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ORIGINAL ARTICLE

Geotechnical and Geochemical Assessments of Shales in Anambra Basin, Southeastern Nigeria, as Landfill Liners

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Abstract
Background The use of landfills as containment for municipal solid waste management has received wide acceptance the world over. Its development in countries like Nigeria is constrained by high cost and scarcity of synthetic liners in the local markets. Exploration of the abundant locally available clay deposits in the country's sedimentary Basins will prove economical, provided it satisfies the standard specifications for design and construction of landfill liners.
Purpose This study thus evaluates the suitability of shales from three formations (Enugu, Ameki and Imo) within Anambra Basin of Southeastern Nigeria as liner materials.
Method Geotechnical tests such as particle size distribution, Atterberg's limits, compaction, coefficient of permeability and consolidation were performed on the shale samples. Geochemical analyses involving the inductively coupled plasma emission spectroscopy (ICPES) and cation exchange capacity (CEC) were also conducted; all employing standard methods.
Results Based on the Unified Soil Classification System (USCS), Enugu and Imo shales contain high-plastic inorganic clay, while Ameki shales comprise low–medium-plastic inorganic clay. Coefficient of permeability result ranging from 9.12×10^{-6} to 2.14×10^{-6} cm/s indicates an increase above the standard specification. Expectedly, the cation exchange capacity (CEC), compressibility and plasticity index of the shales are positively related suggesting strong influence of the geotechnical properties on their sorption potentials. Overall assessment revealed that the high hydraulic conductivity and swelling potentials of the shales are not suitable for natural clay liners. Nevertheless, Enugu and Imo shales can further be stabilized chemically to the desired hydraulic conductivity of liners considering other suitable geotechnical properties and their CECs.

Keywords Engineered landfill · Shale · Anambra basin · Liner materials · Nigeria

1 Introduction

Increasing population, especially in developing countries like Nigeria, is a major factor responsible for increased municipal solid waste (MSW). The use of landfills to contain MSW is a common waste management practice and one of the cheapest methods for organized waste management practices in many parts of the world (Dsakalopouos et al. 1998; Jhamnani and Singh 2009; Longe and Balogun 2010). The performances of landfills depend greatly on their impact in the environment, so it is important to design adequate control to protect public health and the environment. The public health and environmental hazards associated with unengineered landfills are well-recorded in Nigeria (Asiwaju-Bello and Akande 2002; Odukoya and Abimbola 2010; Longe and Balogun 2010), and calls for the need to source for local clay materials that are relatively cheap, and can retard the migration of leachates from landfills. Leachate containing trace metals are considered hazardous, and are commonly found in several kinds of waste and landfill effluents

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(Shackelford 1990; Manassero et al. 1996; Odukoya and Abimbola 2010). To protect the environment from these contaminants, waste disposal sites are commonly lined with the combination of a geological barrier and a bottom liner (Declan and Paul 2003), or a composite liner consisting of compacted clay and geomembrane. The geological barrier and underlying soils in the landfills tend to provide sufficient attenuation capacity to prevent a potential risk to surrounding soils and groundwater.

Review of literature shows that toxic leakage through landfill liners can cause a very harmful effect on the environment. As a result, clay liners should have a low hydraulic conductivity to control leachate from the waste (Mitchell et al. 1995). The hydraulic conductivity must also not increase due to chemical and biological attacks from the waste leachate. Clay-rich soils are used for constructing soil liners, because of their low hydraulic conductivity and their ability to attenuate inorganic contaminants (Manassero et al. 1996). In addition, the addition of finely ground shale to barrier walls of landfills has shown to be inexpensive and effective in retarding the spread of toxic contaminants from hazardous waste sites (Gullick and Weber 2001). Chemical sorption and engineering hydraulic characters of fine-grained materials are very significant in landfill barrier and liner system (Tijani and Bolaji 2007), and shales tend to have a higher retardation factor and lower diffusion coefficients, when compared to lateritic clay in retention of heavy metals (Charlermyanont et al. 2009). Ige (2011) recommends higher compaction energy for liner materials to achieve a better coefficient of permeability to impede flow of leachates.

Based on the performance of constructed landfill facilities and extensive research, standard specifications were proposed on the selection of materials, design and construction of landfills. However, the poor nature of liner materials has been highlighted as a major factor responsible for the influx of contaminants to soils and groundwater. A major constraint to the utilization of quality landfill liner is the high cost of synthetic liners and its scarcity in the local markets in Nigeria. This calls for the need to intensify exploration of alternative local clay-rich soils that can effectively retard the spread of leachates in landfills. Consequently, shale could effectively retard the spread of leachate from landfills (Gullick and Weber 2001), and they are available in different sedimentary basins in Nigeria. This study, hence, focuses on the geotechnical and chemical assessments of three shale formations in Anambra basin of Nigeria for suitability, or otherwise, as landfill liner material.

1.1 Geological Settings of the Study Area

The study area is within the Anambra basin of southeastern Nigeria. The basin is roughly triangular (Fig. 1), covering an area of approximately 40,000 km^2 (Nwajide and Reijers 1996), and has an approximate thickness of 5000 m (Uma and Onuoha 1997). The shale samples analysed in this study were obtained from Enugu, Ameki and Imo formations of the basin (Fig. 2). Outcrops studied are road cuts which are accessible through major roads and quarry exposures. Enugu formation consists of black-bluish shale interbedded with dark grey siltstones and fine-grained sandstones, belonging to the brackish marsh environment (Petters 1979), and its age is reported to be Campanian–Maastrichtian (Agagu et al. 1985). The Ameki formation overlies the Imo formation (Simpson 1954), and its shale unit consists of argillaceous, weakly consolidated sandstones. The Imo formation consists of thick, fine texture, dark/bluish grey clayey shale, with occasional admixture of clayey ironstone and sandstone bands.

2 Materials and Methods

A total of nine samples were obtained; three each from the three shale formations namely: Enugu, Ameki and Imo formations (Fig. 1). The samples were excavated with shovels and diggers from the sides of natural slopes, air-dried and pulverised resulting in fine-grained soils, with a maximum material size of about 4.75 mm, before being subjected to laboratory analyses. To assess the suitability of the shales as liner material, some geotechnical and geochemical tests were performed on the samples. The geotechnical tests conducted on the samples include: particle size distribution, Atterberg's limits, compaction, coefficient of permeability and consolidation tests employing British Standard BS 1377-1 (2016) and ASTM (2016) standard methods. Geochemical analyses involving the induced coupled plasma–emission spectroscopy were employed for the whole rock determination. Cation exchange capacity (CEC) was conducted using the atomic absorption spectrophotometry method for calcium (Ca^{2+}) and magnesium (Mg^{2+}) determination, and flame photometry to determine potassium (K^{+}) and sodium (Na^{+}) exchange capacities. Average values of the data obtained from the laboratory analyses from each location were used in result interpretation. No detailed description of the analyses is presented since the procedures are standardized.

3 Results and Discussion

3.1 Index Properties of the Studied Shale Samples

The results of the index test on the soils are presented in Table 1, while the Casagrande (1948) chart classification is presented in Fig. 3. The percentage fines and coarse

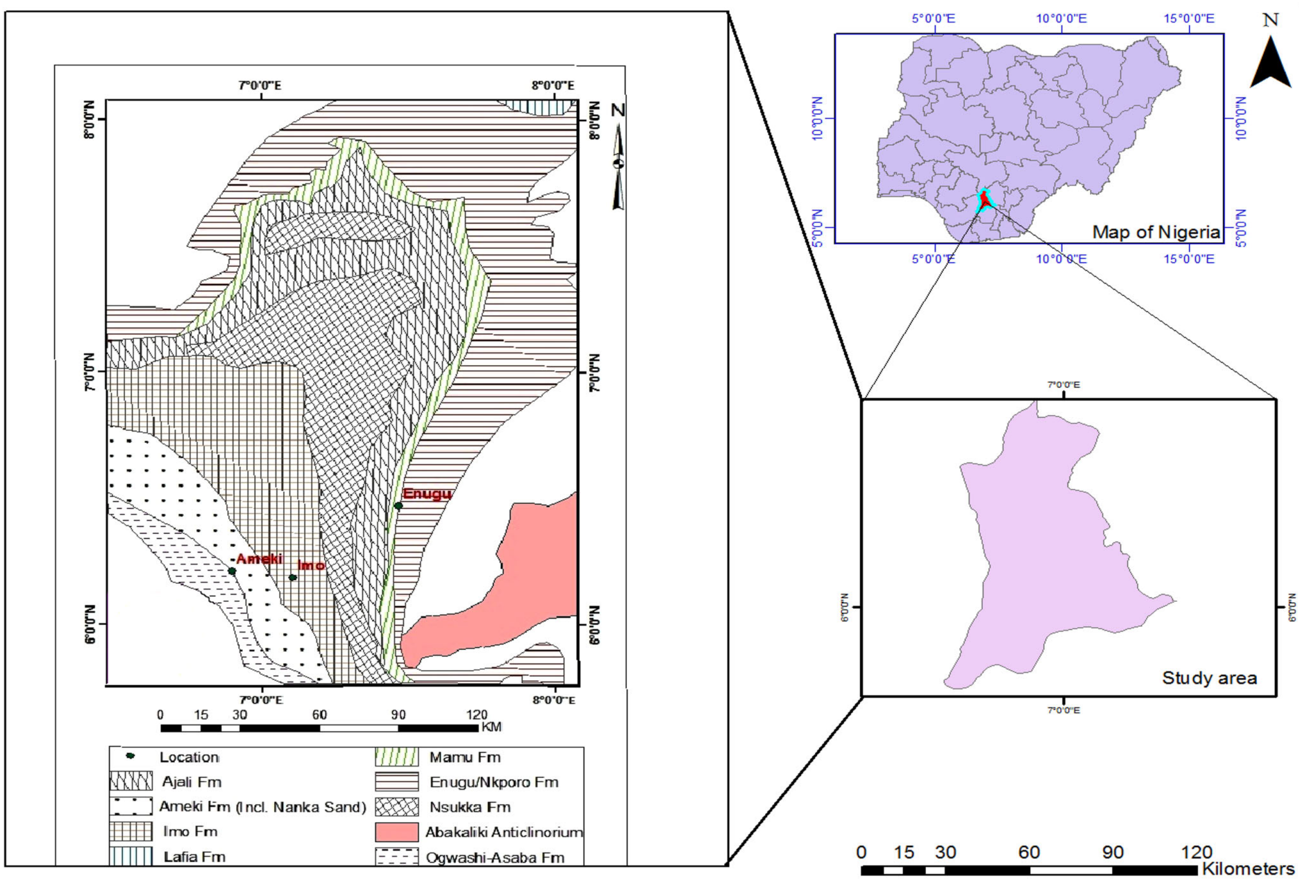

Fig. 1 Geological map of Anambra basin showing sampling location (Modified from Obaje 2009)

particles in the shales range from 79 to 92 and 8 to 21%, respectively, while the clay content is in a maximum of 10% which meets the requirement of Declan and Paul (2003). This is consistent with the previous studies of Daniel (1993); Benson et al. (1994), Rowe et al. (1995) who all recommended a minimum of $>$ 30% fines and $<$ 30% coarse particles for soil liners. The shales has an average liquid limit (LL) and plasticity index (PI) of 67 and 40.22%, 54.60 and 29.76%, and 79.2 and 54.05% for Enugu, Ameki and Imo shales, respectively (Table 1). Thus, the studied samples satisfy the requirements for the grain size and Atterberg's limits for clay liners in landfills.

The shales have clay activity values of 1.44 for Enugu shale; 2.08 for Imo shale and 0.82 for Ameki shale (Table 1). These values are favourable for clay liners, as they meet the recommended minimum value of 0.3 as specified by Daniel (1993). According to Skempton (1954), Enugu and Imo shales tend to display excessive shrinkage and settlement when exposed to leachates, since they are active clays. Ameki shale, on the other hand has inactive–normal activity, and is less expected to display excessive shrinkage. Moreover, the activity value, further indicates the presence of active clay minerals in the shales, and was corroborated by the Casagrande chart distribution of the shale samples presented in Fig. 3. The chart indicates that Enugu and Imo shales are inorganic clays with high plasticity/compressibility, while Ameki shale is made up of inorganic clay/silt of low–medium plasticity. This classification, together with their activity values, further expresses the expected behaviour of Enugu and Imo shales when in contact with leachate, as they have high plasticity and compressibility.

3.2 Compaction Parameters

The pulverised shale samples were compacted at two compacted efforts: standard proctor (SP) and the modified AASHTO (MA). The compaction curves shown in Fig. 4 reveal that the optimum moisture content (OMC) and maximum dry density (MDD) for Enugu shales are 19.2% and 17.5 kN/m^3 and 18.0% and 18.1 kN/m^3 for SP and MA efforts, respectively. For Ameki shales, the OMC and MDD are 18.5% and 18.4 kN/m^3 and 16.6% and 19.1 kN/m^3 for SP and MA, respectively. The OMC and MDD for Imo shales are 20% and 16.8 kN/m^3 and 19.3% and 17.3 kN/m^3 for SP and MA, respectively. The samples

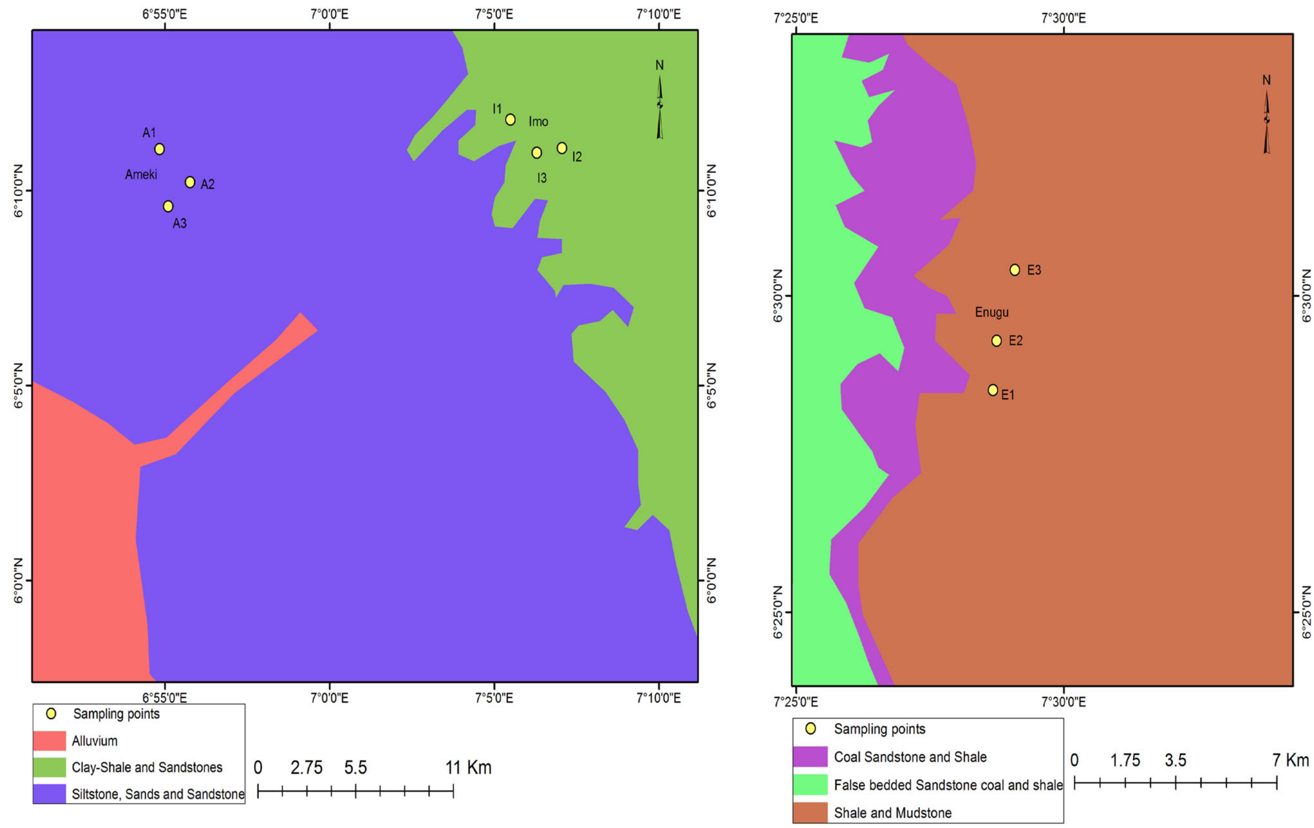

Fig. 2 Geological map of the area showing sampling points

Table 1 Index properties of the studied shales

Property	Enugu	Ameki	Imo
Liquid limit (%)	67.00	54.60	79.20
Plasticity index (%)	40.22	29.76	54.05
Percentage of coarse (%)	8	21	12
Percentage of fines (silt and clay)	92	79	88
Percentage of clay (particles < 2 μm)	27	36	26
Activity	1.44	0.82	2.08

when compacted at Modified AASHTO level have a relatively similar maximum dry density (MDD) to those compacted at standard proctor energy level. Thus, the percentage decrease in optimum moisture content (OMC) (range of 3.5–10.27%) and increase in MDD (range 2.98–3.80%) suggest no significant change in density, irrespective of the compaction level. The plots in Fig. 4a–c show that trends in variations of MDD and OMC at both energy levels are uniform for all the samples.

3.3 Coefficient of Permeability

The coefficient of permeability determined in the laboratory for the different compaction energy as presented in Table 2 shows that the shales have a value range of 9.12×10^{-6}–2.14×10^{-6} cm/s. These values show that the shales have very slow permeability (USEPA 1978), and permeability of 10^{-6} cm/s is frequently described as a borderline between pervious and impervious soils. However, the sampled clays do not directly meet the requirement as an isolation barrier for clay-rich soils, according to Daniel (1993), Rowe et al. (1995) and Mohammed and Antia (1998), who all agreed that clay materials should have permeability of 1×10^{-7} cm/s if to be used as a single liner/isolation barrier. Nevertheless, the shales have optimum permeability as an attenuation layer, as they are in the order of 10^{-6} cm/s (Manassero et al. 1996).

3.4 Consolidation Test

Wastes deposited in landfills tend to change the volume of clay liners as a result of static loading, which makes the consolidation test an important parameter in material selection. The expected compressibility of the shales is inferred from the result of the consolidation test and is presented in Fig. 5.

Although, there is no established criterion for compressibility of landfill liners, the compressibility of the

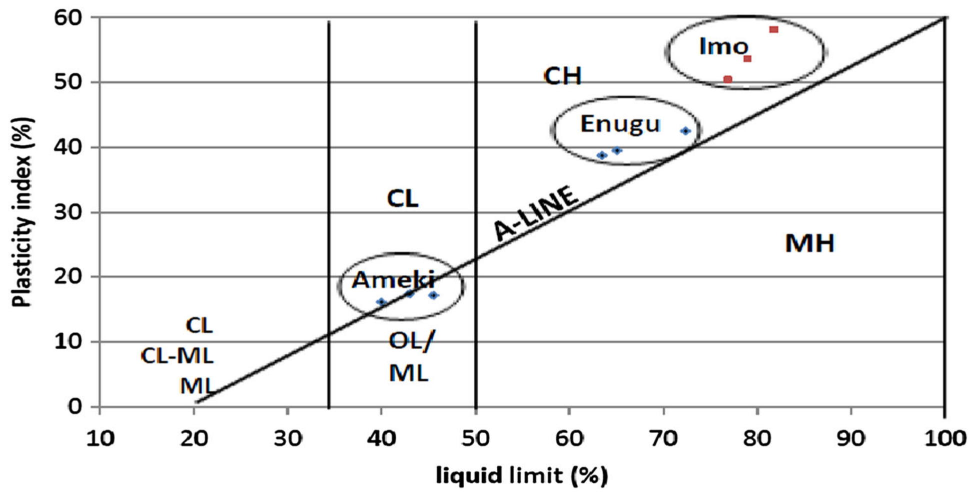

Fig. 3 Casagrande chart classification of the samples. *CL* inorganic clays of low to medium plasticity, *OL/ML* organic clay/silts, very fine sands, silty or clayey fine sands of low plasticity, *CI* inorganic clay of intermediate plasticity, *MI* inorganic silt of intermediate plasticity, *CH* inorganic clays of high plasticity, *MH* inorganic silts of high plasticity (Modified from Casagrande 1948)

shales is expressed in terms of their coefficient of volume compressibility (M_v) and their compressibility index (C_c), using $M_v = -\Delta e/\Delta ò$ and $C_c = \Delta e/\log ò_2/ò_1$, respectively. The coefficient of volume compressibility and the compressibility index of the shales are presented in Table 2. The results, however, show that Enugu and Ameki shales have a medium degree of compressibility, while Imo shale has a high degree of compressibility (Bell 2007). Clays with a high degree of compressibility are considerably stronger than those with lower degrees, when subjected to static load. The compressibility index of the shales is consistent with their liquid limits, also suggesting the influence and presence of some active clay minerals on their geotechnical properties.

3.5 Geochemical Composition of the Shales

The results of the chemical analyses presented in Table 3 and Fig. 6 show that all the shales have high SiO_2 content, suggesting the dominance of quartz and kaolinite. The high amount of potassium oxide (K_2O) in Enugu shale indicates the presence of potassium feldspar, while a high degree of weathering could have accounted for the low K_2O in Ameki shale. The high values of Fe_2O_3 in the shales are a result of the influence of associated ferruginized materials. Furthermore, the loss of ignition (LOI) on the samples is relatively high, and could be a result of the inorganic contents of the shales. Also, the concentration of the five trace metals commonly released to the environment from leachates was analysed on the shales and the result shows a relatively high trace metal concentration value. Although, there is no widely acceptable standard for the trace metal concentration in liner materials, clays with moderately low concentration of trace metals with respect to their sorption parameters can be utilized (Charlermyanont et al. 2009).

3.6 Cation Exchange Capacity (CEC)

In this study, the CEC of the shale samples presented in Table 4 ranges from 5.29 to 10.11 cmol/kg. The CEC values of Imo shales indicate a higher negative charge of the clay fraction and hence, heavy metal sorption capacity (Weaver 1989). High values of CEC will result in a greater amount of contaminant tobe removed from leachate flowing through the clay (Taha and Kabir 2003).

Although there is no widely acceptable criterion for a minimum value, some researchers recommend a minimum CEC value of 10 cmol/kg (Rowe et al. 1995; Taha and Kabir 2003). In view of this, Enugu and Imo shale fairly falls within the recommended minimum. Moreover, the high activity of the shales (Table 1) is consistent with their respective CECs, with a significant correlation at $R^2 = 0.9545$ (Fig. 7). This clearly indicates the influence of clay fractions on their sorption properties. The CEC of Enugu shale, and to some extent, Imo shale, falls within this specification, and can be considered for usage as an attenuating layer ,provided their sorption capacities with respect to their inherent trace metal concentrations are favourable.

4 Conclusion

This study clearly showed the relationship between the geotechnical and geochemical characteristics of shales, as regards to their application in landfill liner system. The geological origins of the shales play a significant role on their physicochemical and cation exchange capacities. Based on their geotechnical characteristics, the shales have the basic engineering requirements such as percentage fines, activity and plasticity index. The Unified Soil Classification System (USCS) indicates that Enugu and Imo

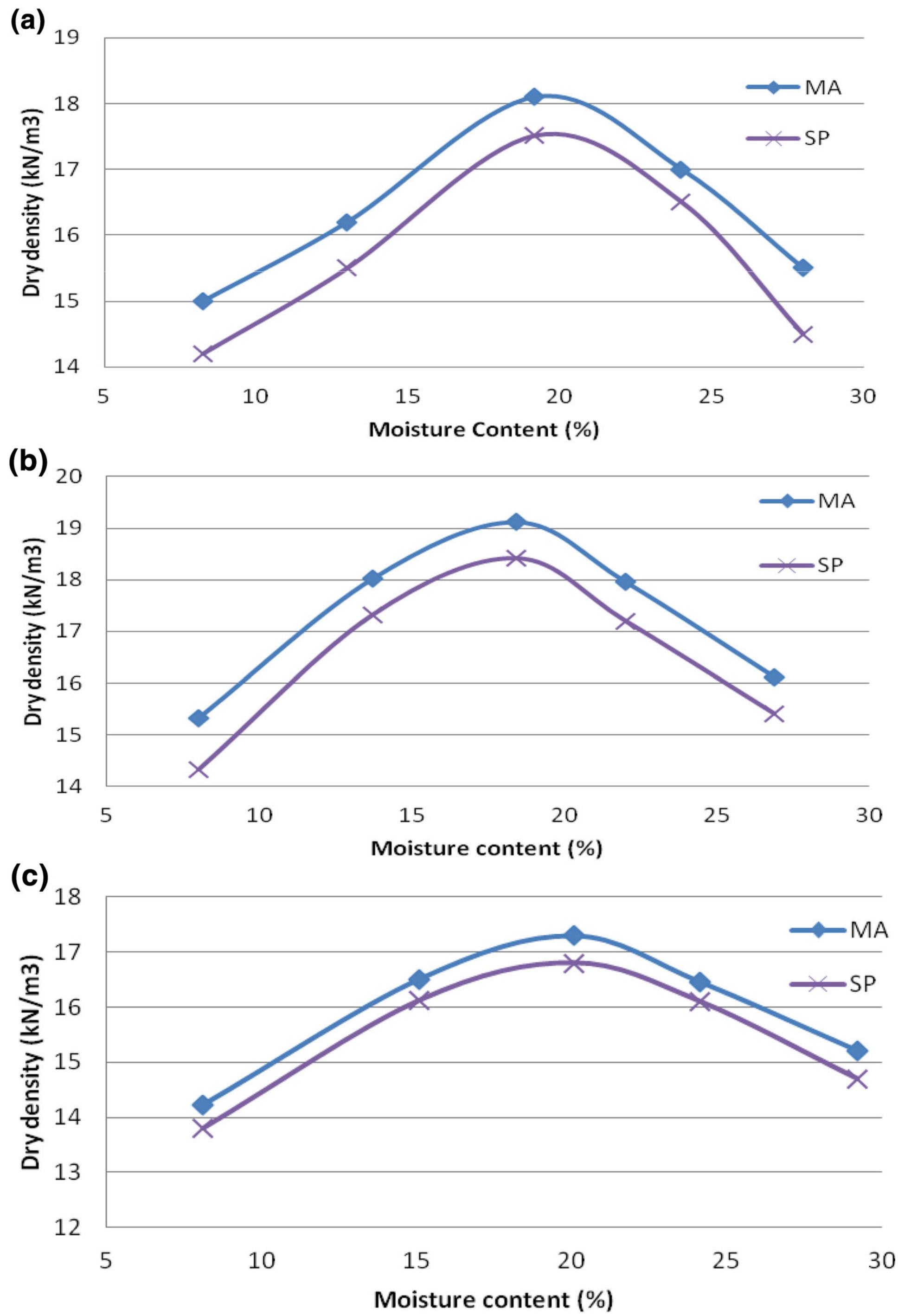

Fig. 4 Compaction curves for the shales **a** Enugu, **b** Ameki, **c** Imo

shales are inorganic clays with high plasticity/compressibility, while Ameki shale is made up of inorganic clay/silt of low–medium plasticity. Enugu and Imo shales, however, contain active clay minerals, which pose a great concern for their swelling potential when in contact with leachates. Furthermore, the experimental hydraulic conductivity of the shales at both Standard Proctor and Modified AASHTO are significantly higher than the minimum value of 10^{-7} cm/s recommended for liner materials, which is a constraint to direct usage in a single lining system. Enugu and Ameki shales have a medium degree of compressibility, while Imo shale has a high degree of compressibility, and it is considerably stronger than the other shale types when subjected to static load.

The whole rock analyses of the shales indicate the presence of a high percentage of SiO_2 content, suggesting

Table 2 Compaction, permeability and consolidation parameters of the shales

Shale type	Compaction				Variations		K ($\times 10^{-6}$ cm)		Consolidation parameters	
	SP		MA							
	OMC, %	MDD, kN/m^3	OMC, %	MDD, kN/m^3	% decrease in OMC	% increase in MDD	SP	MA	M_v, m^2/MN	C_c
Enugu	19.2	17.5	18.0	18.1	6.25	3.43	8.05	2.14	0.208	0.065
Ameki	18.5	18.4	16.6	19.1	10.27	3.80	9.12	7.13	0.171	0.054
Imo	20.0	16.8	19.3	17.3	3.5	2.98	8.57	3.21	0.315	0.098

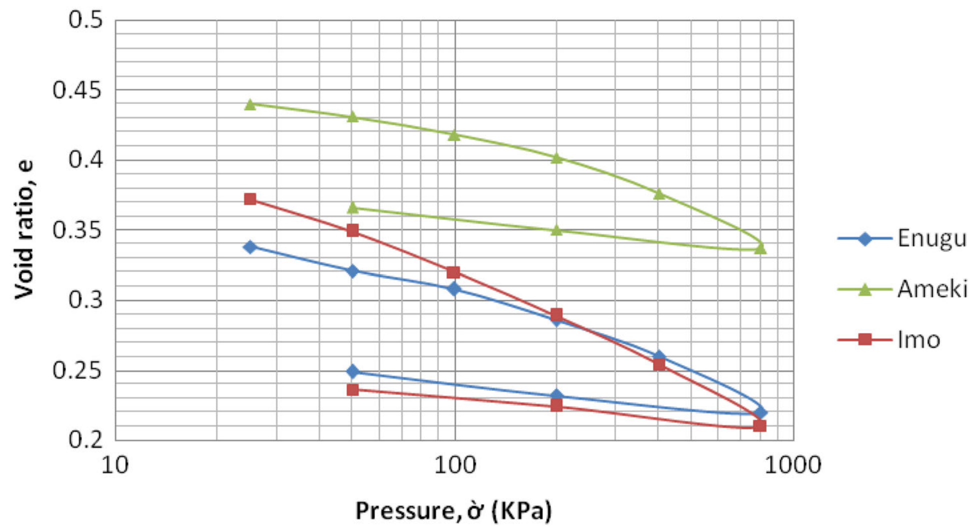

Fig. 5 Consolidation curve for the shales

Table 3 Chemical compositions of the samples

Shale type	SiO_2, %	Al_2O_3, %	Fe_2O_3, %	K_2O, %	TiO_2, %	LOI, %
Enugu	54.65	19.82	5.53	1.38	1.36	16.2
Ameki	55.83	27.45	3.10	0.17	1.93	11.2
Imo	55.33	16.96	7.19	1.62	1.10	15.9

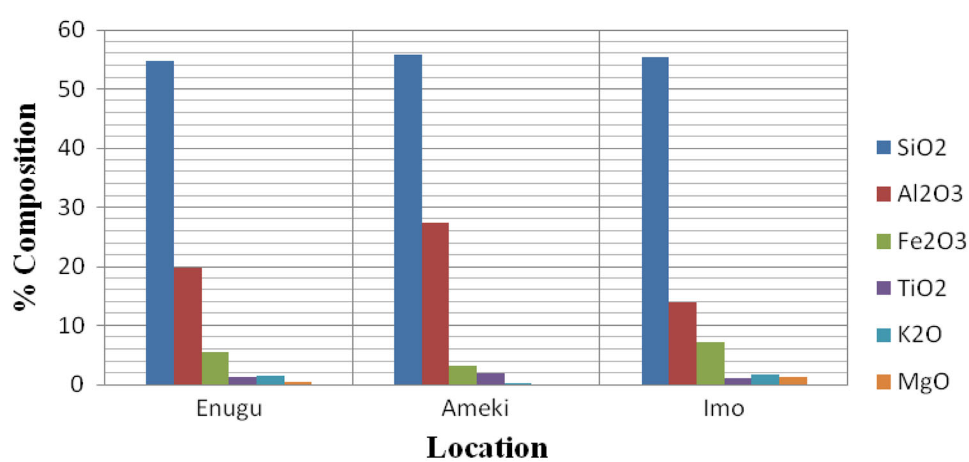

Fig. 6 Percentage composition of major oxides in the shale samples

Table 4 Exchangeable cations in the shales

Shale	Na^+ (cmol/kg)	K^+ (cmol/kg)	Ca^{2+} (cmol/kg)	Mg^{2+} (cmol/kg)	CEC (cmol/kg)
Enugu	0.35	0.54	7.52	1.70	10.11
Ameki	0.27	0.30	3.37	1.35	5.29
Imo	0.35	0.55	7.02	1.61	9.53

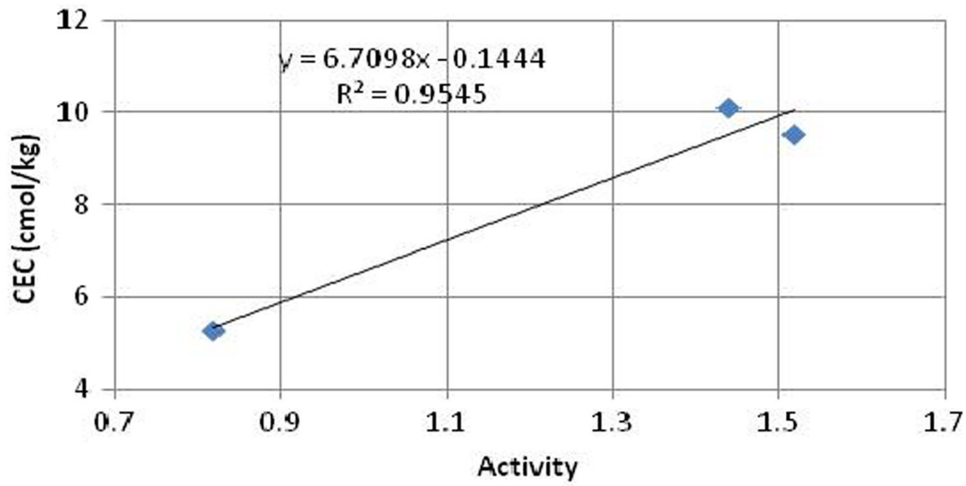

Fig. 7 Relationship between activity of clay fraction and CEC

the dominance of quartz and kaolinite. The higher amount of potassium oxide (K_2O) in Enugu shale indicates the presence of potassium feldspar (K-feldspar), while a high degree of weathering would have accounted for the low K_2O in Ameki shale. The high values of Fe_2O_3 are a result of the influence of the ferruginized overlying materials on the shale formations. Also, the loss of ignition (LOI) on the samples is relatively high as a result of the inorganic nature of the shales. Relatively high CEC values in Enugu and Imo shale compared to Ameki shale indicate a higher negative charge of the clay fraction and will result in a greater amount of contaminant tobe removed through them. The CEC values show a positive correlation with their activity, suggesting the influence of their mineralogical composition.

Considering the relatively high permeability and swelling potential of the shales, they could not directly be utilized as natural clay liners. However, Enugu and Imo shales can further be subjected to kinetic experiments to determine their adsorption capacities with respect to some common trace metals as contaminant cations in leachates. Ameki shale on the other hand, could not be effectively utilized considering its relatively low CEC.

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