



Physico-chemical and Mineralogical Characterisation of Subsurface Sediments around Gaborone Landfill, Botswana

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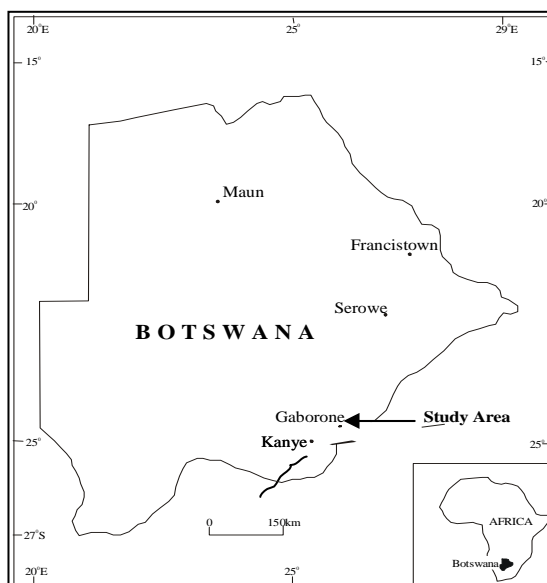
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ABSTRACT: Studies were carried out on subsurface sediments obtained around the Gaborone landfill area Botswana, in order to characterize their mineralogy and physico-chemistry, appraise any contaminant inputs from the landfill and assess their ability to attenuate contaminants from the landfill. Physico-chemical properties investigated included particle size distribution (PSD), moisture content, bulk density (D_b), porosity, surface area, pH, electrical conductivity (EC), and cation exchange capacity (CEC). The mineral phases occurring in the subsurface sediments were identified by use of X-ray powder diffraction (XRPD) technique. Grain size analyses of the subsurface sediments revealed sandy loam, silty loam, and silt as the main textural classes. The values obtained for D_b and porosity is reflective of the textural classes of the different samples. Moisture content values of the studied samples are characteristic of sediments in semi-arid environments. Apart from two samples, which were acidic, others were alkaline. The EC values were indicative of significant amounts of total dissolved salts (TDS) especially along the eastern corner of the landfill. Cation exchange capacity values were relatively low. Minerals identified by XRPD included quartz, microcline, muscovite and kaolinite in bulk subsurface sediments, whereas kaolinite, smectite and /or illite occurred in the clay fractions. Sediment pH, EC and TDS suggests inputs from the landfill. The sediments seem to have a low attenuation capacity as a result of their physico-chemical and mineralogical properties. Further geophysical and hydrogeochemical research is needed to verify if the Gaborone landfill area is environmentally safe. @JASEM

Environmentally safe landfilling of waste is based on technologies that aim at protecting aquifers, reducing gaseous emissions, and curbing the spread of leachate whereas poor waste disposal practices are usually caused by weak environmental protection standards. In several cases, this leads to leachate from landfill sites to migrate and affect the quality of soil and water resources in the vicinity (Rushbrock, 1997). To minimize the negative impacts of landfilling on the surrounding environment, the underlying and

surrounding soil strata of the landfill should have the ability to retard contaminant spread within the surrounding environment. This capacity is determined by the physico-chemical and mineralogical properties of the sediment strata (Thornton et al., 2000).

Gaborone Landfill which became operational in 1994 is a municipal solid waste landfill located south east of Gaborone city, the capital of Botswana (Figure 1).



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Fig 1: Map of Botswana showing the study area

The landfill covers an area of about 204 800 m² with a topographic gradient of 1.77 from west to east. It is underlain by the Thamaga Granite of the Gaborone Granite Complex (GGC), which is composed of varying percentages of quartz, orthoclase, microcline, muscovite, albite, and plagioclase. Sediments around Gaborone Landfill consist of coarse-grained sands, which become clayey and plastic with depth (Arup, 1994). Permeability of sediments around the Gaborone landfill prior to its construction ranged from $2.3 \times 10^{-8} \text{ ms}^{-2}$ to $5.7 \times 10^{-7} \text{ ms}^{-2}$ at depths between 1.3 m and 4.0 m Arup (1994). The permanent water table around the landfill according to Arup (1994) varies from 4.48 m to 7.86 m below the ground surface. Gaborone Dam reservoir and Notwane River are the two permanent surface water bodies around the landfill area. The landfill is not lined; consequently, there is a risk of groundwater contamination from leachate. Apart from site investigations which included determination of site boundaries and topography, stress tests to assess mass permeability, and suitability of excavated soils for use as sub tip liner and cover material, carried out before its design (Arup, 1994), the other documented study focused on aquifer mineralogy and geophysical characterization of the subsurface environment around the landfill (Bogatsu et al., 1999; 2000). No other research has been conducted to characterize the subsurface sediments around the Gaborone Landfill area in order to establish whether landfilling of waste would be environmentally safe. The main objective of this work was to study the physico-chemical properties and identify the mineral composition of subsurface sediments around the Gaborone Landfill - Botswana, in an endeavor to appraise their capacity to attenuate contaminants emanating from the landfill and to determine possible contaminant inputs resulting from landfilling activities.

MATERIAL AND METHODS

Fifty-seven subsurface sediment samples were collected at a 50 cm depth interval from eleven profiles; ten (P 2 – P 11) spread around the landfill vicinity, and one (P 1) located about 6 km northeast of the landfill. Samples from P 1 were selected as baseline samples because this profile was located in a relatively undisturbed area outside the main study site but having the same geologic formation and lithology. The PSD of the samples was determined by both wet and dry sieving as well as centrifuging using a Retsch AS 200 Basic Analytical Sieve Shaker, a nest of sieves with respective mesh sizes, and an SA - CP4 Schimadzu Centrifugal Particle Size Analyzer respectively (Okalebo et al., 1993; van Reeuwijk, 1993). The soil moisture content and D_b were determined according to the methods highlighted by Tan, (1996). Soil porosity was calculated from D_b

values as explained by Brady and Weil, (1999). The pH of samples was determined with a pH Meter both in a 1:2.5 sediment: water and sediment : 1 M KCl mixture as described by van Reeuwijk, (1993) and Igwe et al., (1999). Sediment EC was determined in the same 1 : 2.5 sediment : water suspension used for pH determination with a conductivity-meter (Okalebo et al., 1993). The amounts of total dissolved salts in the samples were estimated from the EC values obtained (Ekosse, 2000; Sparks, 1995). The barium chloride–triethanolamine method as described by Hendershot and Duquette, (1986); and Ma and Eggleton, (1999) was used to determine the CEC of the samples. The mineral composition in both the bulk subsurface sediments as well as their clay fractions was identified with a Philips PW 3710 XRPD unit and a 1999 version of Philips X'PERT Graphics and Identify Software package according to methods described by Ekosse, (2000) and Melkerud et al., (2000).

RESULTS AND DISCUSSION

Sandy loam, silty loam and silt are the main textural classes of the subsurface sediments as confirmed by Ngole et al., (2002) in a related study. Lack of uniformity in the PSD of sediments along different profiles (Figure 2) and the smooth and rounded pebbles observed could indicate alluvial transport from elsewhere. They could also have been deposited as a result of translocation from surface to bottom horizon through the cracks caused by the swelling and shrinkage of the smectitic sediments especially along the eastern corner of the landfill. The coarse nature of the sediments does not constitute an effective hydraulic barrier. The thin-layered sediments characteristic of the landfill environment may also encourage horizontal and lateral migration of contaminants along the sediment-bedrock interface. Notwane River at the bottom of the slope of the landfill is at risk of contamination. The percent moisture content of studied samples range from 0.36 % (P 3) to 5.46 % (P 9). At the control site (P 1), the percent moisture content was between 0.63 and 4.02. Sediment moisture content values are typical of soils of semi-arid environments (Ringrose *et. al.*, 1995). Bulk density values were between 1.12 (P 5) and 1.55 (P 3), with an outlier value of 2.04 (P 2). The lowest porosity value was 41.32 % (P 3), whereas the highest was 57.61 (P 5). At P 1, the porosity values were between 49.08 % and 61.74 %. D_b values obtained for the studied sediments are classified as low, which are characteristic of sands, and sandy loam soils (Tan, 1996). They are generally well aerated allowing for migration of fluids. This is further substantiated by the values of porosity obtained for the sediments. Sediments around the Gaborone landfill were more alkaline than those

from the control profile (Table 1). The alkaline conditions that prevail within the sediments may reduce the spread of heavy metal ions due to

precipitation (Alloway and Ayres, 1997; Christensen et al., 1996; Wilcke and Kaupenjoham, 1994).

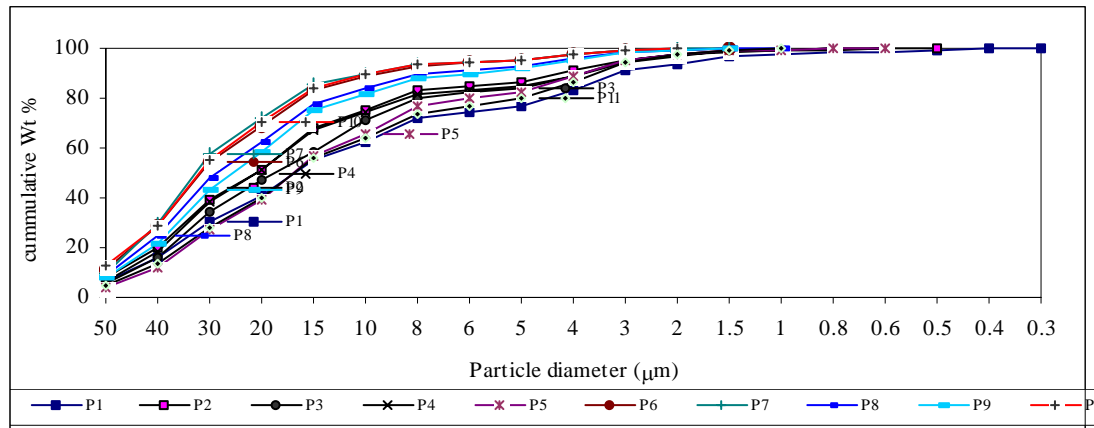


Fig 2: Mean cumulative particle size distribution along profiles

Table 1: Mean EC, pH, CEC, D_b and %pore space along profiles

Profile	Mean EC ($\mu\text{S}/\text{cm}$)	Mean pH		Mean CEC (meq/100g soil)	D_b (g/cm^3)	% Pore space
		KCl	H_2O			
1	122.32	6.97	7.54	21.36	1.19	55.03
2	268.23	7.87	8.16	17.00	1.53	42.41
3	399.33	8.18	9.34	26.55	1.46	44.74
4	255.33	7.53	8.27	24.44	1.36	48.67
5	370.50	6.35	6.81	26.82	1.28	51.86
6	887.67	7.62	8.82	26.00	1.43	46.11
7	350.00	7.81	9.05	26.41	1.40	47.13
8	1377.75	8.05	9.44	26.11	1.36	48.82
9	2111.83	7.98	8.99	27.13	1.42	46.41
10	667.00	7.70	8.89	25.97	1.48	44.11
11	49.37	6.32	7.24	28.31	1.39	47.61

The EC values were also higher around the landfill than the control profile with the eastern corner having the highest values. This is indicative of a high concentration of total dissolved salts (Ekosse, 2000), which in turn suggests that a contaminant plume from the landfill flows towards the eastern corner. Previous geophysical investigations carried out at the Gaborone landfill area by Bogatsu et al., (2000) confirmed the existence of a contaminant plume along its eastern corner. Furthermore, in semi - arid regions such as Botswana, salts would be precipitated in the surface horizons of the soil due to a high rate of evapo-transpiration. The increase in pH and EC values with depth around the landfill indicates downward movement of ions especially along P 8

and P 9. The lowest CEC value was recorded along P 2 while P 9 and P 11 had the highest (Table 1). P 1 had CEC values lower than those around the landfill (Table 1). The CEC of sediments is related to the PSD, SSA, mineral composition and pH of the sediments (Alloway and Ayres, 1997; Sparks, 1995). A low wt % clay and SSA of the sediments may explain the low CEC values observed. The small SSA may have caused a low surface charge density, offering little opportunity for ionic exchange within the sediments (Sparks, 1995). XRPD analyses revealed quartz, hematite, muscovite, plagioclase and microcline to be contained in the saprolite and quartz, muscovite, albite, microcline, and kaolinite in the whole soil (Figure 3). Quartz and microcline were the

dominant mineral phases whereas kaolinite was minor. The dominant mineral phases in the clay fraction were quartz and kaolinite whereas smectite

occurred in minor and/ or trace quantities along all the profiles (Figure 4).

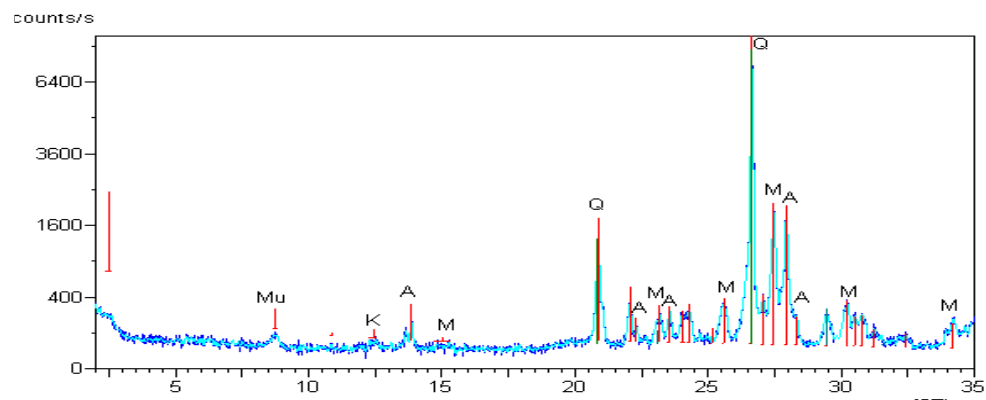


Fig 3: XRPD Diffraction pattern of a representative bulk subsurface sediment sample from the Landfill showing muscovite, kaolinite (K), albite (A), microcline (M), muscovite (Mu), and quartz (Q) peaks

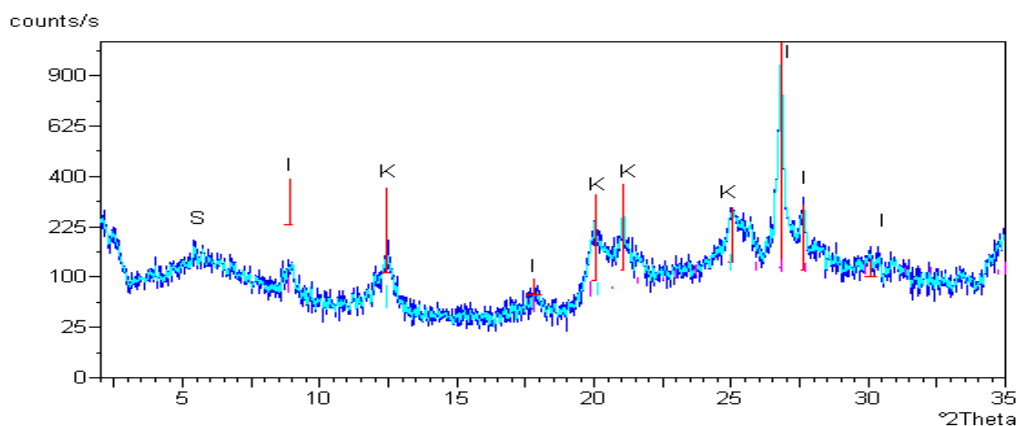


Fig 4: Typical XRPD diffractogram of the clay fraction of a representative subsurface sample from the landfill area showing smectite, illite, and kaolinite peaks. (I = illite, K = kaolinite, S = smectite.)

Illite was identified as a major mineral phase in samples from P 8, as a minor mineral phase in samples from P 7 and P 9, and as trace in samples from P 1, P 2, P 3, P 4, P 5, P 6, P 10 and P 11. Calcite was identified in samples from P 2, P 3, and P 6. Although natural phenomena are mainly responsible for the alteration of the feldspars and micas to kaolinite and smectites (Faure, 1997), leachate migration could have played a contributory role. Illite formation occurs as a result of incomplete loss of K^+ from the K-feldspars-muscovite-kaolinite alteration system (Pickering and Murray, 1995). Kaolinite minerals, which dominate the mineral composition of the sediments possess a small external surface, which limits its adsorptive properties. In addition it is inert over a wide range of acid / alkali pH which further reduces its adsorptive capacity. The sediments will therefore have a reduced ability to adsorb contaminants from the leachate plume because of the dominance of chemically inert soil minerals.

The prevailing moist environment, the abundant CO_3^{2-} in landfill leachate (Christensen et al., 1994) and the alkaline conditions in the subsurface environment around the landfill is likely to encourage the precipitation of $CaCO_3$ as observed along P 2, P 3 and P 6.

The physicochemical and mineralogical properties of the subsurface sediments around the Gaborone Landfill area offer a poor ability to adsorb contaminants from any plume migrating from the landfill. Though the high pH of these sediments is likely to result in precipitation of some ionic contaminants, there is a likelihood of contaminants seeping through the soil layer into surrounding groundwater resources in the vicinity of the landfill due to the porous nature of subsurface deposits. The mineral composition does not favor the attenuation of contaminants within the sediment because of the dominance of chemically inert minerals. This study

suggests the installation of remediation measures such as a leachate drainage and collection system to reduce its seepage into the surrounding environment. Monitoring of the water quality in the surrounding surface and groundwater resources is recommended as environmental health hazard measures.

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