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Geotechnical and Mineralogical Evaluation of Lateritic Soils to Access Their Suitability for Engineering Construction Works: A Case Study of Some Selected Residual Soils in Parts of the Southwestern Nigeria

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Abstract

This study investigate the geotechnical and mineralogical properties of differently sourced lateritic soils in order to determine their suitability for engineering construction purposes. In addition, attempts were made to establish the relationships between mineralogy and some geotechnical/engineering properties. Five lateritic soil samples derived from quartzite, mica schist, amphibolite, sandstone and migmatite-gneiss in parts of the southwestern Nigeria were collected in the field for geotechnical tests as well as determine their mineralogical compositions using x-ray diffraction (XRD). Result from grain size analysis shows that the soils are generally fine to medium grained consisting mainly of clayey silty sand. The Atterberg consistency limits revealed that the soils contain inorganic clay of low to intermediate plasticity, with linear shrinkage limit between 7% and 10%, indicating medium shrink potential. Based on the Skempton's activity chart, the soil can be classified as active to moderately active soils. The maximum dry density values of the samples at standard proctor energy of compaction range from about 1.46 g/cm^3 to 1.96 g/cm^3, while those obtained at modified proctor energy vary between 1.57 g/cm^3 and 2.09 g/cm^3. The shear strength tests give angle of internal friction between 31^o and 33^o and cohesion values ranging between 59kPa and 70kPa for the standard and modified proctor compaction, respectively. These values indicate that the soils will have high bearing capacity and could support a moderately steep slope. The coefficient of permeability of the soils is low with k ranging from 0.7 x 10^{-8} m/sec to 8.79 x 10^{-8} m/s, which falls within the range considered to be impermeable. The soaked and unsoaked California Bearing Ratio (CBR) values vary from about 1% up to 6%. Based on the geotechnical analysis, the soils can be used as liners in landfill system, fill materials in embankments and earthfill dam construction as well as subgrade and fill materials for road pavement in highway construction. The mineralogical analysis showed that the soils are mostly composed of illite, kaolinite, quartz, feldspar, hematite and goethite.

Keywords*: Geotechnical; Mineralogical; Lateritic soils; Engineering; Nigeria.*

1. Introduction

Civil engineering construction works in Nigeria are beset with multi-facetted problems [1-4]. Devastating flood from excessive rainfall are accelerating the failure process, which results in immense damage to agriculture and infrastructures every year [5]. Over the last few decades, there have been several cases of structures failure that were initially thought to be well engineered. The major causes of these failures were identified to be erosion, seepage and sliding. Furthermore, insufficient supervision during construction results in poor-quality earthworks with the use of inappropriate soil materials, insufficient or no clod breaking, inadequate compaction and the use of inferior materials as well as inadequate maintenance [6-7]. Among many reasons, the improper design, methodology and construction procedure is prime and one of the most important causes of failure in engineering structures [8]. However, clear understanding of material behavior is necessary to interpret the failure phenomenon of a particular problem.

The response of Engineering geologists to the growth in developmental projects, the difficulty in understanding soil conditions and the failures associated with tropical soils, and the need to address these failures, has led to the apparent increase in research on the tropical soil types and their engineering properties, especially laterite soils [9-10]. The importance of these laterite soils cannot be more emphasized as they are being used as construction and engineering material for roads and airfield sub-bases and sub-grades; fills and embankments for bridges and dams and other engineering uses as may require soil materials in the tropics [11-14]. Several authors like *Baiyegunhi et al.* [4], *Gidigasu* [10], *Ige* [11], *Jegede* [14], *and Ogunsanwo* [14-15] have worked on the geotechnical properties of lateritic soils, since their properties change even within few meters, and have reported topography, climate, soil type, parent material etc., as major controlling factors of their engineering properties. Suitability of lateritic soils as base and subbase course material in road construction and barriers in sanitary landfill have been reported with no particular interest in the influence of rock types [4,11-17].Thus, this study focuses at comparing the geotechnical properties in relation to the mineralogy of soils derived from five different rock types. Rocks of the study area can be broadly divided into the Basement Complex rocks and sedimentary rocks (Figure 1). Four of the lateritic soils under consideration are derived from Basement Complex rocks. The fifth sample is derived from the Santorian-Maastrichian units (Nupe sandstone) of the Lower Bida Basin.

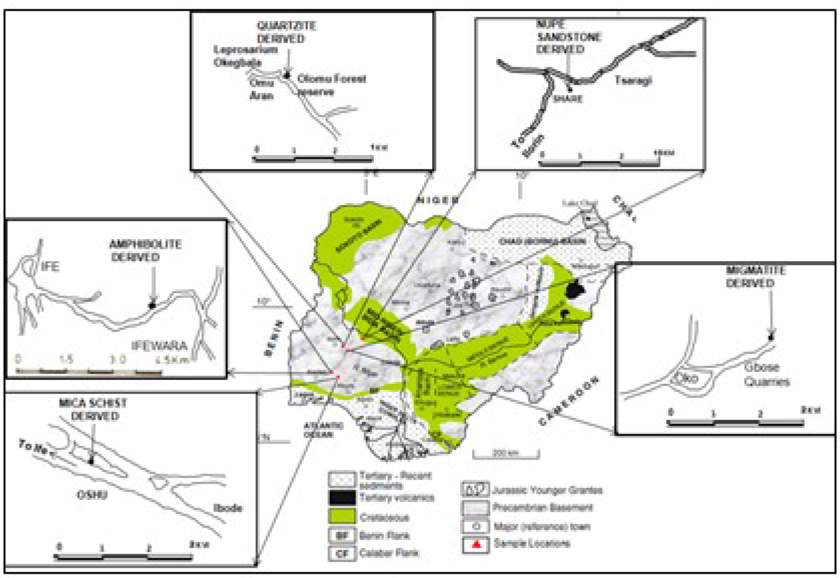

Figure 1. Geology map of Nigeria showing the sample localities (modified from Obaje[18])

2. Materials and methods

Field investigation was carried out within the study area to collect soil samples. A total of five samples with different parent rock were obtained in road-cut exposures of laterites soils in Omu-Aran, Osho, Ife-Ifewara, Share and Oko (Figure 1). The five lateritic soil samples, labelled QTZ, MCS, AMP, NPS and MIG were collected from the aforementioned locations are derived from quartzite, mica schist, amphibolite, sandstone and migmatite-gneiss, respectively. These rock types are among the most widespread rock types in these areas. The collected fresh soil samples were kept in a neat and labelled polythene bag. The samples were sun dried for 10 days to ensure removal of moisture content. The index properties of the soil including specific gravity, moisture content, linear shrinkage, bulk density and dry density determination, Atterberg limits and grain size analysis were determined in accordance with British Standard (BS 1377) test procedures. Other test carried out are dispersion test, swelling test, permeability test (falling head), standard and modified proctor compaction, California bearing ratio (CBR), direct shear test and mineralogy. Each geotechnical test was performed at least twice on the same soil sample under the same condition in order to determine the reliability of the geotechnical test results.

3. Results and discussion

3.1. Specific gravity

The summary of geotechnical tests results is presented in Table 1. The specific gravity of the soils range from 2.55 – 2.70. The obtained specific gravity values are indicative of a high degree of laterization of the soils [5]. Tuncer and Lohnes [8] noted that specific gravity is important in estimating the degree of weathering of soils. Rocks rich in heavy minerals weather to soils whose grains have high values of specific gravity. Also, soils that are rich in iron and titanium bearing compounds have high values of specific gravity. According to Ramamurty and Sitharam [20], the studied soils can be classified as inorganic soils based on the specific gravity. Amphibolite derived soil (AMP) has the highest value of 2.70, while Nupe Sandstone (NPS) derived soil has the least value of 2.55. The results place, in order of competence, solis derived from amphibolite (AMP), mignatitte (MIG) and quartzite (QTZ) as the more suitable in road and building construction when compare to other soil analyzed.

Table 1. Summary of geotechnical tests results of soil samples

Traverse	VES station	No of layers	Apparent resistivity (Ωm)	Thickness (m)	Depth to basement (m)
1	1	4	796/1883/903/4455	1.45/8.38/17.4/...	27.2
	2	4	120/522/685/1000	1.18/6.57/16.6/...	24.4
	3	4	74.2/415/755/2663	1.19/4.92/15.9/...	22.0
	4	4	742/1474/590/3026	1.28/5.17/13.4/...	19.8
	5	4	916/3871/1579/4780	1.47/11.8/8.38/...	21.6
2	6	4	613/3190/1018/4249	1.0/6.99/15.7/...	23.7
	7	4	461/850/554/5652	1.88/7.72/11.7/...	21.3
	8	4	231/1503/554/4080	1.13/8.09/12.0/...	21.2
	9	4	490/1699/922/6790	1.13/2.79/15.3/...	19.2
3	10	3	5426/2040/8849	2.31/15.2/...	17.5
	11	3	356/478/1000	0.5/6.05/...	6.6
	12	3	686/416/1570	2.17/4.76/...	6.9
4	13	4	2945/408/1818/4455	1.08/4.92/8.72	14.7
	14	3	1519/3334/7682	2.1/3.49/...	5.6
	15	3	2659/1279/7483	1.02/3.51/...	4.5
5	16	3	752/2353/5599	2.17/3.94	6.1
	17	3	3799/1264/6453	0.79/6.58	7.4
	18	3	1000/2259/5427	1.18/4.08	5.3
	19	3	110/736/5934	0.13/7.0/...	7.1

3.2. Grain size distribution

The grain size analysis was performed to determine the particle size distributions in the soil. The distribution of different grain sizes affects engineering properties of soil, which in turn influences their usability in construction works. The summary of grain sizes distribution parameters of the soil samples are shown in Table 2. It is evident from the Table 2 and Figure 2, sand and silt fractions are predominant in the particle size distribution of the soils. The mica schist derived soil (MCS) has the highest amount of fines (38%), while the amphibolite derived soil (AMP) has the lowest amount of fines (30%). The plot of the soils in the AASHTO classification system shows that the quartz schist (QTZ) and amphibolite derived soils (AMP) plotted in the A-2-6 field, Sandstone derived (NPS) and mica schist derived (MCS) soil falls under A-6, whereas migmatite gneiss derived soils (MIG) falls under A-2-7. All the soils are grouped as clayey silty sand based on the grain size fractions. FMWH [9] stipulated amount of fines is ≤

35% for use as sub-base materials. On the basis of this, the soils except MCS fall into the category and therefore they have good potential in the construction industry as they will be suitable for use as road sub-base material. Furthermore, various authors have affirmed that lateritic soil might be useful as landfill liners if the fine component is greater than 30% [13,21-30]. Thus, all the studied soils are useable as landfill in sanitary.

Table 2. Summary of the distribution of grains within soil samples

Sample	WC (%)	BD (kg/m^3)	SG	USC	Atterberg Limit	Compaction Test		Permeability, k (m/sec)
						Standard	Modified	
T1	1.3	1.28	2.55	SC-SM	LL= 39%; PL= 21%; Ip = 21%; FI= ; TI= AC=0.33 ; SL=	OMC = 16 %; MDD =1.8g/cm^3	OMC = 14 %; MDD =1.83g/cm^3	4.892 x 10^{-7}
T2	2.8	1.26	2.64	SC-SM	LL= 35%; PL= 21%; Ip =14% ; FI=22 ; TI=0.64; AC=0.28 ; SL=	OMC =16.5 %; MDD =1.73g/cm^3	OMC = 16 %; MDD =1.78g/cm^3	4.467 x 10^{-7}
T3	0.6	1.66	2.60	SP		OMC = 10 %; MDD =1.8g/cm^3	OMC = 9 %; MDD =1.83g/cm^3	1.361 x 10^{-6}
T4	3.7	1.38	2.66	SC-SM	LL=30% ; PL=18% ; Ip =21% ; FI= ; TI= AC= 0.33; SL=	OMC = 15.5 %; MDD =1.8g/cm^3	OMC = 14.5%; MDD =1.85g/cm^3	6.080 x 10^{-7}
T5	2.1	1.65	2.65	SC-SM	LL=30% ; PL=17%; Ip =13% ; FI= 25; TI= 0.5; AC=0.6 ; SL=	OMC =12 %; MDD =1.79g/cm^3	OMC = 11 %; MDD =1.82g/cm^3	1.101 x 10^{-6}
T6	5.9	1.35	2.60	SC-SM	LL= 34%; PL=23% ; Ip =11% ; FI= 25; TI= 0.6; AC=0.2 ; SL=	OMC = 16 %; MDD =1.7g/cm^3	OMC = 14 %; MDD =1.76g/cm^3	5.142 x 10^{-7}
BH1	14.6	1.82	2.55	SC	LL= 24%; PL=16% ; Ip = 7%; FI= ; TI= AC= ; SL=	OMC = ; MDD =	OMC = ; MDD =	
BH2	11	1.85	2.64	SC	LL=28% ; PL=17% ; Ip = 11%; FI= ; TI= AC= ; SL=	OMC = ; MDD =	OMC = ; MDD =	

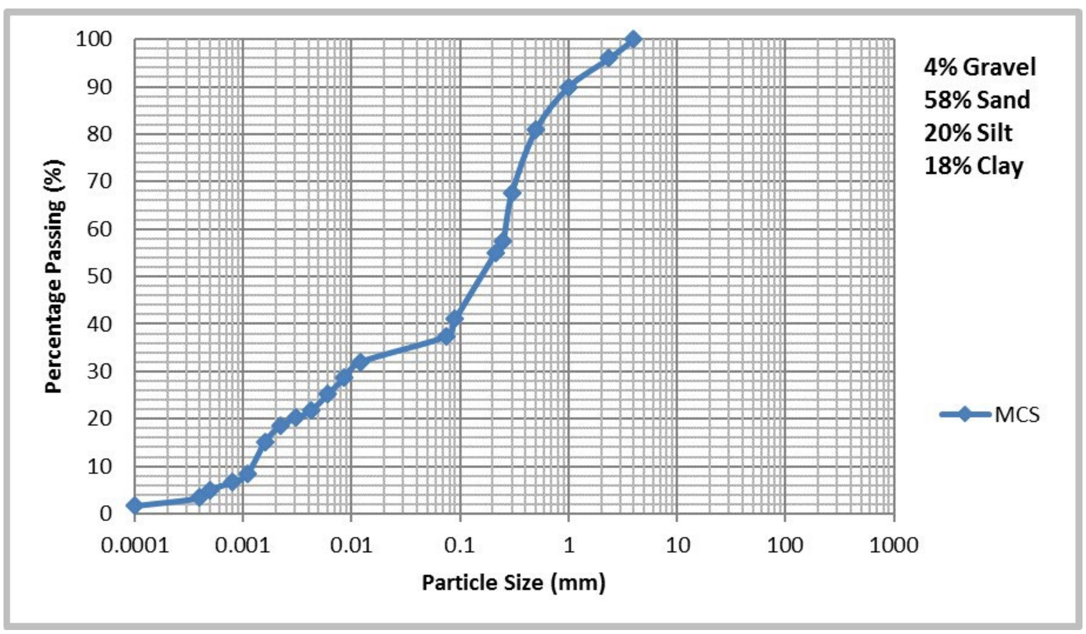

Figure 2. Typical grain size distribution curve for soil samples (MCS soil)

3.3. Atterberg consistency limits

The results of the Atterberg consistency limits and classification tests is presented in Table 1. The soils have liquid limit ranging between 29% - 41% and plasticity index between 13.8% – 19.6%. According to FMWH [9] specification, subgrade materials should have a liquid limit ≤ 50% and plasticity index ≤ 30%, while for subbase, liquid limit should be ≤ 30% and plasticity index ≤ 12%. According to Wright [30], the liquid limit values of 40% and above are assumed high in pavement construction. Furthermore, they reported that plasticity index value of 10% and above are also assumed high in pavement design. All the soils meet the requirement for use as subgrade materials since they have plasticity index values within the threshold. Atterberg limits are also important in the selection of materials for use as liners in landfill systems. Benson *et al.* [6] recommended that the liquid limit of the liner materials must be at least 20%. Most of the specification for soil liners proposed by various researchers or waste regulatory agencies does not generally prescribe any limit (maximum value) for the liquid limit [10-12]. As long as it does not create any working problem, soils with high liquid limit are generally preferable because of their low hydraulic conductivity [10,21]. The liquid limit of all the studied soil is higher than the minimum prescribed value. The value also falls within the range obtained by Ige [11,13], hence could be promising for use as barriers in landfill systems.

3.4. Clay activity (Ac)

The 'activity' of the soil samples can be calculated from the relationship between the plasticity index and percentage of clay in a particular sample by weight.

Ac = PI/ (% of clay-sized fraction by weight)

where A = Activity, PL = Plastic Index

The calculated 'activity' of the soils is shown in Table 1. The plastic properties of the soils result from the adsorbed water that surrounds the clay particles. This is directly related to the type of clay minerals and their amount in the soil, which in turn affect the liquid limit and plastic limit [21-23]. The clay activity results revealed that the soils exhibit activity Casagrande's plot which shows that the samples can be interpreted as inorganic clay of low plasticity (Figure 3), ranging from 0.5-2.1 and 0.7-2.2 for unstable and stable locations, respectively.

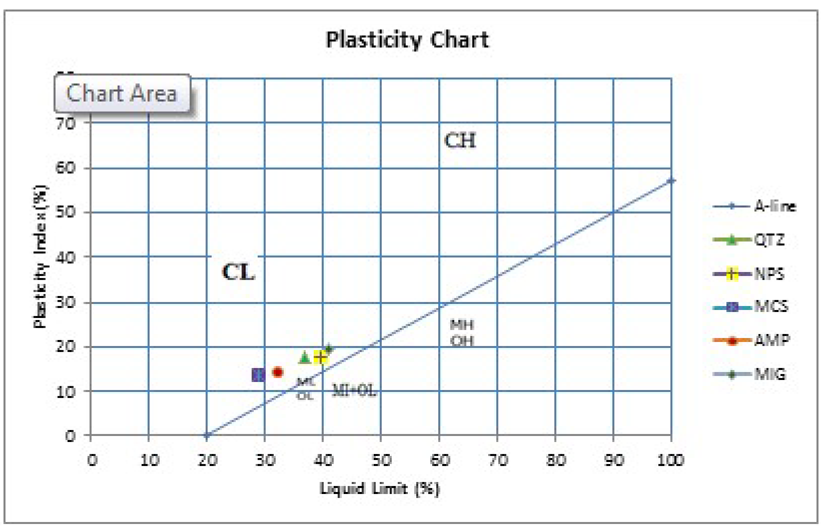

Figure 3. Positions of the soil samples in the Casagrande's plasticity chart

3.5. Free swell

Swelling soils are often deleterious when used directly in constructions works. This is because of the ability of these soils to absorb high moisture. Both the amount of swelling and magnitude of swelling pressure are known to be dependent on the clay minerals, the soil mineralogy and structure, fabrics and several physic-chemical aspects of the soil [24-26]. Based on the free swell test result shown in Table 1, the studied soil samples with the exception of sample MCS, tend to be non-expansive. The MCS soil had intermediate degree of expansiveness, which is probably due to the occurrence of Illite as one of its major minerals. Hence, it has to be subjected to some form of treatment before it can be utilized successfully in construction works.

3.6. Dispersive test

Soil gets dispersed and washed away in water. This process is termed as dispersiveness. Non-plastic nature of the soil particles and its inadequate inter-particles attraction causes dispersal. Dispersive property of soil cannot be identified by the standard laboratory index tests, such as visual classification, grain size analysis, specific gravity or Atterberg limits. In this study, crumb test, double hydrometer test and turbidity tests have been performed to identify dispersive clays. It is observed that MCS is highly dispersive, while MIG, NPS, QTZ and AMP tend to have intermediate-high dispersiveness. The presence of dispersive soils in the embankment dam or foundation has been said to be one of the factors contributing to failures in structures which are reasonably well engineered [2,16-17,26].

3.7. Compaction test

The compaction test result is presented in Table 1. It can be seen that the optimum moisture content (OMC) of the soils showed a decrease at the modified proctor energy when compared to the value at the standard proctor energy. At standard proctor compaction, the QTZ, MCS and MCS samples have the highest MDD of 1.81g/cm^3, 1.70g/cm^3 and 1.63g/cm^3, respectively. The AMP and MIG lateritic soils have the lowest, with equal MDD value of 1.57g/cm^3. At the energy of the modified proctor, the QTZ, MCS and NPS lateritic soils have the highest MDD of 1.85g/cm^3, 1.80g/cm^3 and 1.75g/cm^3, respectively. The AMP and MIG lateritic soils have the lowest MDD values of 1.65g/cm^3 and 1.64g/cm^3, respectively. The MIG lateritic soil has the highest moisture content of 18% at standard proctor energy, it also has the highest moisture content of 17% at modified proctor energy. The OMC serves as a guide to know the amount of water required during construction. Thus, MIG requires the highest water content on the field to achieve maximum dry density at low energy of compaction. However, the values generally fall within the values that were recommended by Baiyegunhi *et al.* [4], Ige [11,13], Ogunsanwo [14-15] and Jegede [17], for materials before they can be used fills in dams, building, and base course in road and liner in landfill.

3.8. Permeability test

The result of the co-efficient of permeability of the remolded soil samples is depicted in Table 1. The values of permeability co-efficient range from 10^{-8} to 10^{-11} m/s, which falls into the soils classified as impervious soils [21,27]. It is considered that such practically impermeable soils will be useful as fill materials in values much lower than $7.54\text{x}10^{-10}$ and 1.12×10^{-11} m/sec. Thus, this make the MSC and AMP samples most suitable as barrier in sanitary landfill dam constructions. Several researchers have also suggested a maximum coefficient of permeability value $1\text{x}10^{-9}$m/sec for landfill barrier soils [7,19,28-30].

3.9. California bearing ratio (CBR)

The Nigerian specification for roads and bridges as stipulated by FMWH [8] is a minimum CBR of 8% for sub-grade/fill, while the asphalt [1] stipulated CBR value of between 0% to 3% for sub-grade and 3% to 7% for sub-base. In align with the aforementioned values, the studied lateritic soils can be classified as having poor to fair CBR and can only be used as sub-grade and fill materials in highway construction. Highest CBR value was recorded in QTZ under unsoaked condition through modified proctor energy, while the least CBR value was recorded in MSC under soaked condition through standard proctor energy (Table 1). This may be connected to the ability of the clay mineral to absorb water. The MSC sample has illite as major mineral, which is responsible for it swelling and shrinking attribute.

3.10. Shear strength

The computed values of the undrained shear strength parameters, C and ϕ are shown in Table 1. For the shear tests carried out using samples compacted at standard proctor, the NPS lateritic soil has the highest cohesion value (45 kPa), while the AMP lateritic soil have the lowest cohesion value (25 kPa) at this same energy. At modified Proctor energy, the QTZ soil has the highest cohesion value (120 kPa), while the cohesion value of 30 kPa, which is the lowest was recorded for MCS, AMP and MIG lateritic soils. For lateritic residual soils, Mitchell and Sitar [21] reported that for compacted samples the majority of the friction angles range (ϕ) from 28° to 38° and cohesion values range (C) from 0 to 48 kPa. The results obtained in this study is close or similar to the values recommended by Mitchell and Sitar [16] for cohesion (C) and internal friction angle (ϕ) values.

3.11. Mineralogy

The minerals identified in the soils using X-ray diffraction are shown in Table 3. Soils that contain swelling clays minerals have been reported to have deleterious effects on the optimum utilization of these soils in engineering works.

Table 3. Summary of major and minor mineral identified in the samples

Sample symbol	Major minerals identified	Minor minerals identified
MCS	Quartz, Kaolinite, Illite	Hematite
QTZ	Quartz, Kaolinite	Feldspar
MIG	Quartz, Kaolinite	Feldspar, Goethite
NPS	Quartz, Kaolinite,	Hematite
AMP	Quartz, Kaolinite,	Hematite, Goethite

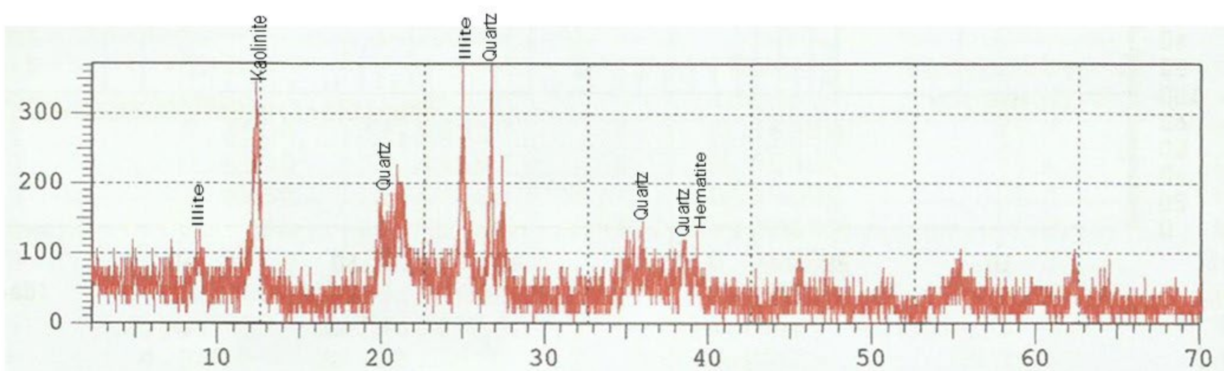

Figure 4. Typical x-ray diffractogram of the soil samples (MCS)

The dispersivity of a soil is directly related to its clay mineralogy [23]. The presence of dispersive soils in the embankment dam or foundation has been said to be one of the factors contributing factor to failures in structures which were reasonably well engineered [26-27]. Soils containing clay minerals such as montmorillonite tend to be dispersive, while those with kaolinite and related minerals (halloysite) are non-dispersive. Soils with illite tend to be moderately dispersive [24]. The xrd result shows that the analyzed five soil samples contain no undesirable mineral constituents except for MCS, which has illite as one of its major minerals, therefore making the soil less suitable in engineering works, particularly in dam construction due to its high swelling potential.

4. Conclusions

This study has investigated the principal engineering properties of lateritic soils derived from quartzite/quartz-schist, Mica Schist, Amphibolite, Nupe Sandstone and migmatite gneiss in parts of south-western Nigeria for their usability as engineering construction materials. Based on the geotechnical test results, AMP, NPS, QTZ and MIG soils could be used in dam and embankment construction, liners in landfill system, foundation and could also support the construction of drainage. MCS showed tendency to swell, shrink and disperse due to the presence of illite. Also, it can be inferred that the soils are limited in their potential for application as base course material in road construction due to their low values of CBR. However, the soils are still useable as subgrade materials. The soil properties such as permeability and strength generally reduces in soil samples with high amount of clay minerals. Furthermore, the suitability of the soil sample derived from different rock types in civil construction works is greatly influenced by the presence and type of clay mineral present.

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