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The Influence of Soil Mineralogy on the Failure of the A123 Ilorin – Lokoja highway, Nigeria

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Abstract

Due to incessant highway failures, the mineralogy, geological and geotechnical properties and behavior of the subgrades were investigated. Methods involved field sampling, geotechnical laboratory and x-ray diffraction analysis. Results show a complex mineral assemblage consisting of varying proportions of several clay and non-clay minerals with a general prevalence in kaolinite (0.9 – 57.3%) and quartz (3.4 - 87.3%). One-fifth of the soils contain 2:1 expansive clay minerals of the smectite (Na-montmorillonite) group, with at least 20% of each sample recording 10 – 30% of the expansive clay minerals in the failed highway sections. The maximum range of the 2:1 expansive clay was 14.0 – 22.0cts with a mean range of 7.2 – 9.7cts and standard deviation varying from 7.0 to 7.9 across the different rock terrains. The 2:1 expansive clay mineral of smectite group depicted weak and low bearing strength characteristics (CBR range of 1. 09–3.0%) natural bulk density of 720 kg/m^3 – 1010kg/m^3, maximum dry density (MDD) ranging from 670 kg/m^3 – 890kg/m^3 and optimum moisture content (OMC) varying from 7.75 – 18.75% and classifying as A6/7 AASHTO materials. Other clay minerals were identified and XRD analysis with mineralogical intensities range from 10cts – >15cts showed CBR strength as high as 12.28% and classifying as A-4 (silts) and A-2 AASHTO materials in stable highway sections.

Keywords: Clay minerals, Engineering properties, composite and permeable pavement.

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1. Introduction

The frequent need to evaluate and examine clay materials in soils for civil engineering projects was suggested by Reeves et al. (2006) and Murthy (2014) because the mineralogy of any parent rock has significant effects on the engineering properties and behaviour of their derived soils. The physical properties of soils are dictated by the size, shape, and chemical composition of the mineral grains (Das and Sobhan, 2014). The stability, weatherability and engineering behaviour of all constituent minerals of the parent rocks, relate to the temperature of crystallization of the melt from the magmatic reservoir. Scoffield and Wroth (1968) noted that reaffirming mechanical grading and index properties as the basis of soil classification, asserts that the influence of mineralogy, chemistry and origin of a soil on its mechanical behaviour is adequately measured by these simple index tests. However, research evidence has proven that such assertion is not completely true and relying on these index tests parameters alone is inadequate for the understanding and providing for the engineering behavior of the different classes of clays with their characteristic behavior. This has to led to premature failures in structures (Figure 1) as observed in works by Meshida, (2006), Teme et al. (1987), Adeyemi, (1992), Mohammed and Salami, (2013), and Osadebe *et al.* (2010). Each soil mineral type imparts signature characteristics and engineering behaviour of the clay fractions, therefore knowledge of the behavior of ideal minerals is useful in understanding the aggregate behavior of clays (Reddi and Inyang, 2000) in soils.

Figure 1: Some failed sections of the A123 Ilorin – Lokoja federal highway.

Whether sedimentary, igneous or metamorphic in origin, high crystallization temperature minerals of the Bowen's classification series (Bowen, 1922) are the most unstable and easily weathered (Gillot, 1968) and the condition of stability or otherwise transmit to the soils. Bowen's continuous series minerals namely calcic plagioclase, calcic- alkalic plagioclase, alkalic-calcic plagioclase, and alkali plagioclase together with K-Feldspars (Orthoclase); the mica group (Biotite and muscovite) and feldspathoids (Nepheline, Leucite) would weather and form the different types of clays in soils. Clays are phyllosilicates consisting of composite layers of Aluminum octahedron and Silica tetrahedron; with cations of Fe^{3+}, Fe^{2+}, Mg^{2+} or other trivalent ions (Reeves et al., 2006). They are very fine grained with no large crystals, electrochemically active with a small layer charge that allows for exchange of interlayer cation with very strong affinity for water (Gillot, 1986) composition al characteristics inherited from their parent rocks. The weathering product of the sodic plagioclase, Albite and the Feldspathoid, Nepheline results in the formation of Na-montmorillonite clay, the most problematic clay soil in the foundation of civil engineering structures (Abija, 2022).

Na-montmorillonite is a 2:1 clay with a very weak (Vander Waal) interlayer hydrogen bond and a hydrated Sodium Calcium Aluminum Magnesium Silicate Hydroxide $(Na,Ca)x(Al,Mg)_2(Si4O10)(OH)_2{\cdot}nH_2O$ (Grim, 1968; Theng, 1979) that give to it very high range of geotechnical properties such as liquid limit (100–900%), plastic limit (50–100%), shrinkage (8.5–15%) and activity (1 – 7) reported by Mitchell (1993**).** The 2:1 group of clays have two (2) silica sheets and one (1) alumina sheet bonded by an interlayer of water and or ions. They are characteristically of expansive types such as smectite and vermiculite. The smectites have expanding lattice that makes them highly susceptible to swelling. Their weak interlayer bonding allows water to form a spacing between the molecules of 10Å to 18Å (Grim, 1968; Theng, 1979**).** The interlayer spacing is highly amenable to water absorption, expansion and swelling upon wetting; and shrinkage when dry. The structural layers of swelling clays (smectites) are always deficient in positive charges due to cation substitution, and interlayer cations are required to balance the negative layer charge. Interlayer cations are exchangeable and the exchange is reversible for simple cations. When the exchangeable cations are hydrated and water molecules enter the space between the structural layers, the distance between two structural layers increases and the volume of the clay expand. The smectite group includes Aliettite, Beidellite, Hectorite, Montmorillonite, Nontronite, Saponite, Sauconite, Stevensite, Swinefordite, Volkonskoite, Yakhontovite, and Zincsilite. The second group of 2:1 clay is non-expansive and includes illite, mica, muscovite, pyrophyllite, talc and chlorite types. The calcic plagioclase feldspars (Anorthite, Bytownite, Labradorite etc.) weathers into non-expansive 2:1 Ca-montmorillonite group of clays. Similarly, the illite group of clays (2:1) are the weathering products of micaceous minerals. The weathering products of potassic-feldspar, Orthoclase and feldspathoid, Leucite form the 1:1 Kaolinite group of clays. They consist of one (1) silica tetrahedron and one (1) alumina octahedron with a hydrogen interlayer bond. Mixed layer clays such as 2:1:1 could also coexist in the soils further complicating the material composition and behavior when admixed with water. Due to their ubiquity, clays also constitute the most abundant and dominant mineral in soils and a major design factor in the engineering behaviour of weathering products of rocks. Clay water interaction in any soil increases its plasticity, shrinkage, swell potential, compressibility and decreases its permeability and shearing resistance (Abija *et al.*, 2019). It's response to load as a construction and foundation material under its natural consistency, affects the serviceability performance of any civil engineering structure. Terzaghi (1939) noted that in engineering practice, difficulties with soils are almost exclusively due not to the soils themselves, but to the water contained in their voids. The progressive interactions that can occur in a clay-water system include hydration, dispersion (or disaggregation), flocculation and deflocculation; and aggregation. This is exacerbated by the global climate induced rise in rainfall and flooding of the roadbed under cyclic extreme weather events. Water in road bed leads to increased unit weight under saturated conditions, reduced shear strength, excess pore water pressures, increased seepage pressure and reduced effective stress constituting the major culprit in road failures (Abija *et al.*, 2019**).** Geotechnical failures are the consequences of not recognizing and or adequately evaluating site geologic and geotechnical conditions as input into the design and construction of the road. Such inadequacy in any subsurface engineering was also observed by McNeilan and Smith (2014), to affect the management of risk and uncertainty of site and subsurface conditions and site variability, applicability of assumptions in design methods and quality of the constructed in ground foundations; and choice of foundation type, capacity of the foundation, foundation construction methods and cost**.** The identification of potential problem soils along a highway route is a primary objective of the pavement geotechnical design because pavements are characteristically linear structures that traverse different terrain morphological features, hydrological and soil and or rock types along the route. This research evaluated the effect of the parent rocks on the soil mineralogy and their derived engineering properties and behavior along failed sections of the studied highway.

2. Geologic and Geohydrologic Setting of the Study Area

The Ilorin-Kabba section of the A123, Ilorin - Lokoja highway is located within latitude 7°25'N - 8°40'N and longitude 4°30'E – 6°45'E covering an approximate area of 15,612km^2 (Figure 2). The study area is underlain by the Precambrian rocks of the Basement Complex, composed of the migmatite-gneiss complex intruded by banded gneiss, meta-sedimentary suite and meta-volcanic schists and the Older Granites rocks believed to be pre -, syn- and post-tectonic rocks, which cut both the migmatite-gneiss-quartzite complex and the schist belts **(**Oyinloye, 2011). The highway also sits on these Precambrian Basement complex rocks and cuts across three lithologic units: the migmatite - gneiss complex, the meta-sediments, and the older granite series (NGSA, 2004). Predominantly, by it is underlain migmatite – gneiss composed of migmatite and banded gneiss along the highway route (Figure 3).

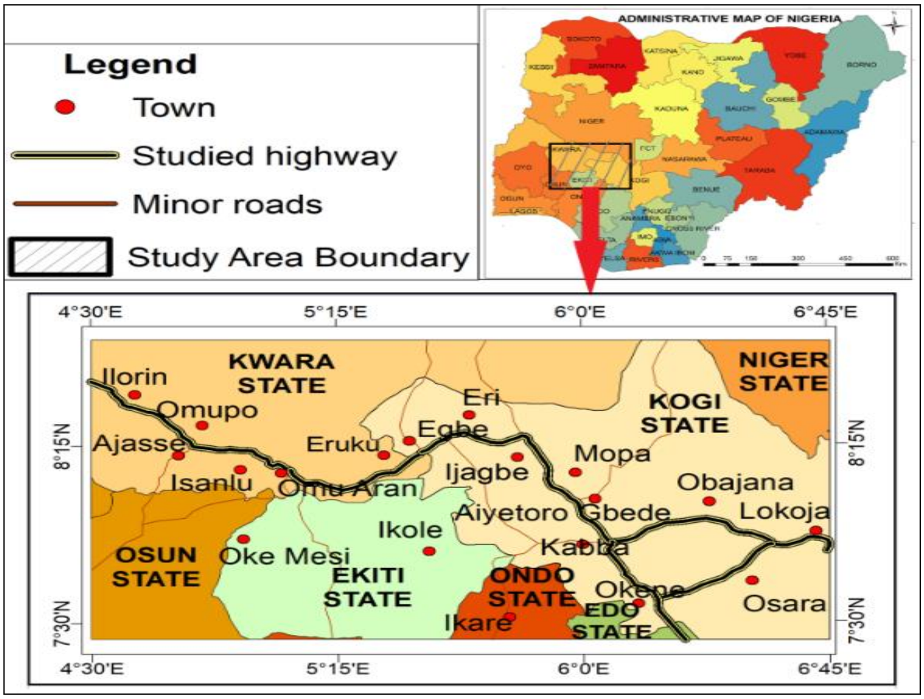

Figure 2: Administrative Map of the study area

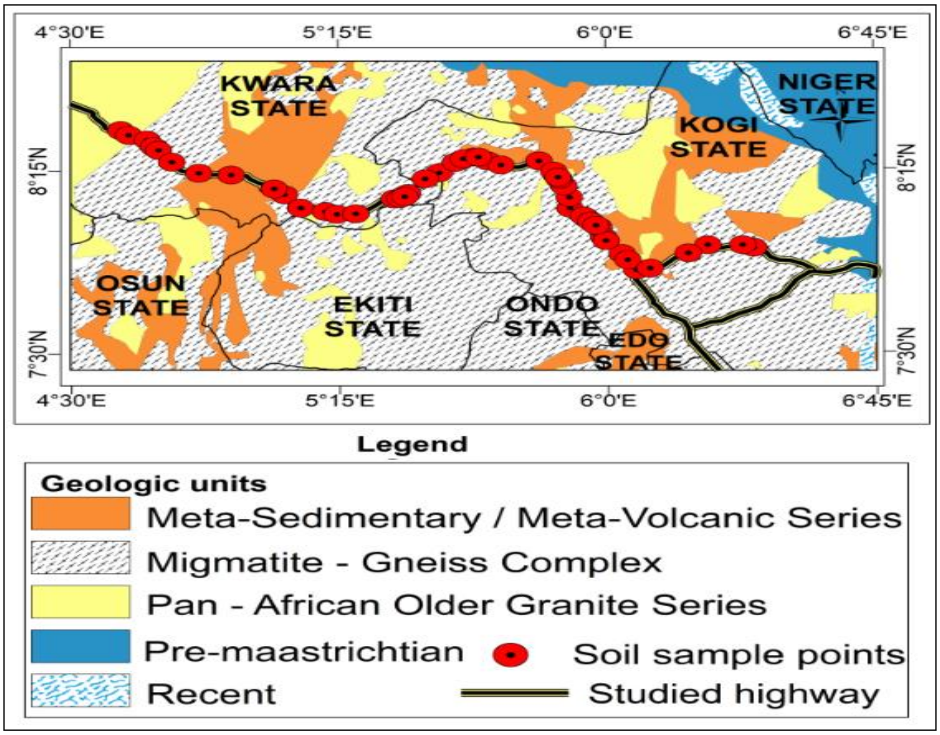

Figure 3: Geologic map of the study area extracted from geologic map of Nigeria (NGSA, 2004)

Other rock types include flaggy quartzite with biotite gneiss, undifferentiated schists, porphyritic granite (porphyroblastic), and medium to coarse-grained biotite and hornblende granite. Two main widespread types of gneisses common in the area are the fine-grained biotite gneiss with strong foliation and the banded gneiss earlier reported by Adekeye and Akande (2006). The Older Granites occur as large circular masses within the schists belt and the older migmatite-gneiss complex which represent a lasting magmatic cycle associated with the Pan African orogeny. Their rock type consists of diorites, granodiorite, granitoid, and charnockites which do not host any form of mineralization and are classified as migmatite granite; granite gneiss; pegmatite and fine-grained granite; homogenous to coarse porphyritic granite; two-mica granites and vein quartz. Older granite rocks are dark, greenish-grey granites with significant quantities of olivine, pyroxene, quartz, feldspar and micas (Figures 3 and 4) (Oyawoye, 1972).

Quartzite

Pegmatite outcrop

Fractured Quartzite outcrop

Migmatite Gneiss outcrop

Figure 4: Pictures of some rock exposures in the study area.

The Schist Belts comprising of metasedimentary and metavolcanic rocks are composed of low-grade metasediments-dominated belts that trends N-S in the western part of Nigeria. These belts are considered to be Upper Proterozoic supracrustal rocks which have been in-folded into the migmatite-gneiss-quartzite complex. The lithology is comprised of coarse to fine-grained clastics, pelitic schists, phyllites, banded iron formation, carbonate rocks and mafic metavolcanic amphibolite (Rahaman, 1976; Grant, 1978). Migmatite-Gneiss Complex occupies about 60% of the surface area of Nigeria basement and records three major geological events (Rahaman and Lancelot, 1984). The earliest at 2,500 Ma, involved crust forming process (e.g., the banded Ibadan grey gneiss of mantle origin), followed by the Eburnean at 2,000 ± 200 Ma, marked by Ibadan granite gneisses and then came the imprint of the Pan African event in the range age 900 to 450 Ma which gave rise to granite gneisses, migmatite and other lithological units (Figure 4). The geomorphology (Figure 5) depicts ground elevations in the study area to vary from 200 to 800m above mean sea level ranking moderately high to high elevation. The climate is dry to wet, described as hot humid and categorized as Zone 3 of Nigeria's climatological zones. Geohydrologically, the area is drained by the tributaries of the Niger and Benue rivers. Groundwater is controlled by rock fracturing and the thickness of the weathered zoned which porosity influences transmissivity and storage. Rainfall which range ranges from 1,183 – 1,786 with mean annual rainfall of 1200mm (FMR, Highway Manual Part 1, 2013) in the region constitute the main source of groundwater recharge with contributions from streams and rivers.

3. Materials and methods

3.1 Field Investigations

Field observations, descriptions and documentation of rock exposures, local geology of the area (Figure 5) and identification as well as the georeferencing of failed and stable sections of the studied road were carried out in the months of May - June, 2019. The soil strata from excavated borrow pit were studied. Soil sampling was done through auger boring to a representative depth of 1.2m within which subgrade behaviour has influence on pavement response and for sample collection. Care was taken to ensure that a distance of 5 – 10m away from the highway right of way was maintained to prevent sampling from borrowed filled fills during construction. Trial pits were also dug to expose the subsurface for visual examination of the soil profile variation within the 1.2m – 1.5m. The boring and trial pit locations were selected at intervals of 3 – 5km distance both at stable and failed sections. Visual examination, description of fresh soil samples and the variability of the ground mass were noted at locations especially where changes were observed on soil strata. In addition, vertical variations in soil profile were observed in areas where construction activities had occurred with apparent cuttings and open excavations. Soil samples were, however, not taken from areas where construction works and man-made deposits were seen to avoid influence on the natural soils. Furthermore, sample locations on bedrocks, inaccessible valleys/hills, marshy areas or reserved areas were rejected and replaced with other locations. Strategic soil sampling collection followed a 3 by 5km interval distance (Figure 3) at a depth of 0.8 – 1.5m from both failed and stable portions of the highway with coordinates readings of each sample point. All soil samples were carefully labeled in sample bags to prevent contamination and loss of moisture. Prior to laboratory analyses, the soil samples were air-dried at 30 – 35^{o}C for two weeks and gently sieved with 2mm sieve. Fifty soil samples were collected from 5m – 10m distance away from the highway right of way to ensure the trial pits are from borrowed fills used during construction.

Figure 5: Geomorphology of the study area showing some rock exposures.

3.2 Laboratory Analyses

Geotechnical analysis of the soil samples was carried out at the laboratory of the Nigerian Building and Road Research Institute (NBRRI). The analyses of the clay fraction were done by the hydrometer method while wet sieving was used for the other fractions. Classification and index tests were carried out in accordance with BS 1377 (British Standard, 1990). Soil activity (Ac) was obtained as the ratio of the plasticity index to clay fraction. Heavy compaction test - maximum dry density (MDD), optimum moisture content (OMC) and California Bearing Ratio followed modified Standard Proctor method as specified by the BS 1377 (British Standard, 1990). Mineralogical and spectroscopic analyses were conducted at the Department of Chemical Sciences Laboratory, University of Johannesburg, Doornfontein Campus, South Africa. The soil sample pool was formed by 89 soil samples in Section A, and 42 samples in Section B from 30 – 60, 60 – 150cm depth at intervals of 3 – 5 km. All soil samples were air – dried (35 – 40^{o}C) for two weeks to allow for partial removal of natural water for further analysis and sieved to 2mm. The X-ray diffraction (XRD) analysis was carried out on each soil sample using Bruker D8 Advance X-ray diffractometer with monochromatic Cu- $K\alpha_1$ radiation ($\lambda = 1.54$Å) in the range of 10° and 90°. XRD is a rapid analytical technique used extensively for phase identification of crystalline materials based on constructive inference of X-ray and crystalline sample. The diffractograms with the corresponding intensity and 2θ were analyzed using Match 3 software packages for pattern fitting with established Mineral Power Diffraction File Data Book (ICDD, 2001).

4. Results and Discussions

4.1 Soil Mineralogical characterization

The result of the mineralogical analysis is presented Table 1 and Figures 6a - d, while Table 2 presents the statistical summaries on the basis of the geology of the area. The result shows a complex mineral assemblage consisting of varying proportions of several clay and non-clay minerals with a general prevalence in kaolinite of (0.9 – 57.3%) and quartz of (3.4 - 87.3%) which agrees with findings of many researchers including Ige (2015). The X-ray diffraction analytical results of the samples from the failed sections depicted a preponderance of 2:1 expansive clay type as exemplified by sample A15 with abundance of smectite, nontronites (Figure 6a); sample A23 has smectite (Figure 6c) and sample A70 with vermiculite (Figure 6d) clay minerals which would form water retaining sites and resulting in shrink and swell over seasonal wetting and drying cycles. The plagioclase feldspar was found to be mostly Na- montmorillonite (albite) mineral with one-fifth of the soils contain 2:1 smectite (Na-montmorillonite) clay minerals and at least 20% of each sample recorded 10 – 30% of the expansive clay minerals (Table 1) particularly around Yagba, Ijagbe and Mopa areas which indicated failed highway sections. Table 2 also indicates that the maximum range of the 2:1 expansive clays was 14.0 – 22.0cts with a mean range of 7.2 – 9.7cts and standard deviation varying from 7.0 to 7.9 across the different terrains The expansive soils formed sites of water absorption, swelling and shrinkage engendering causative failure mechanisms such as increased unit weight, reduced shear strength, excess pore water pressures, increased seepage pressure and reduced effective stress. The non-expansive clays were dominated by 1:1 kaolinite and 2:1 clay mineral such as leucite, labradorite etc. and the K-feldspar was dominantly orthoclase.

The metasediments/metavolcanic terrain derived soils indicated a Smectite $(Na,Ca)([Mg,Fe]Al_3)[Si_8O_{20}](OH)$ - minimum of 4.4, maximum - 22.0 with a mean of 9.7 and standard deviation of 7.0. The Migmatite-gneiss complex terrain derived soils indicated smectite minimum of 0.1, maximum of 23.2 with a mean of 8.7 and standard deviation of 7.8. The Pan African Older Granitoid terrain derived soils showed a minimum smectite 0.2cts, maximum of 14.8 with average of 7.2 and standard deviation of 7.8. The standard deviation values indicate a general clustering around and closeness the mean x-ray diffraction mineralogical intensities in samples from all the geological terrains.

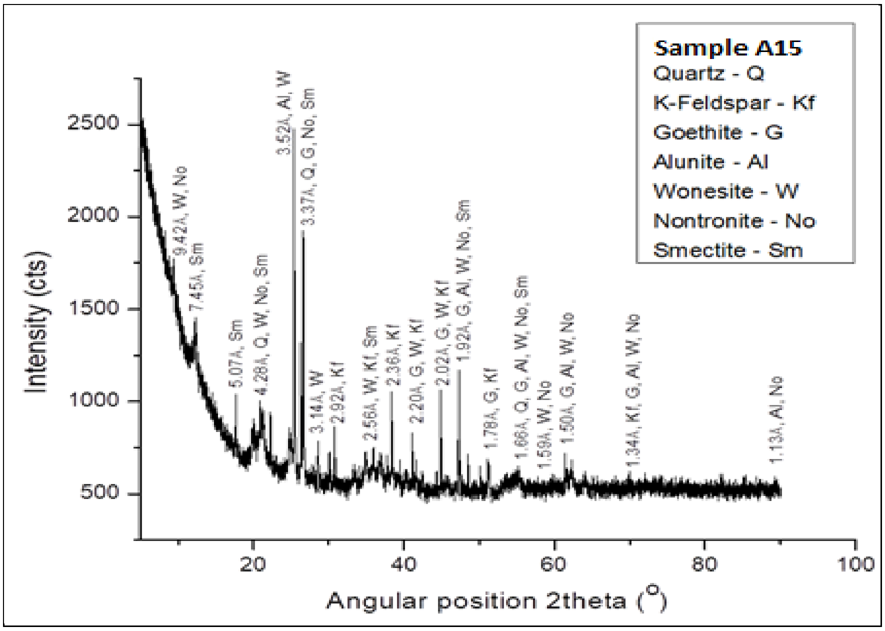

Figure 6a: Diffractogram of the A15 sample from Undifferentiated Schist with 2:1 expansive clays typifying materials from the failed highway sections.

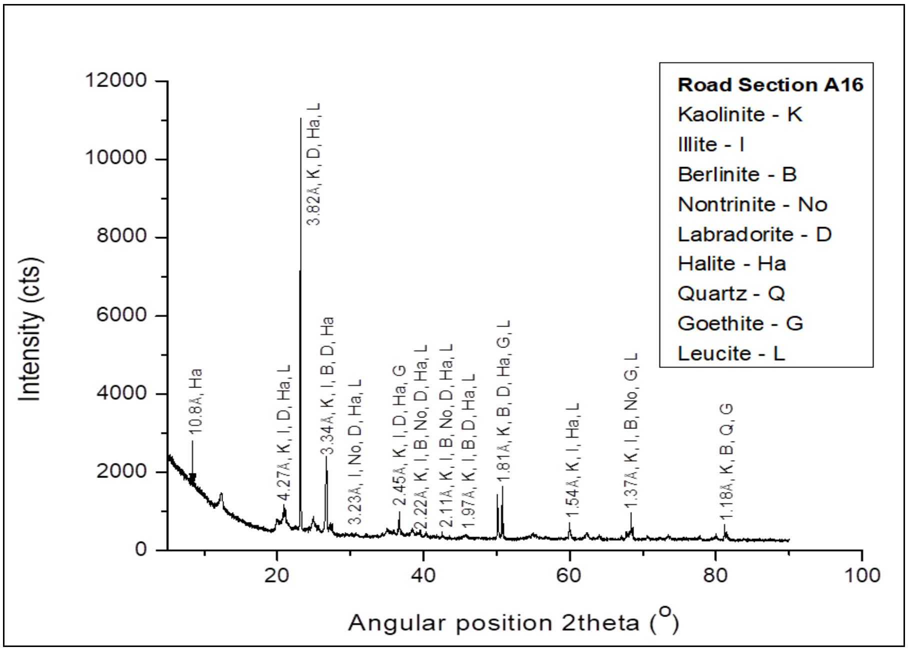

Figure 6b: Diffractogram of the A16 soil sample from a Quartzitic gneiss rock terrain 1:1 and 2:1 non-expanding clays).

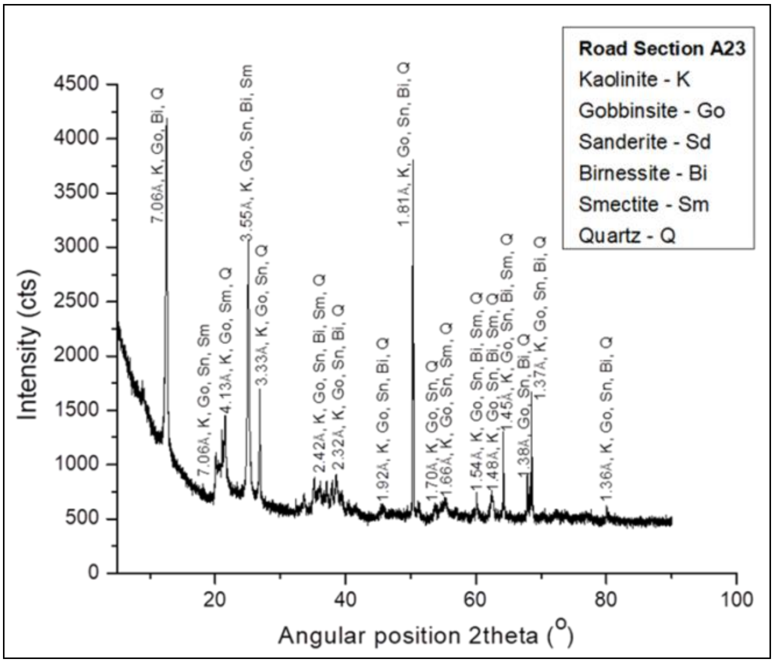

Figure 6c: Diffractogram of Porphyritic granite showing 1:1 kaolinite dominance admixed with 2:1 expansive smectite minerals.

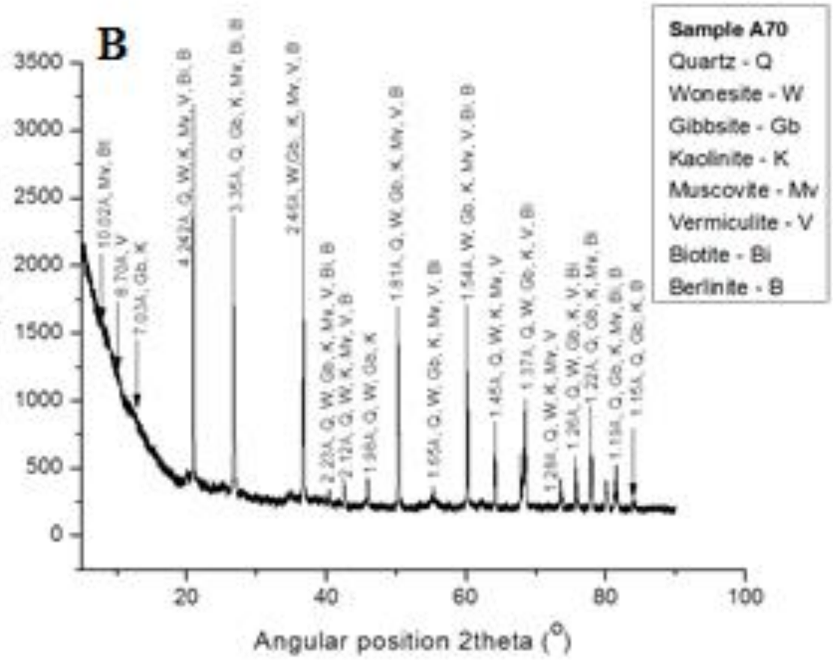

Figure 6d: Diffractogram of Biotite & Hornblende granite derived soil 1:1 kaolinite non-expanding clay dominance mixed with 2:1 expansive vermiculite minerals, the active swelling sites upon wetting.

Table 1: X-ray diffraction analysis showing abundance of different minerals in the soil samples.

Sample No	Major (>30%)	Moderate (10 – 30%)	Minor (2 – 10%)	Trace (<2%)	Expansive or non-expansive dominance
A1	-	Quartz, Pyrophyllite, Chlorite, Goethite, Plagioclase	-	-	Non-expansive
A2	-	Quartz, Kaolinite, Plagioclase, Calcite	Berlinite	Smectite	Non-expansive with <2% of expansive clays
A4	Pyrophyllite	Kaolinite, Plagioclase, K-Feldspar	Quartz	-	Non-expanding clay
A5	Chlorite	Quartz, Berlinite, Graphite	-	-	Non-expansive dominance
A6	Berlinite, Illite	Kaolinite	Quartz	-	Non-expansive dominance
A9	Kaolinite	Quartz, Berlinite, Calcite	Goethite	-	Non-expansive clay
A12	Kaolinite	Quartz, Pyrophyllite, Berlinite	Goethite, Calcite	-	Non-expansive clay dominance
A15	Quartz	Goethite, K-Feldspar	Smectite (Nontronite), Alunite, Illite, Zeolite	-	Mixed non-expansive with <2% of expansive clays
A16	Kaolinite	Illite	Quartz, Plagioclase, Berlinite, Smectite (Nontronite), Calcite	K-Feldspar, Goethite	Mixed non-expansive with 2-10% of expansive clays
A19	Kaolinite, Plagioclase	Quartz, Smectite	-	-	Mixed non-expansive with 10 – 30% of expansive clays
A22	Plagioclase	Kaolinite	Quartz	Smectite	Mixed non-expansive with <2% of expansive clays
A23	Kaolinite, Plagioclase	Quartz, Alunite	Smectite (Montmorillonite)	-	Mixed non-expansive with 2-20% of expansive clays
A25	Quartz	Chlorite, Illite	Pyrophyllite, Berlinite	Kaolinite, Smectite	Mixed non-expansive with <2% of expansive
A30	Quartz	Kaolinite, Illite	Plagioclase, Smectite	-	Mixed non-expansive with minor of expansive clays
A31	Pyrophyllite	Quartz, Kaolinite, Berlinite	K-Feldspar	Plagioclase, Illite	Non-expansive
A34	Quartz	Kaolinite, Illite	Pyrophyllite, Chlorite, K-Feldspar	Plagioclase, Smectite	Mixed non-expansive with traces of expansive clays
A36	Quartz, Kaolinite	Zeolite	Plagioclase, Calcite	-	Non-expansive
A38	Kaolinite	Quartz, Chlorite, Smectite	Illite	-	Mixed non-expansive with 10-30% of expansive clays
A40	Kaolinite	Quartz, Plagioclase, Illite, Berlinite	Goethite, Smectite	-	Mixed non-expansive with 2-10% of expansive clays
A43	Quartz	Plagioclase, Berlinite, Smectite	-	-	Mixed non-expansive with 10-30% of expansive clays
A45	K-Feldspar	Quartz	Kaolinite, Illite	Chlorite	Non-expansive
A48	Illite	Quartz, Pyrophyllite, Berlinite	Chlorite	K-Feldspar	Non-expansive clay
A52	Plagioclase	Quartz, K-Feldspar	Kaolinite, Pyrophyllite	Smectite, Berlinite	Mixed non-expansive with <2% of expansive clays
A55	Kaolinite, Berlinite	Quartz, Alunite	Illite	-	Non-expansive

A57	Kaolinite	Quartz, Plagioclase, Berlinite	Illite, Smectite	-	Mixed non-expansive with 2-10% of expansive clays
A60	Kaolinite	Quartz, Plagioclase	Pyrophyllite	Chlorite	Non-expansive
A63	Quartz	-	Kaolinite, Berlinite	Pyrophyllite, Plagioclase	Non-expansive
A64	Berlinite	Quartz, Kaolinite	-	Smectite, Alunite, Calcite	Mixed non-expansive with <2% of expansive clays
A67	Quartz	Kaolinite	Chlorite	K-Feldspar	Non-expansive
A69	Quartz	Chlorite	Kaolinite	Smectite, Goethite, Illite	Mixed non-expansive with <2% of expansive clays
A70	Quartz	Illite, Smectite	Kaolinite, Berlinite	-	Mixed non-expansive with 10-30% of expansive clays
A71	Quartz	Chlorite, Smectite	-	K-Feldspar	Mixed non-expansive with 10-30% of expansive clays
C81	Quartz, Berlinite	Plagioclase	Smectite	-	Mixed non-expansive with 10-30% of expansive clays
C82	Kaolinite	Quartz, Berlinite	Plagioclase, Chlorite, Smectite	-	Mixed non-expansive with 10-30% of expansive clays
C83	Quartz	Pyrophyllite	Berlinite	Alunite, Smectite	Mixed non-expansive with <2% of expansive clays
C84	Quartz	Kaolinite, Zeolite	Plagioclase, Smectite, Goethite	-	Mixed non-expansive with 2-10% of expansive clays
C85	Kaolinite, Chlorite	Quartz, Illite	-	-	Non-expansive clay
C86	Quartz	Kaolinite, Alunite, Berlinite	-	-	Non-expansive clay
C87	Quartz	Kaolinite, Berlinite	Pyrophyllite, Calcite	-	Non-expansive clay
C88	Kaolinite	Quartz, Smectite, Zeolite	Plagioclase, Illite	-	Mixed non-expansive with 10-30% of expansive clays
C89	Berlinite	Plagioclase	Quartz, Pyrophyllite, Illite	Kaolinite, Alunite	Non-expansive clay
C90	Kaolinite	Quartz, Smectite, Berlinite	Alunite	-	Mixed non-expanding with 10-30% of expansive clays
C91	Kaolinite	Quartz, Illite, Smectite	Alunite, Berlinite	-	Non-expansive clay
C92	Quartz, Pyrophyllite	-	Kaolinite, Illite	-	Non-expansive clay
C94	Plagioclase	Quartz	Kaolinite, Illite, Feldspar	-	Non-expansive clay
C95	Quartz	Kaolinite, Berlinite	Chlorite, Plagioclase	-	Non-expansive clay
C97	Quartz, Kaolinite	Illite	K-Feldspar	-	Non-expansive clay
C98	Chlorite	Quartz, Smectite	-	Berlinite	Non-expansive clay
C99	Quartz, Kaolinite	-	Goethite	-	Non-expansive clay
C100	Quartz	Kaolinite, Illite, Berlinite	-	-	Non-expansive clay
A16	Kaolinite	Illite	Quartz, Plagioclase, Berlinite, Smectite (Nontronite), Calcite	K-Feldspar, Goethite	Mixed non-expansive with 2-10% of expansive clays
A19	Kaolinite, Plagioclase	Quartz, Smectite	-	-	Mixed non-expansive with 10 – 30% of expansive clays

Table 2: Summary of mineralogical contents in the soil samples from the study

Geologic environment	Statistical parameters	Kaolinite (Al$_2$(Si$_2$O$_5$)(OH)$_4$	Pyrophyllite Al$_2$Si$_4$O$_{10}$(OH)$_2$	Chlorite Al$_2$(Mg,Fe)$_5$SiO$_{11}$(OH)$_2$	Illite K$_{1.5}$Al$_4$(Si$_{6.5}$,Al$_{1.5}$)O$_{20}$(OH)$_4$	Smectite (Na,Ca)([Mg,Fe]Al$_3$)[Si$_8$O$_{20}$](OH)$_4$	Quartz SiO$_2$	Plagioclase (Ca,Na)Al$_{1.2}$Si$_{3.2}$O$_8$	K-Feldspar KAlSi$_3$O$_8$	Berlinite AlPO$_4$	Alunite Al$_3$H$_6$K$_{0.8}$Na$_{0.5}$O$_{14}$S$_2$	Goethite FeOOH	Calcite CCa$_{0.9}$Mg$_{0.1}$O$_3$	Zeolite Mg$_2$Na$_7$(Si,Al)$_{12}$O$_{48}$
MIGMATITE-GNEISS COMPLEX TERRAIN	Minimum	0.9	0.1	1.0	0.8	0.1	3.4	0.7	0.9	1.5	0.2	3.1	0.8	11.9
	Maximum	57.3	51.0	55.3	40.3	23.2	87.3	78.7	21.6	69.3	12.3	9.1	17.2	18.9
	Mean	22.9	18.7	18.4	14.3	8.7	28.9	20.9	7.4	22.8	4.7	6.1	9.0	15.4
	SD	14.1	15.4	20.2	12.7	7.8	23.4	20.4	8.4	18.4	5.0	3.0	11.6	4.9
META-SEDIMENT / META-VOLCANIC SERIES TERRAIN	Minimum	4.3	5.7	1.4	2.8	4.4	3.6	2.5	0.8	1.3	4.4	1.3	4.0	6.1
	Maximum	50.5	17.9	22.1	28.8	22.0	58.3	32.2	63.5	34.6	16.4	10.9	7.9	17.5
	Mean	31.5	11.8	10.8	15.7	9.7	26.2	10.7	20.0	14.2	9.7	6.7	6.4	11.8
	SD	13.4	8.6	10.5	10.7	7.0	16.8	14.3	25.7	11.1	6.1	4.3	2.1	8.1
PAN AFRICAN OLDER GRANITOID	Minimum	5.9	5.4	10.6	0.2	0.2	13.6	23.7	1.9	2.1	13.6	1.1	8.1	-
	Maximum	29.3	28.9	26.1	17.8	14.8	82	27.2	1.9	13	13.6	18.7	20.7	-
	Mean	17.4	17.2	17.3	9.0	7.2	47.5	25.5	1.9	8.5	13.6	9.9	14.4	-
	SD	10.1	16.6	8.0	12.4	7.9	23.6	2.5	-	4.8	-	12.4	8.9	-

Table 3: Summary of geotechnical properties of soils

	Sand %	*Silt %*	*Clay %*	*LL %*	*PL %*	I_p *%*	W_n *%*	*Ac*	*OMC %*	*MDD kg/*m^3	*CBRu %*	*CBRs %*
Minimum	44	10.2	10	16.5	4.7	3.8	2.4	0.1	8.12	0.89	2.08	1.09
Maximum	85	50.8	71	53	36.9	24.4	22.7	8.5	25	2.61	30.4	12.3
Range	41	40.6	61	36.5	32.2	20.6	20.3	8.4	16.9	1.72	28.3	11.2
Mean	63.2	20.8	31.2	31.3	17.3	13.8	12.0	1.85	14.5	1.68	8.69	3.87
Standard Deviation	9.89	8.95	13.8	8.87	6.84	4.79	4.23	0.32	3.76	0.23	6.19	2.60
CL	2.81	2.54	3.93	2.52	1.94	1.36	1.32	1.34	1.07	0.07	1.76	0.74

4.2 Geotechnical Properties

The X-ray diffraction analysis depicts that 46% of the total soil samples and 100% of samples from the failed highway sections are composed of 2:1 expansive clay mineral of the smectite (Na-montmorillonite) constituting one-fifth of the soils with at least 20% of each sample recording 10 – 30% of the expansive clay minerals. The maximum range of the x-ray diffraction mineralogical intensities of the 2:1 expansive clay was 14.0 – 22.0cts with a mean range of 7.2 – 9.7cts and standard deviation varying from 7.0 to 7.9 across the different rock terrains. These 2:1 expansive clay mineral depicted weak and low bearing strength characteristics with a soaked California Bearing Ratio range of 1. 09–3.9% (figure 7), natural moisture content varying from 2.4% to 2.6%, bulk density ranging from 800kg/m^3 to 1010kg/m^3, moisture-density variation parameters depicting a maximum dry density (MDD) range of 670kg/m^3 to 890kg/m^3 and optimum moisture content of 7.75% to 14.0% upon com paction (figure 8a); clay content from 15% – 70% with activity ranging from, 0.18 (inactive and insensitive) to 1.4 (active and sensitive) (Skempton, 1953) the degree of soil mixing accounting for the limit of activity, liquid limit 16.5 to 26.4%, plasticity index of 3.8% to 11.8% and classifying as A-2-6, A6 and A7 AASHTO unsuitable materials occurring in the migmatite-gneiss rock terrains and their weathering products (Table 3) (Abija et al. 2024). The mixed mineralogical assemblages impacted on the geotechnical properties range which statistical data corroborate variability in some of the high results of the standard deviation. Subgrade materials which occur in the meta-sediments/meta-volcanic and Pan African granitoid terrains were dominantly 1:1 kaolinite non-expansive clay and the moisture density relationship is presented in figure 8b. These soils have higher range suitability geotechnical design parameters such as natural moisture content varying from 5% to 22.5%, bulk density ranging from 1.4kg/m^3 to 2.14kg/m^3, moisture-density variation parameters depicting a maximum dry density (MDD) range of 1380 to 1890kg/m^3 and optimum moisture content of 4.0% to 32.0% upon com paction (figure 7a); clay content from 10 – 15% with activity ranging less than 0.7; liquid limit as high as 53.0%, plastic limit as high as 36.9%, plasticity index as high as 24.4% and CBR as high as 12.28% and classifying as A1 to A-2-4 AASHTO subgrade materials which is reflected in the lower number of failed sections of the highway.

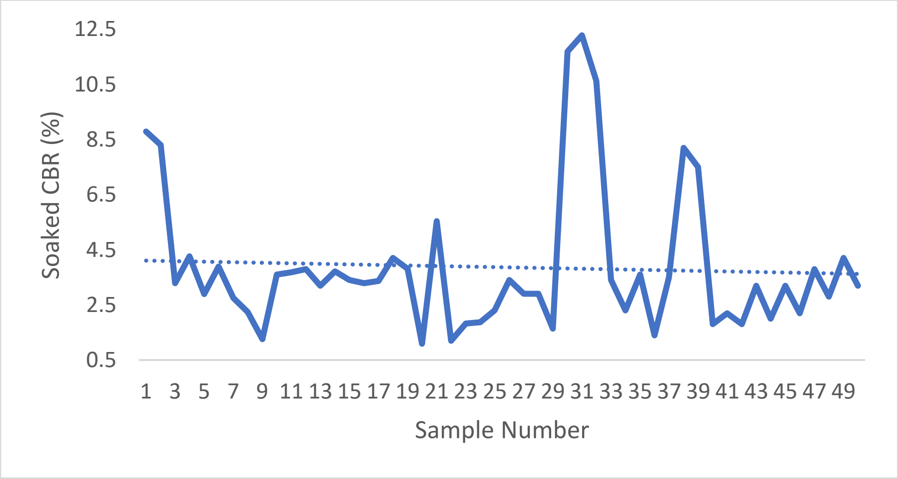

Figure 7: Soaked CBR of samples from the study area

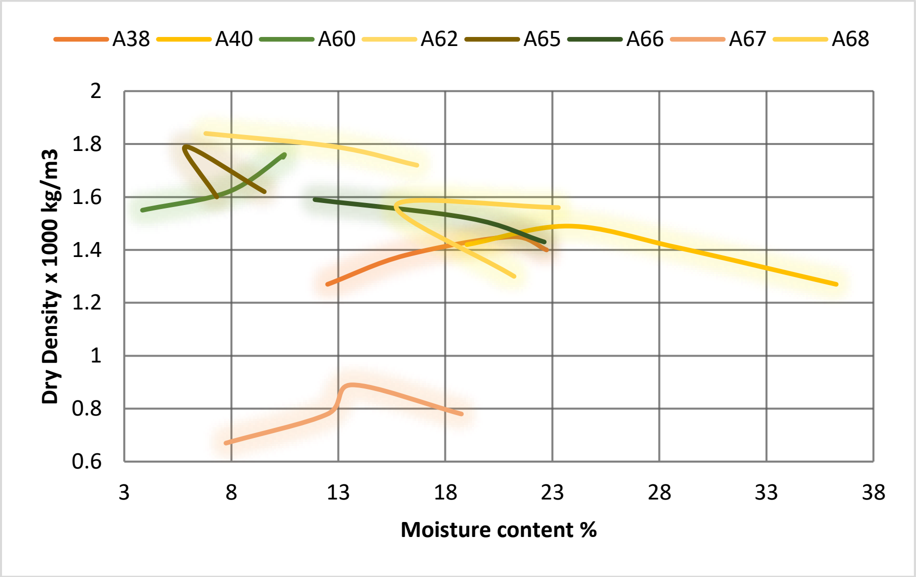

Figure 8a: Compaction test results showing the variation of moisture content with the maximum dry density in 2:1 expansive clay dominated mixed soils.

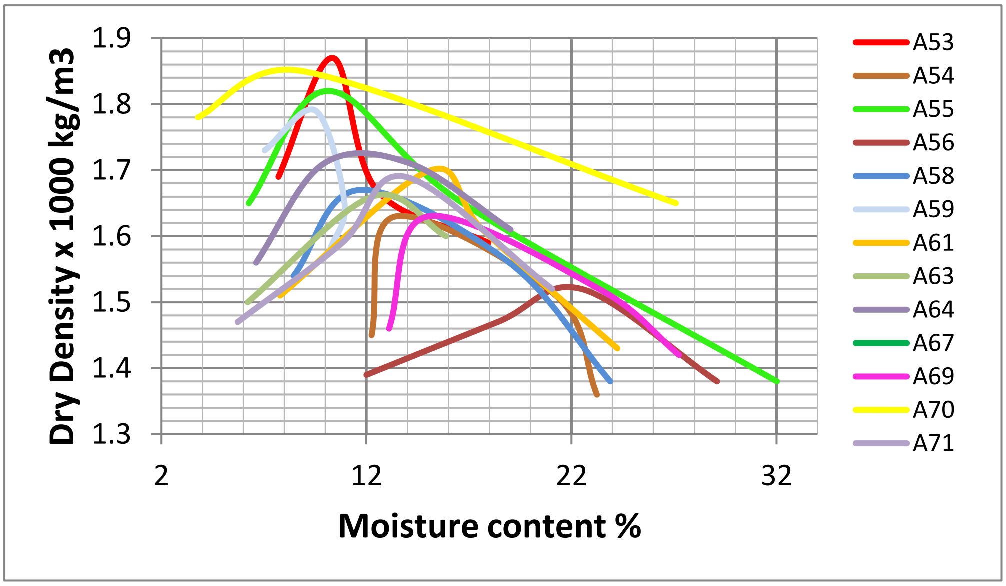

Figure 8b: Compaction test results showing the variation of moisture content with the maximum dry density in the non-expansive clay mixed soils.

5. Conclusion and Recommendations

Failure of the A123 Ilorin – Lokoja highway was found to be due to the mineralogy of the subgrade materials and the effects of groundwater on the soils. Groundwater has been noted by Abija et al. (2019) to increase the subgrades unit weight under saturated conditions, excess pore water pressures, seepage pressure and reduces effective stress and shear strength of the subgrades. It is recommended that a composite pavement structure that includes a geosynthetic layer be considered in view of the advantages of geosynthetics to restrain lateral movement of both the aggregate and the subgrade as well as improve the strength and stiffness of the road structure.

References

[1] Abija, F. A., Fakeye, A. M., Ige, O. O. and Ifedotun, A. I. (2024). Geotechnical Influence Factors in Empirical Design of Highway Pavement: The A123 Ilorin – Lokoja Highway, Nigeria Case Studies. Journal of Geotechnical Engineering, Vol. 11, Issue 3, pp. 53 – 70.

[2] Abija, F. A. (2022). Ground variation, geotechnical uncertainties and reliability of foundation design for sustainable building infrastructures. Guest lecture, Building Summit, Nigerian Building and Roads Research Institute, Abuja, 2022.

[3] Abija, F. A. (2021). Geotechnical assessment of subgrade and sub-base quality for the design and construction of road pavement in parts of the coastal section of Akwa Ibom State, Eastern Niger Delta, Nigeria. International Journal of Scientific and Engineering Research, Volume 10, Issue 7, pp. 1864 – 1877.

[4] Abija, F. A., Ewa, D. E. and Amah, E. A. (2019). Subgrade hydraulic characteristics, seepage induced road failures and design implications for sustainable pavement Infrastructure in parts of the coastal section of Akwa Ibom State, Eastern Niger Delta, Nigeria. International Journal of Civil Engineering, Construction and Estate Management Vol.7, No.4, pp.1-17.

[5] Adeyemi, G., Oyeyemi, F. Geotechnical basis for failure of sections of the Lagos–Ibadan expressway, south western Nigeria. Bull Eng Geol Env 59, 39–45 (2000)

[6] Adekeye, O. A. and Akande, S. O., (2006): Depositional Environments and Reservoir Potential Assessment of the Palaeocene Ewekoro Formation, Eastern Dahomey Basin, Southwestern Nigerian. Journal of Mining and Geology, Vol. 42 (1), 133-140.

[7] Bowen, N. L. (1922). The Reaction Principles in Petrogenesis, Journal of Geology, Vol. 30, 177–198.

[8] British Standards 1377 (1990): Methods of test for soils for civil engineering purposes. General requirements and sample preparation, BS 1377 1990, British Standards Institution, 38pp.

[9] Chen, F. A. (2000). Soil Engineering: Testing, Design, and Remediation. Boca Raton: CRC Press, 280 pages.

[10] Das, B. M. and Sobhan, K. (2014). Principles of Geotechnical Engineering, Eighth Edition, SI. Stamford, USA: Cengage Learning. 770 pages.

[11] Emmanuel, U. O., Igwe O. and Ukah B. U. (2021). An investigation into the cause of road failure along Sagamu-Papalanto highway southwestern Nigeria. Geoenvironmental Disasters, Vol. 8:3, pp. 1 – 19.

[12] Federal Ministry of Works and Housing (FMWH) (2013). Highway Manual Part 1: Designs. Volume 3: Pavement and Materials Design.

[13] Federal ministry of works (2011). Review of subgrade specification: Materials and Geotechnical/quality control department Circular ref. DDHPD/M&G/334/1/19.

[14] Gidigasu, M.D. (1976). Laterite Soil Engineering" Elsevier. Amsterdam, pp. 554.

[15] Gillot, J. E. (1986). Some clay related problems in Engineering Geology. Clay Minerals Vol. 21, pp. 261 – 278.

[16] Gillot, J. E. (1968). Clay in Engineering Geology. London: Elsevier Publishing Company. 320pages

[17] Grim, Ralph E. (1968). Clay Mineralogy, Second Edition", McGraw-Hill Book Company, New York,1968.

[18] Grant, N. K. (1978). Structural distinction between a metasedimentary cover and an underlying basement in the 600 million years Old Pan African domain of Northwestern Nigeria, West Africa. Geological Society of America Bulletin, 89, 50 – 58.

[19] Ige, O.O., Fakeye, A.M. and Ogunsanwo, O., (2018): Geotechnical assessment of some soils along Ilorin-Lokoja highway – implication on suitability for road construction. Bulletin of the Science Association of Nigeria, Vol. 29, 149 – 162.

[20] Ige, O.O. (2015): Use of migmatite-derived residual soil as a barrier in sanitary landfills. Indian Journal of Geosciences, Vol. 69 (1), 75 - 80

[21] Jegede, G. (1997): Highway pavement failure induced by soil properties along the F209 highway at Omuoke, southwestern Nigeria". Nigeria Journal of Science.

[22] Lambe, T. W. (1973). Predictions in soil engineering. Geotechnique 23, No. 2, 149-202.

[23] McNeilan, T. W. and Smith, K. R. (2014). Substructure Design. In: Chen, W. and Duan, L. eds. Bridge Engineering Handbook. 2nd Edition. Florida: Taylor and Francis Group, CRC Press. 378pages.

[24] Mesida, E. A (1980). "Engineering Geology: A Useful Tool in Soil and Foundation Engineering Practice". Proceeding 7th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Accra, pp. 737-740.

[25] Mesida, E. A (1987). Genetic Influence on the Compaction and CBR Characteristics of three Lateirte soils in Ile –Ife, Southwestern Nigeria. Proceeding 9th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Lagos, p. 461-466.

[26] Mesida, E. A. (2006). Highway Failure Over Talc –Tremolite Schist Terrain: A Case Study of the Ife to Ilesha Highway", Southwestern Nigeria. Bull Engineering Geology Environment 65, Pp. 457-461.

[27] Miller J.S. and Bellinger, W. Y. (2003). Distress Identification Manual for the Long-Term Pavement Performance Program. FHWA-RD-03-031. US Department Transp., pp. 115-116.

[28] Mitchell, J. K. (1993). Fundamentals of Soil Behavior, 2nd ed. Wiley, New York

[29] Mohammed, H. and Salami, M. B. (2013). Stratigraphic influence on geotechnical properties of subgrade soils along the Irrua-Auchi Road, South Eastern Nigeria. Journal of Environment and Earth Science, Vol. 3, No.8, 2013, pp. 61 – 78.

[30] Murthy, V. N. S. (2014). Textbook of Soil Mechanics and Foundation Engineering: Geotechnical Engineering series. New Delhi: CBS Publishers and Distributors Pvt Ltd. 10

[31] NGSA, (2004). Nigerian Geological Surveys Agency (NGSA): Geological map of Nigeria. 1:2000000, NGSA, Abuja, Nigeria.

[32] Ogundipe R, Olumide M (2012). Road Pavement Failure Caused by Poor Soil Property. Int. J. Eng. Technol., 2(1): 7-15.

[33] Osadebe, C. C., Salami B. M., Obrike, S. E. and Ajala, M. O. (2010). The Kano-Kazaure highway, north central Nigeria: The significance of the engineering geology in construction

[34] Osuolale, O. M., Oseni, A. A. and Sanni, I. A. (2012). Investigation of Highway Pavement Failure Along Ibadan - Iseyin Road, Oyo State, Nigeria. International Journal of Engineering Research and Technology, Vol. 1 Issue 8, pp. 1 – 6.

[35] Oyawoye, M.O. (1972). The Basement Complex in Nigeria. Geology of African Journal, 52 – 74.

[36] Oyinloye, O. A. (2011): Geology and Geotectonic Setting of the Basement Complex Rocks in South Western Nigeria: Implications on Provenance and Evolution, Earth and Environmental Sciences, 97-118. Dr. Imran Ahmad Dar (Ed.), ISBN: 978-953-307-468-9.

[37] Rahaman, M.A. (1976). Review of Basement geology of southwestern Nigeria. In Geology of Nigeria (ed. Kogbe C.A.) [M], 41 – 57. Elizabethan Press, Lagos.

[38] Rahaman M.A. and Lancelot, J.R. (1984). Continental crust evolution in SW Nigeria: constraints from U/Pb dating of pre-Pan-African gneisses. In: Rapport d'activite 1980–1984 – Documents et Travaux du Centre Geologique et Geophysique de Montpellier 4: pp 41

[39] Reeves, G. M, Sims, I. and Cripps, J. C. (eds) (2006). Clay Materials Used in Construction. Geological Society, London, Engineering Geology Special Publication. 580pages.

[40] Reddi, L. N. and Inyang, H. I. (2000). Geoenvironmental Engineering. New York. Marcel Dekker, Inc. 492 pages.

[41] Schofield, A. N. and Wroth, C. P. (1968). Critical State Soil Mechanics. London: McGraw-Hill Book Coy., 228pages.

[42] Skempton, A. W. (1953). The colloidal activity of clays. Proceedings of the third international conference of soil mechanics and foundation Engineering, Zurich, vol. 1, pp 57 – 60.

[43] Teme, S. C., Ajayi, O. O and Anowai, C. A. (1987). Geological Control on Highway Pavement Performance in Southwestern Nigeria; A preliminary Report. In: Proceedings of the 9th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Lagos, p. 565 – 575.

[44] Terzaghi, K. and Peck, R. B. (1967). Soil mechanics in engineering practice. 2nd Edn. New York: John Wiley and Sons.

[45] Terzaghi, K. (1939). Theoretical soil mechanics. New York: John Wiley and Sons, Inc. 256pages

[46] Theng, b. K. T (1979). Formation and properties of clay polymer complexes", Elsevier Scientific Publishing Company, New York, 1979.

[47] US DOIBR, (1998). Engineering Geology Field Manual, 2nd edn., Vol. 1. U.S. Department of the Interior Bureau of Reclamation. 450 pages.

[48] Wazoh, H. N., Daku, S. S and Samuel, F.G. (2016). Investigative Study of Possible Causes of Failure of A Section of Road in Jos - Plateau, North - Central Nigeria. Journal of Multidisciplinary Engineering Science Studies, Vol. 2 Issue 11, pp. 1128 – 1132.

[49] Waziri, S. H., Ako, T. A., Alabi, A. A. and Asema, A. I. (2018). The impact of geology on the stability of the Minna – Lambata road, North Central Nigeria. Proceedings of the First and Second International conferences of the Nigerian Association for engineering Geology and the environment, Lagos 2016 and 2017, pp. 67 – 76.

[50] Yoder, E. J., and Witczak, M.W. (1975). Principles of Pavement Design, Wiley, New York.