Scientia Africana, Vol. 23 (No. 4), October, 2024. Pp 33-50
© Faculty of Science, University of Port Harcourt, Printed in Nigeria *ISSN 1118 – 1931*

GEOTECHNICAL, GEOCHEMICAL AND MINERALOGICAL EVALUATIONS OF MINE SPOILS OF THE JOS- BUKURU TIN FIELD, CENTRAL NIGERIA: IMPLICATIONS FOR UTILIZATION AS ROAD CONSTRUCTION MATERIAL.

Daku, S.S.[1], Igwe, O. [2] and Bala, D. A.[3]
[1]Department of Geology, Faculty of Natural Sciences, University of Jos, Nigeria.
[2]Department of Geology, Faculty of Physical Sciences, University of Nigeria, Nsukka.
[3]Department of Science Laboratory Technology, Faculty of Natural Sciences, University of Jos, Nigeria
E-mail: [1]dakus@unijos.edu.ng ; [2]ogbonnaya.igwe@unn.edu.ng ; [3]balanite2002@yahoo.com

Received: 13-08-2024
Accepted: 21-08-2024

https://dx.doi.org/10.4314/sa.v23i4.3

Journal Homepage: http://www.scientia-african.uniportjournal.info
Publisher: *Faculty of Science, University of Port Harcourt.*

ABSTRACT

The use of locally available and accessible soils for the construction of roads has become necessary due to the high cost associated with the procurement of soils with good engineering features. A geotechnical, geochemical and mineralogical approach has been adopted to evaluate the mine spoils of the Jos – Bukuru tin field for road construction. X–ray diffraction analysis indicated that mineral phases in the soil are quartz (77.38%), kaolinite (18.70%), hematite (1.57%), rutile (0.42%), goethite (1.56%), gibbsite (0.31%), and a negligible amount of montmorillonite (0.06%) which suggested that the undesirable problem of swelling and shrinking of the soil when utilized for road construction will not be expected. The geochemical test result showed that the investigated soils based on the silica–sesquioxide ratio are residual soils that are not ''true laterites'' and have an average composition of 71.81 wt. % of SiO_2, 17.56 wt.% of Al_2O_3, 9.03 wt. % of Fe_2O_3, 0.86 wt. % of TiO_2 0.07 wt. % of P_2O_5 and less than 0.05% of CaO, MgO, K_2O, MnO and Na_2O. The oxides of silica, iron and aluminum help cement or bind the soil particles together. The results of geotechnical investigation showed that the soils are poorly graded with an average fine (silt and clay) composition of 56.03%, California bearing ratio (CBR) of 34.64%, maximum dry density (MDD) of 1.65g/cm^3, optimum moisture content (OMC) of 18.99%, angle of internal friction (ϕ)of 12.15^O, cohesion of 30.77 KN/M^2 and coefficient of permeability of 1.24x10^{-3} mm/sec respectively. The Atterberg consistency limit showed that the liquid limit, plastic limit, plasticity index and linear shrinkage values have averages of 38.68%, 23.16%, 15.53% and 10.33% respectively. Based on the requirement of the Federal Ministry of Works and Housing, only a few of the soil samples satisfied the requirements for use as a sub-base material for the construction of roads. The undesirable soil samples that did not meet the requirement mentioned can be improved using suitable admixtures.

Keywords: Mine spoil; Geotechnical; Geochemical; Road; Construction material

INTRODUCTION

Tin mining on the Jos-Plateau has led to the devastation of land as can be seen by the presence of mining ponds and pits, mine derelicts and excavated soils, otherwise called mine spoils or mine dumps standing several meters high in most of the locations where mining had previously taken place (Omotehinse and Ako, 2019).These spoils over the years are utilized for the construction of roads, earth dams, making of building bricks as well as filling materials in the construction of houses. Garg (2009) proposed a proper understanding of soils' geotechnical qualities and ascribed the constant occurrence of building collapse and road pavement failure to the soils' weak geotechnical and mechanical properties. The term "lateritic clays," "lateritic gravels," and even "laterites" are still being used by engineers to describe any reddish tropical soils (Northmore *et al.*, 1992), despite the extensive work done by past studies to categorize and distinguish tropical soils. This is because there is currently no uniform nomenclature or classification system for these soils. For engineering purposes, it is more important that the geological and engineering properties predicted or inferred from testing are accurate than if the classification is correct (Kamtchueng *et al.*, 2015).

Roads are constructed on or with geological materials (rocks or soils), and the characteristics of these soils affect how well they function as a transportation medium. It is in the realization of the importance of this, that the Federal government of Nigeria stipulated the Nigerian specifications for roads and bridges (1997) for the different engineering properties of soils be used as subgrade, sub-base, and base course materials for road construction. From the bottom to the top of many conventional flexible highway pavements, the main elements are subgrade, sub-base, base course, and riding surfaces (Adeyemi *et al.*, 2014). Adegoke *et al* (1980); Nwankwoala *et al.* (2014) recognized design and construction flaws, geological, geomorphological, and geotechnical variables, and maintenance as causative factors of road failure in Nigeria. Aghamelu and Okagbare (2011) observed that most road contractors in Abakaliki and environs, because of the high cost of haulage of suitable materials, utilize the Abakaliki shales for road construction which often fail due to its expansive nature. In investigating the potential reasons of road collapse of the Onitsha– Enugu expressway, Onuoha *et al.*, (2014), collected and analyzed residual soil samples and concluded that the soils do not meet up with stipulated standards set by the Federal Ministry of Works and Housing. Tse and Efobo (2016) outlined potential causes for the frequent failure of the Port Harcourt – Enugu expressway to include utilization of substandard soils as the sub-grade, presence of shales of low permeability as well as the presence of significant amount of montmorillonite in the soil.

Furthermore, Oyem *et al.* (2020), Daramola *et al.,* (2018), identified poor drainage and high percentage fines and utilization of soils of high plasticity as some of the causative factors of road failure along the Sagamu- Papalanto highway in Southwestern Nigeria. Daramola *et al.*, (2015) and Momoh *et al.*, (2015) identified poor drainage condition of the soil among other factors such as high linear shrinkage, low California bearing ratio (CBR) and compaction values to be accountable for some of the failing roads in southwest Nigeria. Lagos- Ibadan express way is one of the important and busiest roads in southwestern Nigerian that has continually failed. In finding the root cause of the incessant failure, Layade *et al*., (2017) identified fractured bedrock, clay and sandy clay soil with high permeability and porosity as the causes of the incessant failure of the road. However, Simeon *et al.*, (2018) ascribed the road's failure on the soil's high natural moisture content along the road's problematic portion, high percentage of fines, and high (> 8%) linear shrinkage values which made the soil susceptible to shrinkage and swelling.

Millogo *et al.* (2008), observed that residual soils for road construction chosen solely based

Scientia Africanа, Vol. 23 (No. 4), October, 2024. Pp 33-50
© Faculty of Science, University of Port Harcourt, Printed in Nigeria *ISSN 1118 – 1931*

on the findings of geotechnical studies functioned poorly after a short time. The inadequacy of the geotechnical analyses used to support the selection of lateritic soils for use in road construction may be responsible for this behavior. Tockol 1994, Mahalinger-Iyer and Williams 1997, and Millogo *et al.,* (2008) offered support for this shortcoming by arguing that lateritic soils require chemical and mineralogical investigation besides the geotechnical tests in order to determine their suitability for use in building roads. Naresh and Nowatzk (2006) emphasized the significance of grain size studies in evaluating the strength of soils and also to estimate the distribution of particle sizes of any soil intended for engineering construction of any kind.

The Federal Ministry of Works and Housing recommended that subgrade soils should have fewer than 35% of fines. Clayey soils are categorized by Oyem *et al.*, (2020) as moderate to poor road construction materials, whereas granular soils are categorized as excellent to good road materials. The liquid limit, plastic limit and plasticity index also called consistency limits or Atterberg limits are used to evaluate the soil's settling and tensile strength before building roadways (Adeyemi, 1995). Soils with high liquid and plastic limits are not considered as suitable materials for construction purposes because such soils often have limited bearing capacity as posited by Daramola *et al.,* (2015). The Federal Ministry of Works and Housing (FMWH, 1997) recommended a maximum plasticity index of 20% for highway subgrade materials and a liquid limit of 50% for soil if it is to be used as subgrade, sub-base, and base road construction material. According to O'Flaherty (1988), a clay sample's maximum dry density (MDD) might range between 1.40 and 1.70 g/cm3 while its optimum moisture content (OMC) could be between 20 and 30% when employing the modified proctor test procedures. For silty-clay soils, MDD typically ranges from 1.60 to 1.80 g/cm3 and OMC is between 15 and 25%. Conversely, for sandy-clay soils, the typical values for MDD and OMC are 1.80 and 2.20 g/cm3 and 8 to 15%, respectively. Oyem *et al.* (2020), proposed that the suitability of sub-soils for building roads is determined by the soil's resistance to stress during the application of pressure as measured by tests for compaction, CBR, cohesion, permeability, and porosity. Igwe *et al.,* (2013) stated that materials that have permeability coefficients (k) between 10^{-7} and 10^{-5} m/s are classed as being moderately to highly permeable. By analyzing the silica-sesquioxide (S-S) (SiO_2 / (Fe_2O_3 + Al_2O_3) ratio, Rossiter (2004) classified soils according to the degree of laterization and concluded that soils with S-S ratios > 2 are considered non-lateritic soils, while those with S-S ratios between 1.33 and 2 are lateritic soils, and those with S-S ratios of <1.33 are considered as true laterites. Kamtchueng *et al.,* (2015) evaluated the geotechnical, chemical and mineralogical characteristics of lateritic soils in Central Cameroun for road construction and argued that the presence of goethite and other iron oxides in residual soils may act as cementing compounds, rendering the compacted structure comparatively brittle in turn contributing to tensile cracking.

With increasing population and urbanization and its attendant pressure on land and construction materials, mine spoils of the Jos-Bukuru area produced from previous tin mining activities are being utilized for the construction of roads and other engineering construction purposes. This is done without consideration of the geotechnical, geochemical, and mineralogical properties of this leftover soil material. Therefore, this study seeks to evaluate the geotechnical, geochemical and mineralogical characteristics of these mine spoils since it is used for the construction of roads.

The study area

The study area covered part of Jos South and Barkin Ladi Local Government Areas of Plateau State where mining activities within the Jos area were predominant (Figure 1). The area is situated between latitude 9°40' 00'' – 9°55'00''N and longitude 8°50'00''- 9°00'00''E and covers an area of four hundred and five (405) square kilometers.

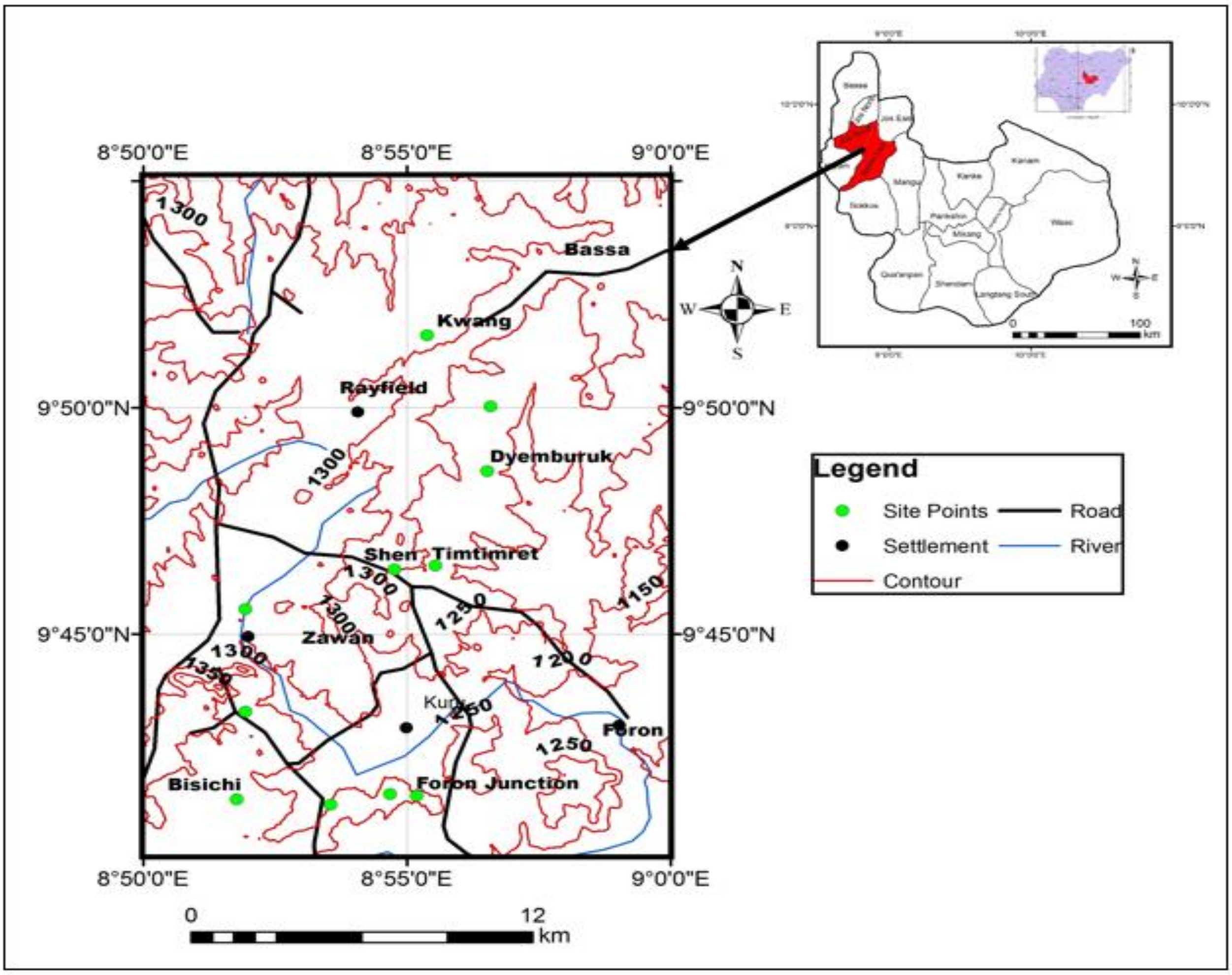

Figure 1: Topographic map of the study area, showing sampling points subset from the map of Plateau State.

The study area lies within the tropical climatic zone, which is characterized by two seasons, namely the dry (April - October) season which is associated with dry- dusty winds and is usually cold and the wet season, which runs from April to October. During the wet season, the average daily temperature ranges between 27^{0}C to 35C while during the dry season which is characterized by the Tropical Continental Wind (T.C.W), the temperature can reach 35^{O}C in the day and as low as 15^{O}C particularly at night. The rainfall is typical of the tropical Sudan Savanna region with a rainfall of about 198mm with the highest rainfall of 481mm experienced in August and a relative humidity of 89%. However, throughout the dry season, the average temperature is about 21.3^{O}C with a drop in relative humidity to 17%. The vegetation type is the Guinea Savannah grassland with many shrubs and few trees. Some of the areas are thickly wooden, especially close to streams channels and on some of the hills where physical and chemical weathering has reduced some of the outcrops to boulders with fertile soil for the growth of some of these plants. During the harmattan period, the grasses and shrubs dry out and the trees shade their leaves. They however regain their lush green nature during the rainy season. The area is characterized by two basic relief systems which are the highlands and lowlands with a

Scientia Africana, Vol. 23 (No. 4), October, 2024. Pp 33-50
© Faculty of Science, University of Port Harcourt, Printed in Nigeria *ISSN 1118 – 1931*

dendritic drainage pattern. The highlands are characterized preponderantly by granitic hills in the Central and North-Eastern parts of the study area. The highest point in the study area is 1418m located at the Central and southwestern part of the study area while the lowest point is 1131m. The land is mainly used for agricultural activities and artisanal mining of tin. The study area's geology is part of the Jos-Bukuru Complex, which has been extensively researched by Falconer (1911), Falconer (1921), and MacLeod et al. (1971). This complex is primarily composed of biotite-granite, namely fine-grained biotite granite and porphyritic biotite granite.

MATERIALS AND METHODS

Sampling

The samples were taken from spoils derived from tin and columbite mining within the Jos-Bukuru tin mining fields. These samples were collected using diggers and shovels from the mine spoils. As a result of the mine spoils' diversity, the different components of the soil were sampled from the top, middle and bottom of the mound to get a representative sample of the soil; the lumps were broken and completely blended to create a composite sample (US EPA, 2012)

X-ray diffraction (XRD)

The clay minerals present in the soil samples were identified using X-ray Diffraction (XRD) technique. XRD is a rapid analytical technique primarily used for phase identification of a crystalline material. X-ray diffraction is based on constructive interference of X-rays and a crystalline sample. Analysis of X-ray powder diffraction was performed on soil samples at the National Geo-Science Research Laboratories of the Nigerian Geological Survey Agency (NGSA) located in Kaduna state, Nigeria. The X-ray powder diffraction patterns were obtained using a Scintag Theta-Theta X-ray diffractometer which is used to analyze powders, bulk samples, polymers, and polycrystalline thin films. The machine has an automated interface with a computer. The samples were automatically run after which the diffractogram with the corresponding data of intensity versus 2θ were displayed on the computer monitor.

X-Ray Fluorescence (XRF)

The X-ray Fluorescence method was adopted to determine the oxide composition of the elements within each soil sample, and the relative abundance in the percentage of these oxides in each of the soil samples. Analysis of X-ray fluorescence was performed on the soil samples at the National Geo-Science Research laboratories of the Nigerian Geological Survey Agency (NGSA) located in Kaduna state, Nigeria.

Geotechnical Tests

The samples were put through several geotechnical tests, including sieve analysis, the Atterberg consistency limits test, compaction, shear strength, permeability, and California bearing ratio (CBR). These tests were conducted in accordance to the British Standard procedures (BS: 1377, Part 2), 1990 for the Atterberg consistency limits test, compaction, shear strength, permeability and California bearing ratio (CBR) while the hydrometer test was done using the ASTM (D 6913)- 04, (2009).

RESULTS AND DISCUSSIONS

Chemical and Mineralogical investigation

The primary determinant of the size, form, physical, and chemical characteristics of soil mechanics is mineral content (Kamtchueng *et al*., 2015). The X-ray diffraction patterns as can be seen in Figure 2a and b show that the mine spoils are made up of kaolinite, quartz, hematite, goethite and rutile as the dominant minerals. Montmorillonite was found in only three of the forty-five samples analyzed namely; (SSD 9, SSD 13 and SSD 33) while gibbsite was found in only one (SSD 33) of the samples. Table 1 and Figure 3 give a summary of the mineralogical content of all the samples analyzed which showed that quartz is the dominant mineral in the soil with an average composition of 77.38%. A clay mineral of geotechnical importance found in the spoil is kaolinite with an average composition of 18.70%, this is followed by hematite, rutile, goethite, gibbsite and montmorillonite whose average mineralogical compositions are 1.57%, 0.42%, 1.56%, 0.31% and 0.06% respectively. Quartz is an important silicate mineral found in almost every granitic rock therefore, considering the geology of the Jos - Plateau, the presence of quartz in the soil resulted from the weathering of granitic rock bodies. The presence of basic intrusive igneous bodies and their subsequent weathering may have resulted in the formation of hematite and also in the reddish-to-brownish colouration of the soil. The mineralogical investigation also shows the presence of a negligible amount of montmorillonite, which suggests that the undesirable problem of swelling and shrinking of the soil when utilized for road construction will not be expected while goethite and hematite may act as cementing or binding agents in the soil.

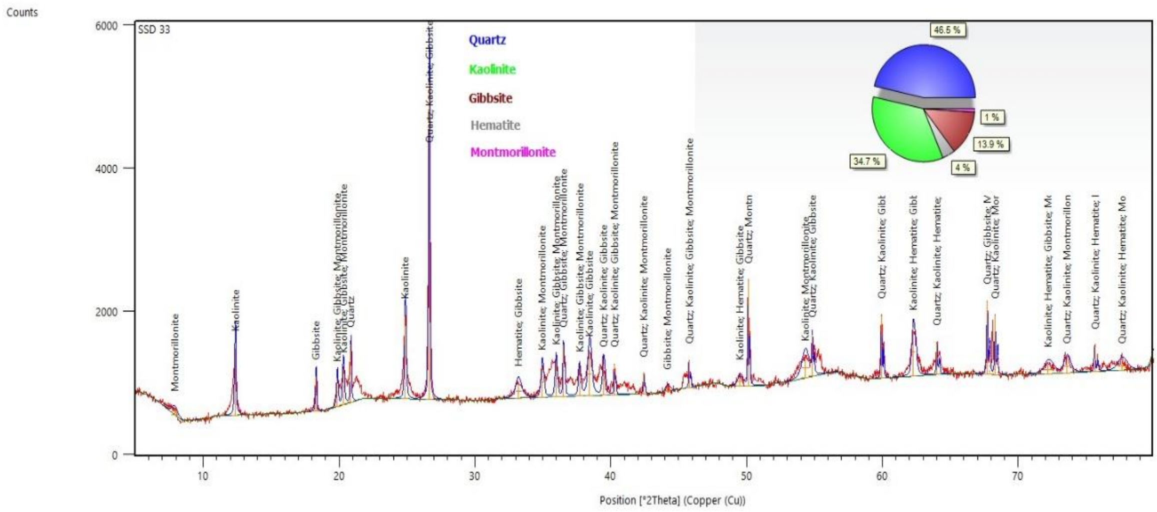

Figure 2a: X-ray Diffractogram showing quartz, kaolinite, gibbsite, hematite and montmorillonite as the dominant minerals of one of the mine spoil samples

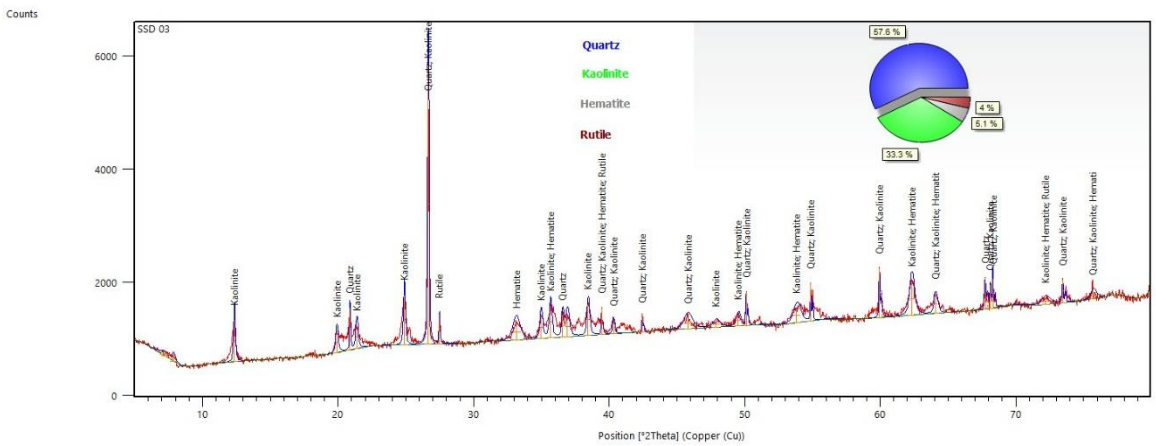

Figure 2b:X-ray Diffractogram showing quartz, kaolinite, hematite and rutileas the dominant minerals of one of the mine spoil samples

Scientia Africana, Vol. 23 (No. 4), October, 2024. Pp 33-50
© Faculty of Science, University of Port Harcourt, Printed in Nigeria *ISSN 1118 – 1931*

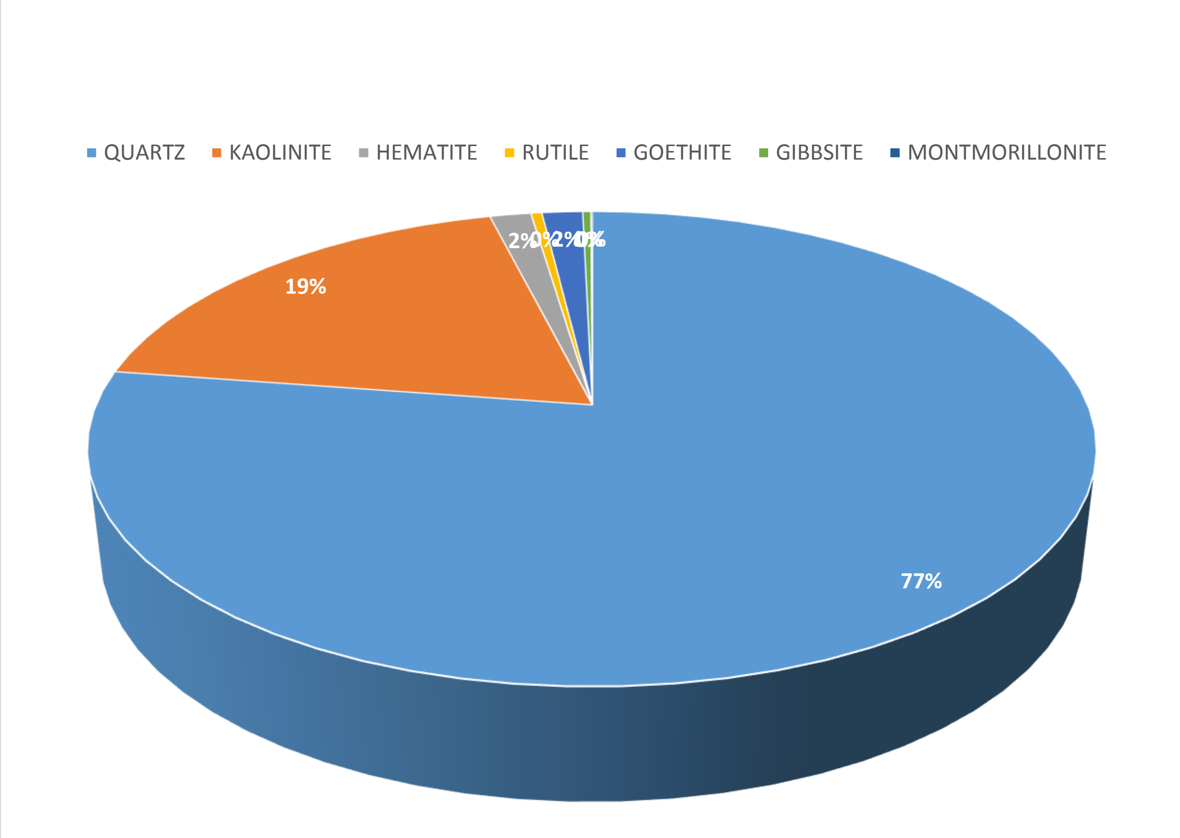

Figure 3: Pie Chart showing the mineralogical composition of mine spoil.

Table 1: Mineralogical Composition in (%) of Mine Spoil in the Study Area

SAMPLE ID	Quartz	Kaolinite	Hematite	Rutile	Goetithe	Gibbsite	Montmorillonite
SSD 1	66.00	31.00	3.00				
SSD 2	81.00	16.00	3.00				
SSD 3	57.60	33.30	5.10	4.00			
SSD 4	69.00	24.00	7.00				
SSD 5	74.00	22.00	4.00				
SSD 6	78.00	19.00	3.00				
SSD 7	83.00	12.00		1.00	4.00		
SSD 8	61.00	39.00					
SSD 9	76.00	18.00			6.00		1.00
SSD 10	76.00	24.00					
SSD 11	79.00	18.00			3.00		
SSD 12	75.00	18.00		3.00	5.00		
SSD 13	65.00	29.00			5.00		1.00
SSD 14	62.00	33.00			5.00		
SSD 15	60.00	34.00			6.00		
SSD 16	78.00	20.00	2.00				
SSD 17	78.00	18.00			4.00		
SSD 18	76.00	19.00			6.00		
SSD 20	88.00	10.00		2.00			
SSD 21	76.00	19.00			6.00		
SSD 22	89.00	10.00		1.00			
SSD 23	88.10	9.90	2.00				
SSD 24	81.00	15.00	4.00				
SSD 25	81.00	19.00					

SSD 26	81.00	16.00	3.00				
SSD 27	88.00	10.00	2.00				
SSD 28	82.20	13.90			4.00		
SSD 29	85.00	15.00					
SSD 30	66.70	27.30	6.10				
SSD 31	76.80	16.20		2.00	5.10		
SSD 32	83.00	14.00	3.00				
SSD 33	46.50	34.70	4.00			13.80	1.00
SSD 34	89.00	11.00					
SSD 35	90.00	10.00					
SSD 36	79.00	17.00	4.00				
SSD 37	82.00	13.00		2.00	3.00		
SSD 38	75.00	19.00			6.00		
SSD 39	76.80	20.20		3.00			
SSD 40	89.00	10.00		1.00			
SSD 41	86.10	11.90	2.00				
SSD 42	66.30	27.70	6.90				
SSD 43	87.00	10.00			3.00		
SSD 44	76.00	22.00	3.00				
SSD 45	93.00	7.00					

The major oxide compositions of mine spoils of the study area as seen in Table 2 indicate that SiO_2, Al_2O_3 and Fe_2O_3 are the dominant oxides in the soil. SiO_2 is most dominant and varies from 58 – 85wt% with an average of 71.78wt% and this is followed by Al_2O_3 which varies from 10 -29 wt. % with an average value of 17.56 wt. %. The Fe_2O_3 concentration varies from 2 – 19 wt. % with a mean value of 9.02 wt. %. The concentrations of Al_2O_3 and Fe_2O_3 found in the mine spoil are much higher when compared with what is obtainable in the playgrounds, farms, stream sediments and roadsides of Jos and environs as reported by Lar *et al.*, (2014). The relatively high concentration of Al_2O_3 can be linked to the weathering of feldspar from the granitic host rocks while Fe_2O_3 may probably be due to the superficial oxidation and percolation of water from Fe-rich capping from some of the surrounding hills. In almost all the mine spoil analyzed, CaO, MgO, and Na_2O contents are <1%. This according to Lar *et al*., (2014) is expected of soils derived from a mostly granitic parent host rock. K_2O as well as MnO occur fairly low in proportion, and it is a sign of severe weathering in a tropical climate from which clays are formed (Aliu *et al.*, 2021). The TiO_2 concentration ranges from 0.039 – 2 wt. % with an average value of 0.86 wt. %. This relatively high value of TiO_2 may be due to the weathering of rutile and or ilmenite which are common accessory minerals found in altered plutonic igneous rocks. However, the concentrations for P_2O_5 and Cr_2O_3 are very low with average values of 0.07 wt. % and 0.02 wt. % respectively.

Table 2: Major Element concentration in (wt.%) of mine spoil in the Study Area

SAMPLE ID	SiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	TiO_2	Al_2O_3	P_2O_5	Cr_2O_3
SSD 1	68.23	9.50	0.60	0.10	0.02	0.21	0.0205	0.80	20.60	0.60	0.017
SSD 2	70.13	8.07	0.07	0.16	0.03	0.50	0.032	1.03	19.10	0.04	0.010
SSD 3	58.46	15.06	BDL	0.05	0.01	0.12	0.025	1.88	24.31	0.06	0.059
SSD 4	58.46	18.86	0.06	0.15	0.02	0.29	0.043	1.37	20.60	0.09	0.066
SSD 5	62.97	15.02	0.10	0.15	0.02	0.34	0.026	1.05	20.23	0.07	0.026
SSD 6	68.98	9.70	0.60	0.13	0.02	0.30	0.046	1.21	18.93	0.07	0.013
SSD 7	71.85	12.02	0.04	0.15	0.03	0.67	0.024	0.78	14.34	0.06	0.027
SSD 8	64.20	15.17	0.07	0.20	0.02	0.46	0.509	0.80	18.54	0.05	0.017
SSD 9	68.49	13.50	0.04	0.08	0.02	0.25	0.027	0.70	16.79	0.08	0.022
SSD 10	83.62	5.26	0.04	0.10	0.03	0.51	0.024	0.58	9.80	0.04	0.006
SSD 11	77.32	4.56	0.03	0.07	0.02	0.22	0.009	0.36	17.40	0.02	0.004

Scientia Africana, Vol. 23 (No. 4), October, 2024. Pp 33-50
© Faculty of Science, University of Port Harcourt, Printed in Nigeria *ISSN 1118 – 1931*

SSD 12	75.50	8.15	0.07	0.13	0.04	0.97	0.041	0.73	14.05	0.04	0.084
SSD 13	74.61	5.43	BDL	0.03	0.01	0.06	0.008	0.73	19.07	0.04	0.012
SSD 14	74.07	4.31	BDL	0.03	0.01	0.08	0.007	0.72	20.72	0.04	0.008
SSD 15	67.66	11.31	0.03	0.01	0.10	0.01	0.014	0.84	19.95	0.05	0.034
SSD 16	69.07	9.49	0.01	0.03	0.11	0.07	0.013	0.91	20.21	0.05	0.021
SSD 17	78.67	5.10	0.10	0.13	0.17	0.27	0.016	0.98	14.52	0.05	0.007
SSD 18	68.49	12.88	0.10	0.15	0.02	0.31	0.019	1.01	16.94	0.06	0.026
SSD 19	84.60	2.03	0.01	0.02	0.01	0.06	0.006	0.46	12.78	0.03	0.003
SSD 20	70.04	12.19	0.07	0.18	0.04	0.86	0.022	0.81	15.18	0.60	0.017
SSD 21	75.82	5.25	0.10	0.17	0.02	0.45	0.013	0.04	17.18	0.04	0.010
SSD 22	82.17	3.26	0.08	0.15	0.02	0.43	0.011	0.69	13.14	0.03	0.007
SSD 23	69.43	12.71	0.04	0.01	0.02	0.30	0.016	0.74	16.22	0.06	0.035
SSD 24	63.15	14.74	0.07	0.01	0.02	0.03	0.026	1.05	20.55	0.06	0.031
SSD 25	82.95	3.73	0.08	0.12	0.02	0.42	0.011	0.73	11.91	0.03	0.005
SSD 26	70.14	9.02	0.03	0.08	0.01	0.33	0.014	0.61	19.72	0.04	0.008
SSD 27	75.57	7.99	0.07	0.12	0.01	0.28	0.016	0.77	15.14	0.05	0.010
SSD 28	74.18	7.22	0.10	0.17	0.02	0.42	0.019	0.99	16.83	0.04	0.130
SSD 29	77.64	5.19	0.06	0.13	0.03	0.04	0.016	0.80	15.69	0.04	0.008
SSD 30	71.78	8.58	0.11	0.17	0.02	0.33	0.019	0.93	18.02	0.05	0.014
SSD 31	68.59	9.72	0.10	0.20	0.03	0.66	0.038	0.93	19.66	0.05	0.019
SSD 32	70.71	10.34	0.07	0.12	0.01	0.21	0.019	0.93	17.51	0.06	0.035
SSD 33	63.85	12.67	BDL	0.07	0.01	0.11	0.024	0.66	22.53	0.05	0.027
SSD 34	59.85	8.49	0.03	0.05	0.01	0.10	0.014	1.89	29.49	0.07	0.023
SSD 35	82.04	5.01	0.04	0.10	0.34	0.65	0.024	0.64	11.14	0.02	0.006
SSD 36	66.23	14.87	0.05	0.10	0.02	0.27	0.024	1.02	17.34	0.06	0.026
SSD 37	71.74	10.29	0.03	0.10	0.02	0.35	0.015	0.73	16.13	0.06	0.016
SSD 38	72.78	5.61	0.70	0.15	0.02	0.33	0.015	1.30	19.09	0.03	0.010
SSD 39	68.99	6.06	0.31	0.48	0.14	2.01	0.03	1.19	20.74	0.05	0.010
SSD 40	76.30	5.99	0.12	0.17	0.03	0.72	0.014	0.99	15.86	0.06	0.015
SSD 41	74.55	7.20	0.04	0.10	0.01	0.22	0.022	0.84	16.96	0.05	0.009
SSD 42	62.30	16.80	0.03	0.07	0.01	0.13	0.023	0.74	19.85	0.04	0.027
SSD 43	84.84	2.63	0.01	0.03	0.01	0.10	0.007	0.44	11.90	0.03	0.004
SSD 44	66.00	9.54	0.03	0.05	0.01	0.13	0.024	1.00	22.95	0.07	0.020
SSD 45	83.11	5.24	0.06	0.10	0.02	0.37	0.028	0.42	10.61	0.04	0.007

Note: BDL= Below Detection Limit

Soils have been classified by Rossiter (2004) based on the silica-sesquioxide (S-S) (SiO_2 / (Fe_2O_3 + Al_2O_3) ratio and linked to the degree of lateralization thus; non-lateritic soils are those with S-S ratios > 2, while lateritic soils have S-S ratios between 1.33 and 2, and real laterites have a ratio of <1.33. The silica-sesquioxide ratio of the mine spoils ranged from 1.48 to 5.48 with an average of 2.99. Thirty-seven (37) of the forty-five (45) samples representing 82.22% of total samples collected have a silica- sesquioxide ratio of > 2 which implies that the majority of the soils are non-laterite while eight (8) samples representing 17.78% of the total samples have silica – sesquioxide ratio of 1.33 – 2 which means that the soils are lateritic. However, none of the samples have a silica- Sesquioxide ratio of < 1.33 which implies that none of the samples analyzed is a true laterite.

Al_2O_3/TiO_2 ratio is a useful provenance indicator for sediments and typical Al_2O_3/TiO_2 ratios are 3-8, 8-21, and 21-70 for sediments generated from mafic, intermediate, and felsic igneous rocks, respectively (Hayashi et al., 1997). The mine spoils have Al_2O_3/TiO_2 ratios of 12.93 - 47.93 with an average of 21.82 indicating an intermediate to felsic igneous rock source. Based on this classification, 57.77% representing 26 of the 45 samples shows that the soils were sourced from intermediate parent rocks while 42.23% representing 19 samples shows that the soils were derived from an entirely felsic origin and none from a mafic parent source.

However, the relationship of the Co/Th vs. La/Sc plot as shown in Figure4 shows that the soils were derived from felsic igneous and granitic rocks and this is consistent with the research area's geology.

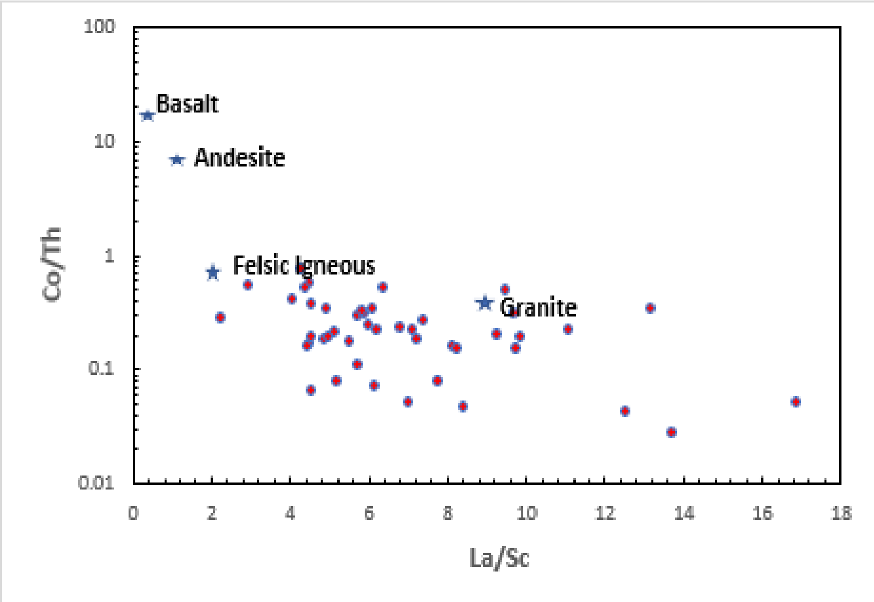

Figure 4: Relationship of La/Sc versus Co/Th plot of mine spoil samples in the study area (After Gu et al, 2002)

The Chemical Index of Alteration (CIA) values for the soil samples as shown in figure 5 ranged from 85% - 97.5%, this shows a significant amount of weathering in the sediment source area. In this type of weathering, K_2O and $CaO + Na_2O$ are depleted and the weathering trend moves from the basic, less advanced stage to the most advanced stage where there is a transformation of muscovite - illite - kaolinite. This result is consistent with the XRD analyses carried out which shows that the most prevalent clay mineral in the samples is kaolinite and is also in line with the works of Hassan et al (2015) and Olowolafe (2002) wherein these authors suggested that low pH levels and rainfall-induced leaching of basic cations are responsible for the prevalence of kaolinite in the soils of the Jos - Plateau.

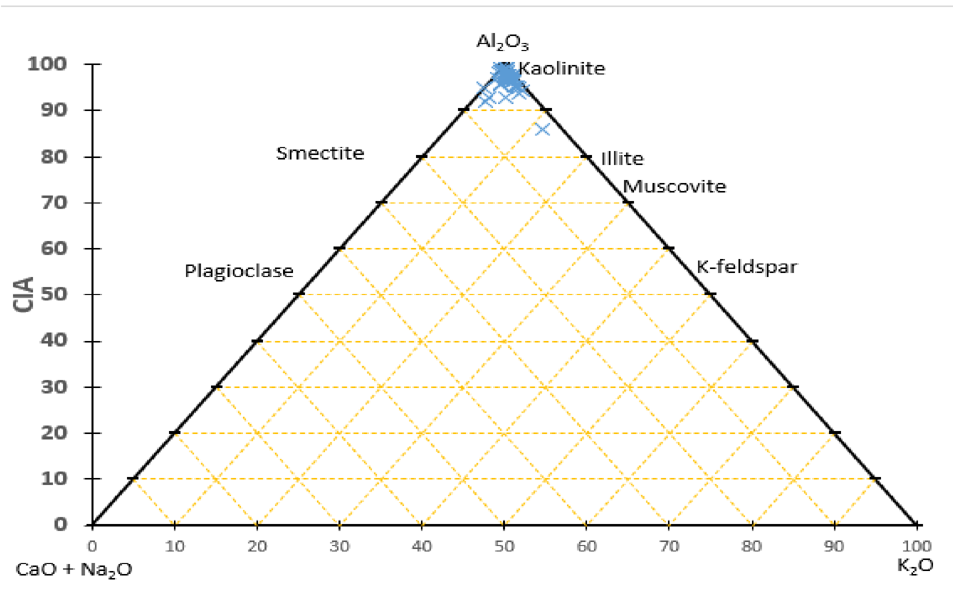

Figure 5: The ($CaO + Na_2O$) - Al_2O_3 -K_2O diagram of samples in the study area (after Nesbitt & Young 1984)

Scientia Africana, Vol. 23 (No. 4), October, 2024. Pp 33-50
© Faculty of Science, University of Port Harcourt, Printed in Nigeria *ISSN 1118 – 1931*

Geotechnical Characteristics of the Mine Spoils

Index properties

Soil index properties reveal how it will behave qualitatively under different kinds of loads. The index properties of the mine spoil are summarized in Table 3.

Table 3: Index Engineering Properties of mine spoils in the study area

Sample ID	LL (%)	PL (%)	PI (%)	LS (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Fine (%)
SSD 1	28	18.18	9.82	7.86	10.5	35.48	33.23	20.79	54.02
SSD 2	40	21.58	18.42	10.71	-	19.51	29.16	51.33	80.49
SSD 3	44	28.72	15.28	11.43	22.8	30.1	30.65	16.45	47.1
SSD 4	33	22.88	10.12	10.00	9.2	27.05	25.91	37.84	63.75
SSD 5	44	20.49	23.51	10.71	-	36.1	21.83	42.07	63.9
SSD 6	45	23.37	21.63	11.43	-	35.34	43.92	20.74	64.66
SSD 7	40	25.66	14.34	11.43	5.6	34.57	30.5	29.33	59.83
SSD 8	44	25.54	18.46	11.43	3.69	44.06	28.75	23.5	52.25
SSD 9	37	22.47	14.53	7.14	21.89	49.33	20.13	8.65	28.78
SSD 10	30	23.08	6.92	5.00	20.38	50.82	18.48	10.32	28.8
SSD 11	55	33.33	21.67	11.43	10.23	50.21	24.61	14.95	39.56
SSD 12	30	20.94	9.06	9.29	9.1	47.82	27.35	15.73	43.08
SSD 13	36	21.98	14.02	10	4.89	53.77	26.86	14.37	41.23
SSD 14	42	26.68	15.32	10.71	2.49	49.1	21.86	26.55	48.41
SSD 15	30	23.53	6.47	10	-	49.78	20.47	29.75	50.22
SSD 16	44	30.00	14.00	11.43	2.1	53.55	17.47	26.46	43.93
SSD 17	40	21.89	18.11	10.71	-	29.79	44.75	25.46	70.21
SSD 18	39	27.27	11.73	10.71	-	32.08	42.31	25.61	67.92
SSD 19	38	23.02	14.98	10.71	5.3	58.45	25.99	10.26	36.25
SSD 20	42	21.98	20.02	10.71	-	25.19	29.73	45.08	74.81
SSD 21	30	20.34	9.66	9.29	-	26.7	53.07	20.23	73.3
SSD 22	42	20.42	21.58	10.71	-	41.7	47.63	10.67	58.3
SSD 23	41	28.58	12.42	11.43	-	42.27	46.92	10.81	57.73
SSD 24	43	20.87	22.13	11.43	-	43.86	50.11	6.03	56.14
SSD 25	43	23.90	19.10	11.43	-	47.33	47.36	5.31	52.67
SSD 26	41	22.42	18.58	10.71	12.36	56.5	19	12.14	31.14
SSD 27	30	22.47	7.53	9.29	-	38.36	27.71	33.93	61.64
SSD 28	30	19.41	10.59	8.57	-	33.06	31.12	35.82	66.94
SSD 29	40	23.54	16.46	10.71	2.46	50.94	24.93	21.24	46.17
SSD 30	40	24.57	15.43	11.43	-	33.31	21.99	44.7	66.69
SSD 31	43	18.71	24.29	12.14	-	43.62	22.99	33.89	56.88
SSD 32	29	18.75	10.25	6.43	-	46.59	16.9	36.51	53.41
SSD 33	40	20.61	19.39	10.71	-	29.24	19.02	51.74	70.76
SSD 34	48	23.81	24.19	13.57	-	15.22	23.56	61.22	84.78
SSD 35	41	21.05	19.95	10.71	-	49.98	29.28	20.74	50.02
SSD 36	39	21.89	17.11	10	-	33.64	41.43	24.93	66.36
SSD 37	38	20.83	17.17	9.29	-	48.95	24.02	27.03	51.05
SSD 38	41	25.00	16.00	11.43	-	49.12	25.2	25.68	50.88
SSD 39	35	21.64	13.36	10	-	0.99	29.35	69.66	99.01
SSD 40	42	27.78	14.22	10.71	-	49.27	28.3	44.58	72.88
SSD 41	31	20.69	10.31	10	-	46.8	34.41	18.79	53.2
SSD 42	40	23.81	16.19	10.71	4.1	51.31	38.32	6.27	44.59
SSD 43	31	21.24	9.76	10	5.26	57.61	31.02	6.11	37.13
SSD 44	47	25.66	21.34	11.43	-	49.87	38.8	11.33	50.13
SSD 45	35	21.89	13.11	10	-	49.57	28.2	22.23	50.43

Atterberg Limits

When assessing the settlement and strength properties of soils used for road construction, the Atterberg or consistency limits are applied (Adeyemi, 1995).The liquid limit, plastic limit, plasticity index and linear shrinkage results from the investigated soils ranged from 28 –55%, 18.18–33.33%, 6.47–24.29% and 5.00 – 13.57% while the average values for the liquid limit, plastic limit, plasticity index and linear shrinkage are 38.06%,15.52%, 15.52% and 10.33% respectively. Evaluating the soil samples for road construction based on the liquid limit values as prescribed by the Federal Ministry of Works and Housing (FMWH, 1997) shows that 33 samples representing 73.33% of the soils have liquid limit values of ≤50% recommended specification for subgrade material for road construction while 12 samples representing 26.66% of the samples have liquid limit values of ≤ 35% recommended specification for sub-base material for road construction. The plasticity index shows that 34 samples representing 75.55% of soils have plasticity index (PI) ≤ 35 making them suitable as subgrade materials for road construction while 11 samples representing 24.44% of the samples have plasticity index (PI) of ≤ 12 thereby meeting the (FMWH, 1997) specification for use as sub–base material for road construction. Based on linear shrinkage, forty- one samples have values >8 making them unfit for use as subgrade materials in the construction of roads (Jegede, 2004).

Casagrande's plasticity chart as shown in figure 6 shows that all the soils analyzed fall under clays of medium or intermediate plasticity. This result is in agreement with Bell, (2007) classification where he considered liquid limit values of 35 – 50 % as clays with intermediate plasticity. Given the intermediate plasticity of these soils, detrimental settlement of the soil may not be experienced if utilized for road construction.

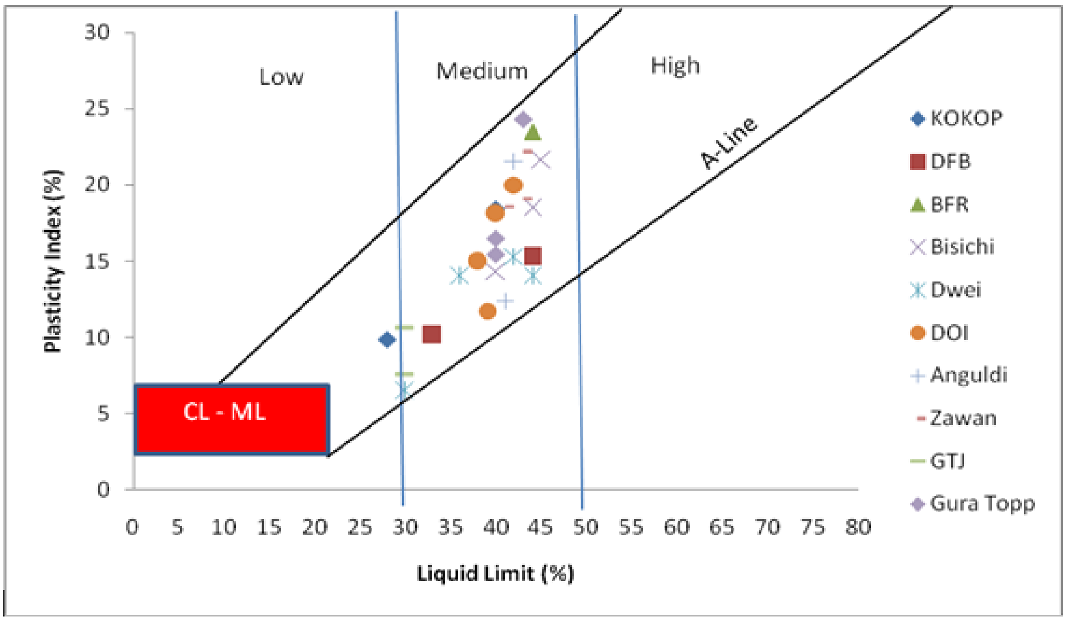

Figure 6: Plasticity Chart showing the intermediate plasticity of mine spoils in the study area.

Grain Size distribution

For engineering reasons, grain size analysis is crucial for assessing the strength of soils (Naresh and Nowatzki, 2006). The grain size distribution results as seen in Table 3show that the percentage of clays, silts, sand and gravel ranged from 5.31– 69.66%, 16.90–53.07%, 0.99–58.45%, and 2.10–22.80% respectively while the average composition of clay, silt, sand and gravel is 25.70%, 30.32%,

Scientia Africana, Vol. 23 (No. 4), October, 2024. Pp 33-50
© Faculty of Science, University of Port Harcourt, Printed in Nigeria *ISSN 1118 – 1931*

41.06% and 8.96% respectively. For subgrade soils to be used in road construction, the Federal Ministry of Works and Housing (FMWH, 1997) advises that they should have fewer than 35% fines (clay and silt). However, the percentage fines ranged from 28.78 – 99.901% with an average of 56.03%. These results when compared with the Federal Ministry of Works and Housing (FMWH, 1997) specification for the construction of roads show that only three (3) samples meet such specifications.

Engineering Properties

Compaction, California Bearing Ratio (CBR), shear strength, and permeability are some examples of the strength or engineering qualities of soils that can be used to characterize the engineering behavior of soils. Tables 4 below have a summary of these characteristics.

Table 4: Summary of Engineering Properties of mine Soils in the Study Area

	Shear Strength Test			Compaction Characteristics			
Sample ID	C (KN/M^2)	ϕ (^{0})	ϒ (KN/M^3)	MDD (g/cm^3)	OMC (%)	CBR (%)	Permeability (mm/Sec)
SSD 1	31	14	18.42	1.52	20.28	59.82	$1.29x10^{-3}$
SSD 2	31	13	19.55	1.56	21.71	48.94	$1.80x10^{-3}$
SSD 3	28	15	14.99	1.51	21.38	37.33	$9.95x10^{-4}$
SSD 4	11	18	17.86	1.62	21.66	29.46	$8.52x10^{-4}$
SSD 5	30	15	17.76	1.6	21.74	24.17	$1.35x10^{-3}$
SSD 6	30	14	15.92	1.5	24.17	43.23	$9.34x10^{-4}$
SSD 7	30	14	20.01	1.71	15.51	27.72	$8.62x10^{-4}$
SSD 8	14	19	18.38	1.64	19.58	24.05	$8.90x10^{-4}$
SSD 9	47	10	18.54	1.74	17.28	22.85	$1.08x10^{-3}$
SSD 10	29	15	18.11	1.82	14.19	30.66	$8.99x10^{-4}$
SSD 11	29	13	20.6	1.53	24.49	26.45	$1.05x10^{-3}$
SSD 12	18	18	17.27	1.84	16.52	26.81	$8.66x10^{-3}$
SSD 13	31	15	17.75	1.72	14.69	27.05	$1.35x10^{-3}$
SSD 14	43	13	17.94	1.66	17.5	20.2	$8.28x10^{-4}$
SSD 15	40	12	18.76	1.58	19.93	32.59	$1.10x10^{-3}$
SSD 16	11	15	18.64	1.72	19.66	48.13	$7.48x10^{-4}$
SSD 17	30	10	18.76	1.7	16.46	28.86	$1.08x10^{-3}$
SSD 18	20	12	20.43	1.56	19.7	39.14	$8.59x10^{-4}$
SSD 19	32	10	19.93	1.56	16.26	24.65	$1.09x10^{-3}$
SSD 20	27	10	17.51	1.61	17.63	36.07	$1.07x10^{-3}$
SSD 21	30	11	16.92	1.65	15.22	24.89	$8.18x10^{-4}$
SSD 22	23	11	19.36	1.77	21.3	26.33	$7.36x10^{-4}$
SSD 23	34	10	19.02	1.60	17.28	25.73	$1.12x10^{-3}$
SSD 24	38	10	17.6	1.62	18.8	48.82	$9.53x10^{-4}$
SSD 25	28	11	18.35	1.74	17.7	34.75	$8.32x10^{-4}$
SSD 26	40	10	17.78	1.64	21.48	32.59	$8.62x10^{-4}$
SSD 27	40	10	18.47	1.76	18.6	41.3	$1.20x10^{-3}$
SSD 28	14	14	17.86	1.88	20.06	23.45	$8.49x10^{-4}$
SSD 29	25	10	18.1	1.72	17.8	47.13	$1.62x10^{-3}$
SSD 30	33	10	17.68	1.77	22.33	44.67	$1.28x10^{-3}$
SSD 31	33	10	19.3	1.62	21.48	47.86	$1.14x10^{-3}$
SSD 32	30	10	19.53	1.63	19.64	26.69	$7.52x10^{-4}$
SSD 33	30	11	19.12	1.66	19.29	29.28	$1.29x10^{-3}$
SSD 34	43	9	15.68	1.63	18.73	60.72	$1.28x10^{-3}$
SSD 35	40	10	19.69	1.64	18.55	34.87	$8.60x10^{-4}$
SSD 36	20	12	16.87	1.65	20.85	51.46	$1.29x10^{-3}$
SSD 37	12	15	18.67	1.64	17.53	33.07	$1.28x10^{-3}$
SSD 38	42	15	18.26	1.61	20.41	28.98	$8.24x10^{-4}$
SSD 39	44	10	18.31	1.47	16.77	42.75	$1.40x10^{-3}$
SSD 40	41	10	18.62	1.63	19.02	35.83	$1.25x10^{-3}$

SSD 41	32	11	18.02	1.59	18.81	34.27	1.73×10^{-3}
SSD 42	44	9	20.19	1.68	20.34	31.56	8.60×10^{-4}
SSD 43	30	11	19.8	1.71	15.33	27.72	1.30×10^{-3}
SSD 44	49	10	18.21	1.59	20.56	35.29	7.64×10^{-4}
SSD 45	28	12	20.15	1.65	16.45	30.72	8.67×10^{-4}

Compaction

The accomplishment of a high degree of densification is necessary for the compaction of soils for construction to avoid harmful consolidation under applied load (Olofinyo *et al*., 2019). The maximum dry density (MDD) of the soils in the study area ranged from 1.47 to 1.88 g/cm3 at the optimum moisture content (OMC) of 10.30 –24.49%. It can be observed from Figure7 below that most of the soil samples have low maximum dry density (MDD) and high optimum water content (OMC), followed by those of both medium MDD and OMC and the least samples have high MDD and low OMC. Thirteen (13) representing 28.88% of the samples have MDD values above the minimum value of 1.70 g/cm3 as specified by the Federal Ministry of Works and Housing (FMWH). This according to Oyem *et al*., (2020), the soils have limited bearing capacities and eventually cannot serve appropriately as construction barriers due to the weak MDD and high OMC unless they are adequately compacted and stabilized to reduce voids, boost strength, and decrease its permeability. This indicates that to give the greatest strength, obstruct water infiltration, and distribute wheel loads evenly throughout the pavement structures, the foundation of pavement structures made of these materials must always be compacted above the MDD and OMC values.

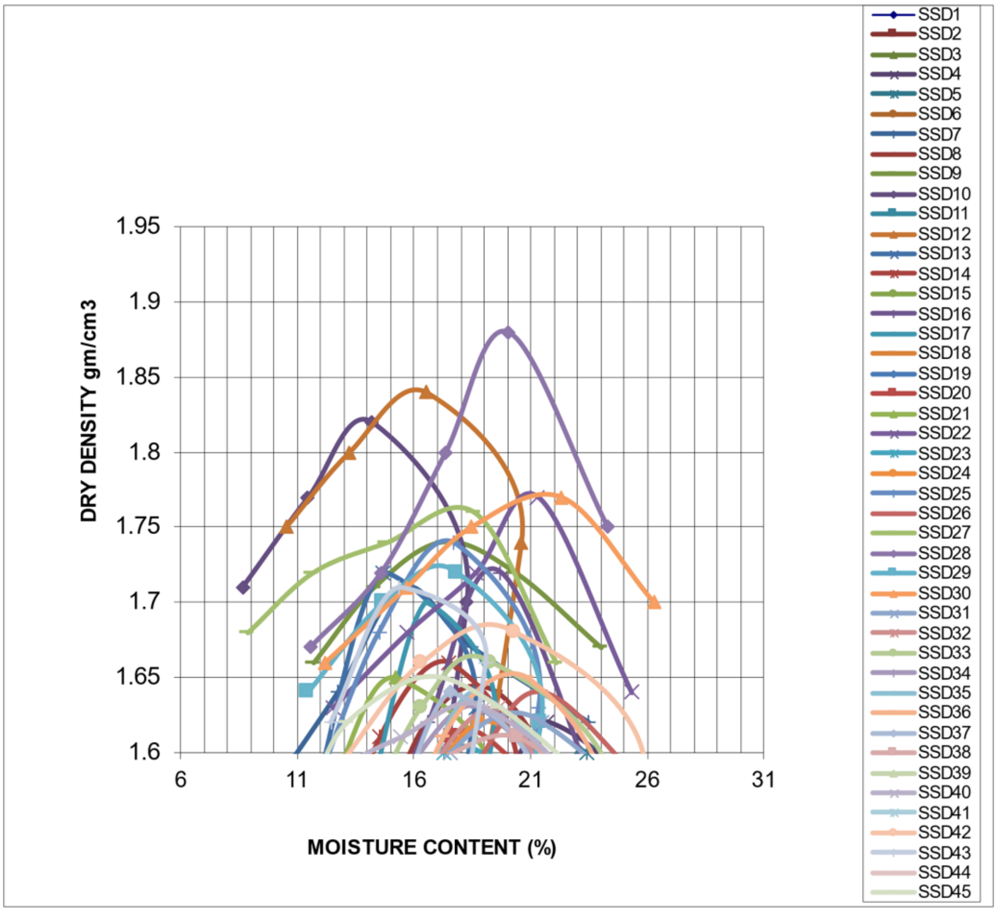

Figure 7: Stacked compaction curve for soil samples in the study area.

Scientia Africana, Vol. 23 (No. 4), October, 2024. Pp 33-50
© Faculty of Science, University of Port Harcourt, Printed in Nigeria *ISSN 1118 – 1931*

California Bearing Ratio (CBR)

A common engineering laboratory test used to evaluate soil strength for sub-grade, sub-base, and base course materials for road, footpath, and airport pavement design is the California bearing ratio (Olofinyo et al., 2019). The results of the unsoaked California Bearing Ratio (CBR) ranged from 20.20–60.72% with an average of 34.64%. All the soil samples analyzed have CBR values greater than the ≥ 15% recommended as subgrade materials for road construction and none meet the ≥ 80% for sub-base material as specified by the Federal Ministry of Works and Housing (FMWH, 1997). To obtain the necessary strength for road construction materials, the soils must be treated to improvement procedures before being used as a sub-base material for road construction.

Direct Shear Strength

One of the most important engineering characteristics of soil is its shear strength, this is essential each time an engineering structure depends on the soil's shearing resistance (Kamtchueng *et al*., 2015). The angle of internal friction (ϕ) ranged from 9–19 ° and the cohesion(C) ranged from 11–49 KN/M^2. These values are closely related to the properties of some Nigeria's lateritic soils (cohesion range of 65– 75KN/M^2 and friction angle range between 26-31°) (Oladele *et al*., 2012; Aloa and Opaleye 2011). Due to their relatively low cohesiveness and angle of internal friction values, these findings demonstrate that the soils in the study area have limited bearing capacity. Consequently, unless the soil is thoroughly compacted, it will be susceptible to erosion and suddenly collapse under applied weight when used for road construction.

Permeability

For the soils, the coefficient of permeability varied from 1.05 x 10^{-3} – 9.95x 10^{-4} mm/sec with a mean value of 1.24x10^{-3} mm/sec. This suggests that the soil is silt to clay and can be classed as medium to low permeable, making the soil suitable as subgrade material for the construction of roads (Igwe *et al*., 2013). One can then conclude that the soils in the study area are impervious and consist of fine sand, silt and clay and can be utilized as construction material for roads and other earthworks.

CONCLUSIONS

The mine spoil of the Jos- Bukuru tin field has been evaluated and the results reveal the following;

1. The soils (mine spoils) produced from tin mining are derived from a granitic to intermediate source having a yellowish to brownish colouration probably formed in an oxidizing environment.
2. The mineralogical evaluation using XRD indicates an average composition of; quartz (77.38%), kaolinite (18.70%), hematite (1.57%), rutile (0.42%), goethite (1.56%), gibbsite (0.31%) and montmorillonite (0.06%). The low composition of montmorillonite which is a high-swelling clay, implies that the undesirable problem of swelling and shrinking of the soil when utilized for construction purposes will not be experienced. A Chemical test based on the silica-sesquioxide ratio shows that most (82.22%) of the soils are non-lateritic tropically weathered soils and 17.78% of the soils are lateritic soils while none is a true laterite.
3. The soils' average composition, as determined by the geotechnical tests, is 56.03% of fines, a liquid limit of 38.06%, a plastic limit of 15.52 % plasticity index of 15.52% and an average linear shrinkage value of 10%. The average maximum dry density (MDD) and the optimum moisture content (OMC) are 1.65g/cm^3 and 19% respectively while the average unsoaked California bearing ratio of the soil samples is 34.64%. This result compared with the specifications by the Federal Ministry of Works and Housing (1997), makes the soil appropriate for use as a subgrade material while only a few satisfy the requirements

for use as a sub-base material for constructing roads.

4. The Atterberg consistency limit tests show that the soil samples are clays of intermediate plasticity with low-medium swelling potential. Consequently, they can be used as subgrade and sub-base building materials for roads with mild traffic.
5. The soil samples have an average permeability of 1.24×10^{-3} mm/sec while the average angle of internal friction (ɸ) and cohesion (C) are 12.15^0 and 30.77 KN/M^2 respectively. In light of these findings, it can be said that the soil has poor to good shear strength capabilities, is impervious, and is composed primarily of fine sand, silt, and clay. It can also be utilized as a material for embankments during the construction of highways and other earthworks.

Conflict of Interests/ Competing Statement

We wish to declare that we (authors) do not have any conflict of interest during and after the preparation of this manuscript.

Authors' Contributions

This work was conceived by SSD and OI. Field investigations and collection of data were done by SSD and DBA under the supervision of OI. Critical and valuable comments to improve the content of the work during the preparation of the manuscript were done by OI.

The manuscript has been read and approved by both authors.

REFERENCES

Adegoke–Anthony WC and Agada, O.A. (1980). Technical Lecture. Lagos Nigeria Geotechnical Characteristics of Some Residual Soils and their Implications on Road Design in Nigeria, 1– 16.

Adeyemi, G.O, Oloruntola, M.O, and Adeleye, A.O (2014). Geotechnical Properties of Subgrade Soils along Sections of the Ibadan–Ife Expressway, South-Western Nigeria. *Journal of Natural Sciences Research,* 4 (23), 67 – 7

Aghamelu, O.P, and Okogbare, C.O. (2011). Geotechnical Assessment of Road Failures in the Abakaliki Area, Southeastern Nigeria. *International Journal of Civil & Environmental Engineering*, 11,12 –19.

Akintorinwa, O.J., Ojo, J.S., Olorunfemi, M.O. (2011). Appraisal of the causes of pavement failure along Ilesa -Akure highway, southwestern Nigeria using remotely sensed and geotechnical data. *Ife Journal of Science*,13(1), 185- 198.

Alao, D. A., and Opaleye, S. T. (2011). Geotechnical analysis of slope failure of a kaolin Quarry at Kura, Jos North-Central. *International Journal of Scientific Research*, 1(1),87–102.

Aliu, J.O., Itiowe, K., Avwenagha, E.O. (2021). Geochemical Composition, Mineralogy and Geotechnical Characteristics of some Clay deposits in parts of the South Niger Delta, Nigeria. *Global Journal of Geological Sciences*. 19, 41-51

ASTM D (6913)- 04 (2009). Standard methods for particle size distribution (Gradation). ASTMinternational, West Conshohocken

British Standard 1377 Part 2 (1990). Standard Methods of testing soils for civil engineering purposes. British Standard Institution, London.

Daramola, S.O., Malomo, S. and Asiwaju-Bello, Y.A. (2015). Engineering Geology of failed sections of Isua – IdoaniRoad southwestern Nigeria. *Journal of Environmental and Earth Science*, 5(19), 38 – 45

Daramola, S.O., Malomo, S. and Asiwaju-Bello, Y.A. (2018). Premature failure of a major highway in southwestern Nigeria: the case of Ipele–Isua highway. *International Journal of Geo-Engineering*, https://doi.org/10.1186/s40703-018-0096-9. 9(28), 1-12.

Falconer, J.D. (1911). The Geology and Geography of Northern Nigeria. Macmillan: London, UK, 147 – 154.

Scientia Africanа, Vol. 23 (No. 4), October, 2024. Pp 33-50
© Faculty of Science, University of Port Harcourt, Printed in Nigeria *ISSN 1118 – 1931*

Falconer, J.D. (1921). The Geology of the Plateau Tin Fields. Bulletinof Geological Survey of Nigeria. No. 1

Garg, S. K. (2009). Soil Mechanics and Foundation. Engineering (7th ed., pp. 673–683). New Delhi: KhanaPublishers.

Gu, X, X., Liu, J.M., Zheng, M.H., Tang, J.X., and Qi, L. (2002). Provenance and tectonic setting of the Proterozoic turbidites in Hunan, South China. Geochemical evidence. *Journal of Geochemical Research*, 72 (3),393-407.

Hassan, A, M., Raji, B.A., Malgwi, W.B and Agbenin, J.O. (2015). The Basaltic soils of the Plateau State, Nigeria: Properties, Classification and Management Practices. *Journal of Soil Science and Environmental Management*, 6 (1), 1-8

Hayashi, K.I.; Fujisawa, H.; Holland, H.D.; Ohmoto, H. (1997**).** Geochemistry of Gasedimentary rocks from northeastern Labrador, Canada. Geochim. Cosmochim. Acta. 61, 4115–4137.

Heinrich, B., Nicole, Dobrzinski (2011). A review of the Chemical Index of Alteration (CIA) and its application to the study of Neoproterozoic glacial deposits and climate transitions. Geological Society of London Memoirs. 36, 81 -92

Igwe, O., Mode, W., Nnebedum, O. Okonkwo, I. Oha, I. (2013). The analysis of rainfall-induced slope failure at the Iva Valley area of Enugu State. *Environmental Earth Science*, https://doi.org/10.1007/s12665-013-2647-x

Kamtchueng, B. T., Onana, V.L., Fantong, W.Y., Ueda, A., Ntouala, F.D.R., Wongo, H.D.M., Ndongo, B.G., Ze, N.A., Kamgang, K.B.V and Ondoa, J.M. (2015). Geotechnical, Chemical and Mineralogical evaluation of lateritic soils in the humid tropical area (Mfou, Central Cameroun): Implications for road construction. *International Journal of Geo-Engineering*, DOI 10. 1186/S 40703 -014-0001. 1-20.

Lar, U., Shettima, E. and Dibal, H. (2014). Heavy metals in the urban soils and vegetables in Jos metropolis, Nigeria: Implication on Children health. *American Journal of Environmental Protection*, 3 (6-2): 70 – 76.

Layade, G.O, Adegoke, J.A, and Oyewole, I.T (2017). Geophysical investigation of the causes of road pavement failure along Ibadan- Lagos dual carriage, South Western Nigeria. Journal of Applied Science Environment and Management 21(3),547 – 554

Macleod, W, N., Turner, D.C., and Wright, E.P. (1971). The Geology Jos-Plateau, vol.1General Geology. Geol. Surv. Of Nigeria. Bull. No. 32.

Mahalinger-Iyer, U., & Williams, D. J. (1997). Properties and performance of lateritic soil in roadpavements. *Engineering Geology*. 46,71–80.

Millogo, Y., Traore, K., Ouedraogo, R., Kabore, K., Blanchart, P., &Thomassin, J. H. (2008). Geotechnical, mechanical, chemical and mineralogical characterization of lateritic gravels of Sapouy (Burkina Faso) used in road construction. Construction Building Materials. 22, 70–76.

Momoh, L.O., Akintorinwa, O., Olorunfemi. M.O. (2008). Geophysical investigation of highway failure- Acase study from a basement complex in southwestern Nigeria. *Journal of Applied Sciences Research*, 4(6),637 – 648.

Naresh, C.S, Nowatzki, P.E. (2006). Soils and foundations. Ref Man Fed Highway Adm 2, 8–75

Nesbitt, H.W. and Young, G.M. (1984). Prediction of some weathering trends of plutonic andvolcanic rocks based on thermodynamic and kinetic considerations. *Journal of Geology*, 48,1523-1534.

Nigerian Federal Ministry of Works and Housing (1997). General specifications for roads and bridges. Federal Government of Nigeria, Lagos.

Northmore, K. J., Culshaw, M. G., Hobbs, P. R., Hallam, J. R., & Entwisle, D. C. (1992). Engineering Geology of Tropical Soils – Summary Finding and their

Application for Engineering Purposes. Nottingham: Technical report WN/93/15, Overseas Development Administration (ODA) and British Geological Survey (BGS).

Nwankwoala, H.O, Amadi, A.N, Ushie, F.A, Warmate, T (2014). Determination of subsurface geotechnical properties for foundation design and construction in Akenfa Community, Bayelsa Nigeria. *American Journal of Civil Engineering and Architecture*, 2(4), 130–135

O'Flaherty, C. A. (1988). Highway Engineering (Vol. 2). London, UK: Edward Arnold Publishers.

Onuoha, D.C. and Onwuka, S.U (2014). The Place of Soil Geotechnical Characteristics in Road Failure, a Study of the Onitsha-Enugu Expressway, Southeastern Nigeria. *Civil and Environmental Research*,6(1), 55 – 67

Oladele, A. O., Olusolo, J. O., & Emmanuel, T. A. (2012). Engineering properties of lateritic soils around Dall Quarry in Sango area, Ilorin, Nigeria. E*arth Science Research*, 1, 2. doi: 105539/esr.v1n2p71.

OlofinyoO.O., Olabode,O.F., Fatoyinbo, I.O. (2019). Engineering properties of residual soils in part of Southwestern Nigeria: implication for road foundation. *SN Appl. Sci*,1:507. https://doi.org/10. 1007/ s42452-019-0515-3

Olowolafe, E.A (2002). Soil Parent material and properties in two separate catchment areas on the Jos Plateau, Nigeria. *GeoJournal*, 56, 201 – 212. https://doi.org/10.1023/A:1025158121610

Omotehinse, A.O., Ako, B.D. (2019). The environmental implications of solid mineral mining in Nigeria with a special focus on tin in Jos and Coal in Enugu. *Journal of sustainable mining*, 18, 18-24

Oyem, E.I., Igwe,O., Bernadette, U.U. (2020). Evaluation of road failure along erosion-pronehighways in Ogun State southwestern Nigeria using integrated methods. *SN Applied Sciences*, (2020) 2:2094 https://doi.org/10.1007/s42452-020-03849-x

Simeon, O.O., Adebayo, O.O., Peter, O.A., Sadiq, M.O. (2018). Geotechnical assessment of pavement failure along the Lagos-Ibadan expressway. *FUOYE Journal of Engineering and Technology, 3(2), 113 – 117.*

Tockol, I., Massiéra, M., Chiasson, P. A., &Maiga, M. S. (1994). Les graveleuxlatéritiquesdans les pays du sahel: Cas des routes non revêtues (pp. 3423–3431). Rotterdam, Holland: 7èmeCongrès International de l'AIGI.

Tse,A.C. and Efobo, O.(2016).Geotechnical and Mineralogical Evaluation of Soils Underlying a Failed Highway Section in South Eastern Nigeria.*Journal of Earth Science and Materials Engineering*,6. 98 – 109

US, EPA (2012). Environmental Response Team. Standard Operating Procedures. 1-13