe. As such, the insistent growing heaps of domestic and industrial wastes in South Africa with resultant environmental pollution challenges and increasing national environmental awareness have resulted in the realisation that waste containment structures such as landfills, tailings dams and effluent ponds should be properly designed and constructed to minimise environmental pollution.

Although, waste recycling has been acknowledged as the first best option of managing waste, landfilling coupled with a simple recycling system like non-sophisticated composting have also been acknowledged as a viable solution to the MSW disposal problems of most developing countries (Zacarias-Farah and Geyer-Allely, 2003). Presently, waste recycling technology has not been effectively initiated in South Africa thus, the continued reliance of South Africa on the landfilling system could extend for many years until economical recycling alternatives are introduced based on current global trends in waste disposal (Slack et al., 2004; 2005; USEPA, 2005; Hobbs and Cobbing, 2007). Drainage from abandoned underground mine shafts into surface water systems (decant) may occur as the mine shafts fill with water. Although, the chemistry of AMD generation is straightforward, the final product is a function of the geology of the mining region, presence of micro-organisms, temperature and also of the availability of water and oxygen. These factors are highly variable from one region to another, and for this reason, the prediction, prevention, containment and treatment of AMD must be considered carefully and with great specificity (DMER, 2008a; 2008b; 2008c; 2008d; 2008e). For appreciable reasons such as ease of installation, cost-effectiveness, versatility, reduction in hydraulic conductivity of liners, advective flow of contaminants and reduction in clay-leachate incompatibility problems, the use of geosynthetics is now incorporated in containment facilities in South Africa (DWA, 2005). Nevertheless, it is crucial to note that geosynthetics are vulnerable to damage and defects are expected to occur even if good construction quality control and assurance procedures are ensured during manufacture, transportation and installation (Bouazza et al., 2002). Hence, the selection of disposal sites depend significantly on the buffering efficacy of the natural surrounding soil and must be based on the following vital considerations: (a) sufficient information on water resources; which requires localised and regional hydro geological data on surface and subsurface water systems of the selected area, and (b) the disposal site must be situated on clay/clayey strata of reasonable depth. Clay/clayey soils in modern environmental science and engineering are well valued and recognised particularly because of their low hydraulic conductivity and attenuation capability (high adsorption capacity).

This has led to the use of clays as chemical and physical absorbers and/or barriers against the transportation of contaminants from disposal sites to regions of significant impact. The precipitation and filtration mechanism plus the net charges present on clay surfaces allows for the adsorption of other ionic species often contained in leachate solution and gives rise to the buffering ability of clay and clayey soils. For these reasons, the pre-use of this form of clay barrier has been stressed as fundamental criteria for a secure disposal site by the South African National Environmental Management (SANEM). However, almost all the data used to draw conclusions have been mostly obtained in North America and Europe using non-tropical clayey soils as barriers. In many sub-tropical and tropical terrains, candidate natural clayey barrier materials abound within economic haul distance from potential waste containment sites for the construction of waste containment facilities (Rowe, 2001). This situation may not be readily obtained in developed, temperate regions of the world due to extensive developments of available lands. Also, the procurement costs of geosynthetic materials for most developing African countries in the tropics and subtropics are quite prohibitive since these materials have to be imported with scarce foreign exchange. The use of geosynthetic materials for liner construction is also plagued with several problems. Prominently are; long-term durability, susceptibility to stress cracking failure nearer welded seams and lack of assurance on long-term compatibility, in particular, with some organic contaminants. If candidate natural clayey soil liners in tropical and subtropical regions are adequately assessed and found suitable, safe and cost-effective waste containment structures could be constructed to accelerate socio-economic growth in many developing African countries particularly, in South Africa and other Southern African countries. However, the compatibility of tropical/subtropical mineral clayey soils and their buffering efficacy with industrial and domestic leachates have not been amply studied and understood. Therefore, subsequent studies following this review were designed to simply complement similar studies in bridging this gap in knowledge.

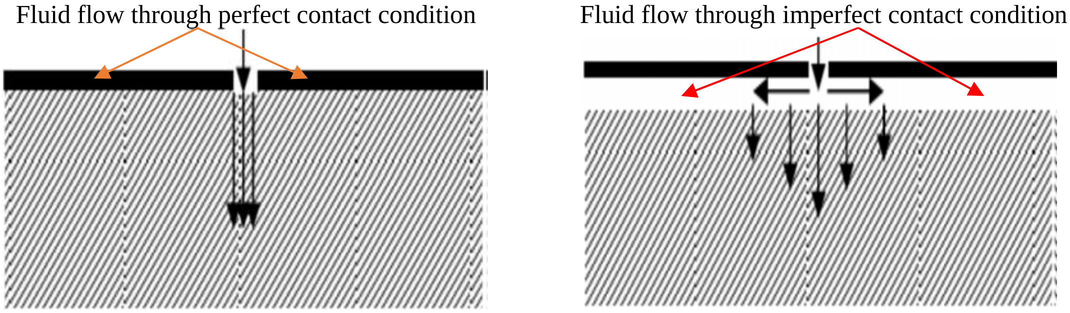
BIRD-EYE VIEW APPROACH

Site Reconnaissance and Existing Challenges from Field Study

From field surveys engaged herein, three different disposal sites were visited around the CoJ, South Africa. On the one hand, the existing field challenges common to all three visited disposal sites were easily accessible and are thus, highlighted as follows:

- The vulnerability of the thin polymeric material (geosynthetics) to damages from the factory, during installation and throughout service life. These damages typically involved tears and punctures which reduced the effectiveness of the geomembrane and geosynthetic clay liner used as infiltration barriers and resulted in leakages into the surrounding soil which over time could migrate to points with consequential impacts.
- For Geosynthetic Clay Liners (GCLs) the presence of defects led to loss of bentonite during leachate infiltration which made the liners less effective.
- For Compacted Clay Liners (CCLs) the leakage through the defects resulted in gradual wash offs and loss of fines leading to instability and in severe cases resulted in collapses.

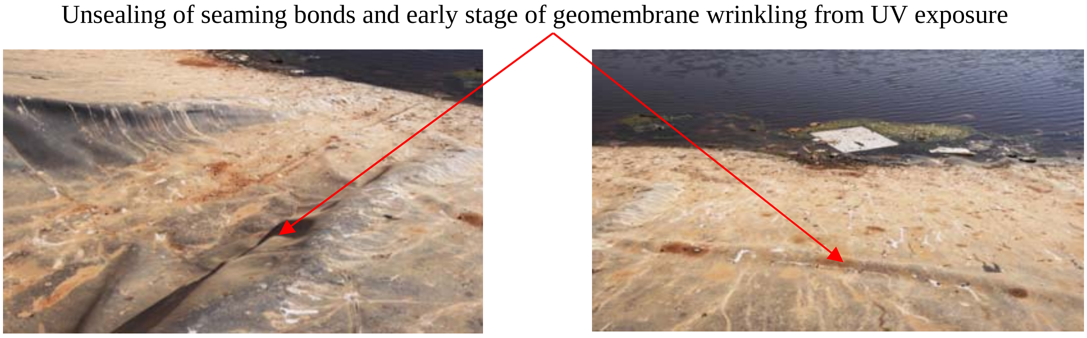
- Transmissivity of the interface loss/gaps caused by the nature of the geosynthetic material and the resultant defect permitted flow across the interface and infiltration into underlying soil layer. It was noticed that if the contact between the geosynthetic material and the soil layer was perfect (no gaps) then flow will occur through the defects and the quantity of leachate flowing into the soil layer is hugely reduced. However, it was gathered that no perfect contact can be achieved in real life scenarios as such; a perfect contact should not be expected in field conditions which ultimately increases the quantity of percolating leachate as the flow is expected to occur in multiple directions through the soil media. For instance, wrinkles and folds formed in the liners due to heat, equipment track lines, contours and indentations in the soil layer are a few factors militating against a perfect contact. Schematics of migrating leachate through a defect for this problem are shown in Figure 2.



(a) With perfect interface contact (b) With imperfect interface contact (gap)

Figure 2: Leachate passage through a geomembrane defect (adapted from Brown et al., 1987)

- Degradation caused by ultraviolet (UV) radiation was another problem encountered on site as stated by the site inspectors and observed from the field study. Figures 3a and b show the early wrinkling stage of the geomembranes from exposure to UV radiation. It was however, emphasised at the respective sites that high density polyethylene (HDPE) geomembranes were more resistant to UV radiation than other geomembranes. Although, the service life of the exposed geomembrane could be increased by additives such as carbon black to improve UV resistance.



(a) Temperature induced unsealing of bonds (b) Early stage wrinkling of geomembrane

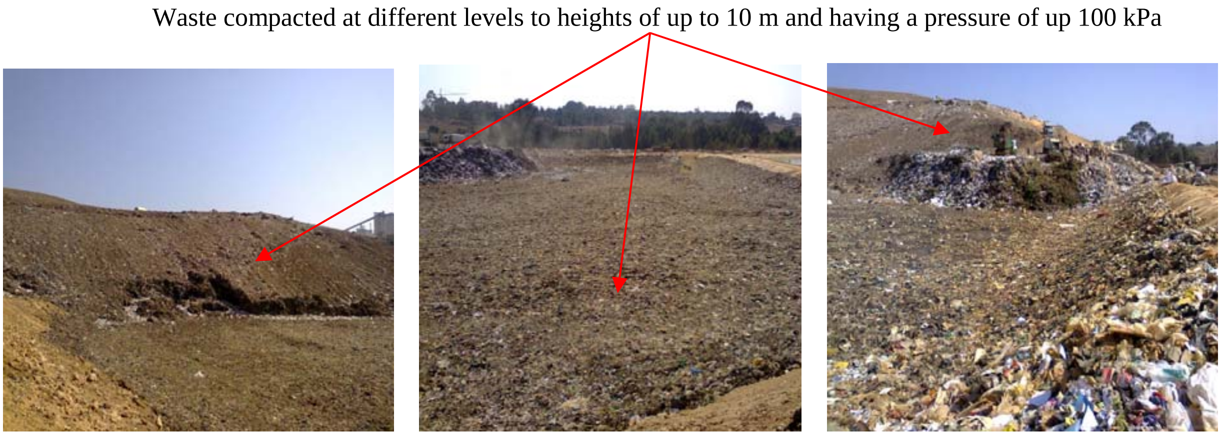
Figure 3(a) and (b): Pictoral view of temperature induced unsealing of seaming bonds and early stage wrinkling of geomembrane caused by UV degradation at one of the visited sites (site recon., 2014)

- The liner materials are easier to repair or replace when exposed to the surface, but exposure leaves the material vulnerable to damage from UV degradation. However, since additives improve resistance to this type of degradation, covered geomaterials were less vulnerable to damage and degradation from the elements; although, repairs on the liner were difficult and more expensive to make since the cover material would have to be excavated to access the liner;
- Finally, cover materials were also pointed out as a field based challenge since they were also responsible for damaging containment liners by puncturing them during the installation processes. Thus, creating a passage for rain/storm water into waste layers and consequently, permitting generated leachate to flow into surrounding soil and ground water reserves.

On the other hand, a lot of reservations and restrictions were encountered with respect to accessing substantial and detailed information during the mine surveys. However, with what was the available and gathered data, the study proceeded in succeeding studies to investigating the buffering efficacy and interaction of minerals in clayey soils with contaminants from both landfilling and mining operations. The studies were experimentally routed towards the buffering capability of surrounding natural mineral soils in affected sites to toxic elements/contaminant species e.g., heavy metals (Fe, Zn, Pb and Cu) usually present in landfill MSW and AMD leachate from the decomposition and decant of toxic substances.

Justification

Land disposal has always been and continues to be the most common form of handling and disposing of various types of waste. The types of waste generally encountered are municipal waste, hazardous waste, agricultural waste, industrial waste and radioactive waste. Findings from the three visited disposal sites around the CoJ showed that only municipal wastes were disposed at the various sites, however, it was observed that in some instances both agricultural and industrial wastes were collected and disposed together with municipal wastes. These wastes were seen to be in solid, semi solid and liquid forms. Solid and semi-solid waste were mostly generated from residential and commercial sources and contained mixtures of food waste, fabrics, paper, oil, rubber, plastics, tyres, metal scrap, glass, wood etc. In other cases, bulky materials such as appliances, furniture, construction and demolition wastes (CDW) and automobile body parts were found in the disposal sites. Pictorial views of the visited sites and AMD affected areas is shown in Figures 4a-e. Some amount from the total content disposed at the sites could be hazardous such as; household cleaning products like bleach, automobile products like antifreeze or batteries and heavy duty industrial chemical fluids like acids and bases. These toxic substances are capable of migrating to levels with consequential impact on the environment by affecting both the soil and surrounding groundwater resources which in turn can affect the health status of inhabitants (Hobbs and Cobbing, 2007). So considering the numerous challenges encountered by landfilling and mining operations, and despite the level of precautions regarding environmental protection i.e., the manufacturing, transportation, handling, storage and installation of leachate liners, efforts to curtail the movement of generated contaminants from these sites by virtue of containment processes often fails.



(a) MSW Site-X (site recon., 2014) (b) MSW Site-Y(site recon., 2014) (c) MSW Site-Z (site recon., 2014)

It was therefore, imperative for succeeding studies to assess the effect of contaminant migration through naked natural clayey soil media, to investigate the contaminant transport mechanism through the soil media and the buffering capabilities of the mineral soils harvested from the respective sites. Furthermore, it was necessary to evaluate the permeant hydraulic rate and the mechanical behaviours of the natural soils collected from the respective sampling areas.


(d) Decant of AMD (site recon., Hobbs and Cobbing, 2007)   (e) Decant of AMD (site recon., Coetzee, 2008b)
Figure 4(a)-(e): Pictoral view of visited waste disposal sites and AMD affected areas under landfilling and mining activities within and around the CoJ, South Africa

In the flooding of Witwatersrand mine voids, two processes resulting in the acidification of water were identified:

i. Interaction between the inflowing water and the sulphides in the ore and host rocks, causing the generation of AMD; this is particularly significant in the unsaturated zone at the top of the void where water and air mixes with the rock material, providing the combination of water, oxygen and sulphides required to produce AMD. Owing to the topography of the Witwatersrand as noted by Rosner et al., (2001) if the mine voids are allowed to flood completely there will always be an unsaturated zone above the final water level within the mine voids, covering most of the geographic extent of the basins. This will result in an environment where new AMD is continually produced due to the interactions between water, air and sulphide minerals.

ii. Ingress of AMD into the mine void after interactions between water and waste rock and tailings stored on the surface; as recorded by Hobbs and Cobbing (2007) this may take the form of contaminated surface water entering the mine workings via surface features, as has been observed in the Western Basin or seepage to the underground water which then recharges the mine void.

Therefore, since limited records have been documented around this research due to the myriad mechanisms and chemical constituents involved, the study opted to pave way for substantial knowledge of the physical, chemical and biological interactions between the clay minerals-buffering strata and the in-situ generated landfill and AMD permeant. Succeeding studies also outlined a laboratory approach to design and simulate clay strata-leachate interaction based on the quality of the effluent and the retained pollutant profiles. A predictive model for permeant migration and contaminant spread through the porous soil systems was also generated to monitor contaminant travel in natural soils towards preventing consequential impacts on the health state of humans and the immediate environment. As such, the evaluation of contaminant migration through porous media and the consequent permeant-soil interaction required the use of a modular laboratory bespoke test equipment (Modular percolation column hybrid device). The fabricated test apparatus was used for subsequent studies and is discussed in detail in there.

Aim and Objectives

On a broader scale, this study points to the efforts made on contaminant migration through porous natural soil media. In this light, through succeeding works, it studied the buffering efficacy of some natural clayey soils to contaminant species generated from landfilling and mining activities- drawn from the laboratory assessment of the interaction of the minerals in the natural soils towards impeding contaminant transport.

With a view to realising the aim, this study outlines the following objectives designed for succeeding works:

I. Evaluating the geo-environmental, geochemical/mechanical properties of three candidate clayey soils used as buffers/mineral liners in waste containment systems in subtropical areas.
II. Assessing the compatibility of the clayey mineral soils with typical MSW landfill and AMD leachates respectively.
III. Assessing the overall suitability of the soils for use as mineral buffers/barrier materials.

For the purpose of the succeeding works, subtropical clayey soils were collected from three respective disposal sites around the CoJ, South Africa. The key pointers considered in the selection of the sampling areas included; sites near areas of high per capita industrial and domestic waste generation as well as areas where mine waste is known to generate AMD. Three permeants obtained from distinct leachate ponds around the CoJ, South Africa, were used for the soil-permeant compatibility assessment (soil-leachate interaction/permeation tests). The choice of permeant samples was partly subject to similarities in some of their characteristics with those of some leachates, as recorded by El-Fadel et al., (2002), Lin and Hansen (2010), Agbenyeku et al., (2013a; 2013b; 2014a; 2014b) and Agbenyeku and Akinseye (2015). Additionally, AMD generated from sulphide ore deposits and mine tailings was also considered for subsequent works.

Scope and Outline

Generally, the succeeding works born out of the bird-eye view entailed the following specific activities:

i. Geo-environmental and mechanical characterisation of the clayey mineral soil samples, and the determination of chemical composition of the permeant samples used as influents;
ii. Determination of chemical and mineralogical composition of the soils, before and after permeation with the respective permeants;
iii. Determination of the hydraulic conductivity of the clayey soil samples when percolated with the respective permeant solutions;
iv. Chemical analysis of the effluents obtained from the percolation tests;
v. Performance of equilibrium speciation modelling of the effluents obtained from the permeation tests to determine either the factors controlling the concentrations of major dissolved species or any new minerals, which may be generated from the soil-permeant interactions;
vi. Performance of batch sorption and column diffusion tests using the permeant solution samples to ascertain sorption and diffusion parameters; and
vii. Modelling of some effluent solute breakthrough curves obtained during percolation testing.

The bird-eye view study gives the breakdown of the succeeding works organised into eight chapters. The content of these chapters are as follows:

Chapter 1 which is the bird-eye view study presents the background information, problem and the purpose of the study. It introduces the study by underlining how essential it is to identify appropriate candidate soils in designing and constructing containment systems for the menacing volumes of AMD and MSW pollutants being insistently generated and disposed in and around Johannesburg, South Africa. The aim, objectives, scope and outline also forms what becomes the introductory representation of this study. A review of literature relevant to the study is presented in Chapter 2 as succeeding works. This includes a review on leachate composition and its effects on soil and water sources, subtropical/tropical soil development and composition, and evaluation criteria of natural soils/clay minerals as compacted clay liners for contaminant buffering. It reviewed factors influencing the hydraulic conductivity of compacted clayey soils, and discussed the types and value of the hydraulic conductivity testing devices and the scale effect of test apparatuses available in assessing soil-permeant interactions/compatibility.

In succeeding works of Chapters 3 and 4, the impact of acid mine drainage on the performance of the three sampled soil types used as buffering/lining materials for mine tailings dams or tailings ponds are discussed. Chapter 3 addresses the chemical and mineralogical alterations that occurred in the respective soil samples after permeation with several pore volumes of AMD, using a bespoke modular percolation column hybrid device. The chapter also describes the experimental procedures adopted in evaluating the chemical, mineralogical and geochemical/mechanical properties and compositions of the soils. The effectiveness of the soils as barrier/buffering materials in reducing or preventing the migration of contaminants such as; heavy metals from AMD is assessed in Chapter 4. Also in Chapter 4, a theoretical discussion of batch sorption, diffusion and advection processes through compacted clayey soils are incorporated. Effluent breakthrough curves, batch sorption and diffusion test results are presented and discussed.

Chapters 5 and 6 of succeeding works investigates the soils-MSW landfill leachate interaction/compatibility. The hydraulic conductivity variations and soil changes that occurred during permeation of the soils with landfill leachate in a bespoke modular percolation column hybrid device, is discussed in Chapter 5. Adding to the presentation and discussion of effluent breakthrough curves obtained from the percolation tests of the soils with the MSW landfill leachate, Chapter 6 offers and analyses the results of batch sorption and diffusion tests carried out. Subsequently, in Chapter 7, the potential impact of three organic compounds, namely; phenol, chlorobenzene and toluene present in landfill leachate, on the performance of the three sampled soils as buffers/barriers to migrating leachate contaminants were examined. Whereas Chapter 8 presents the conclusions of the entire succeeding works and recommendations for further investigations were made.

SUMMARY, CONTRIBUTIONS AND CONCLUSIONS

The bird-eye view study has pointed out that holistically, succeeding works investigated the buffering efficacy of mineral liners towards the direct impacts of contaminants generated from landfilling and mining operations. Generally, the works were steered towards assessing the buffering capabilities of three distinct surrounding natural soils in respective affected sites exposed to contaminant species e.g., heavy metals (Fe, Zn, Pb and Cu) present in AMD and landfill leachates. The contaminant-clay soil mineral interaction was of key focus as it permitted the exploration of the influence of clay mineralogy on buffering capacity and how metallic ions which electrostatically bounds to a unit mass of clay differ in respective clay minerals. Thus, creating correlations from gathered results between the respective clay soil mineral-contaminant interactions and their potential use as natural lining materials towards safeguarding environmental and human health.

The general contributions of the works are:

i. Results of succeeding works have shown that contaminant-soil liner compatibility could be a concern in MSW landfills harboring waste which generates leachate having at least 12 mg/L of phenol as the hydraulic conductivity of the soils increased by up to one order of magnitude on permeation with approximately 6-12 pore volumes of leachate doped with 11.5 mg/L of phenol;
ii. Investigating the impact of AMD and landfill leachate on the physicochemical and mechanical index properties of the sampled soils;
iii. Determining the mineralogical compositions of the sampled soils, before and after percolation with AMD or landfill leachate;
iv. Establishing of sorption selectivity order for sodium, chloride, bromide, potassium, phenol and chlorobenzene for the sampled soils;
v. Determining the distribution and effective diffusion coefficients for some ionic species and low concentrations of phenol, chlorobenzene and toluene present in MSW, co-diffusing through the sampled soils;
vi. Evaluating the impact of AMD and landfill leachate on the hydraulic conductivity, chemical and mineralogical compositions of the respective soils in assessing the buffering efficacy of the soils as liners in waste containment facilities; and
vii. Predicting the times that the migrating fronts of organic compounds and ionic species produced at constant rates from an operating MSW landfill leachate escaping the base of hypothetical 1 m thick compacted liners constructed with each of the three soils would exceed a maximum contaminant concentration threshold in groundwater.

Generated data from the entire works may enable future geo-environmental investigations that would foster the formation of enforceable environmental performance standards in waste management in South Africa; and the results would also aid increase public awareness and stimulate support for sound environmental practices, such as the need to safeguard human and environmental health in areas affected by mining and landfilling operations. Thus, advancing the assessment of compacted clayey soil liner-permeant interaction/compatibility as a requirement in the design of engineered waste containment facilities in South Africa.

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