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Mineralogical and Geotechnical Characterization of Maiduguri Black Cotton Soil by X-Ray Diffraction (XRD), X-Ray Photoelectron (XPS) And Scanning Electron Spectroscopy (SEM)

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ABSTRACT

The focus of this paper is to characterize clayey soil samples along the Maiduguri-Gamboru Road, Borno State, Nigeria using advanced characterization techniques in order to improve the soil engineering properties for road pavement construction and foundations. Soil samples were mineralogically characterized using X-ray Powder diffractometry (XRD), X-ray Photoelectron Spectroscopy (XPS), Scanning Electron Spectroscopy (SEM), soil index properties (Atterberg Limits) and strength tests. X-ray powder diffraction analysis detected the presence of four minerals: Quartz, SiO_2; Calcite, $CaCO_3$; Larnite, Ca_2SiO_4; and a clay mineral Kaolinite, $Al_2(Si_2O_5)(OH)_4$.

XPS peak analysis by CasaXPS software confirmed the availability of eight (8) elements with Percentage Atomic Concentration as: Oxygen (65.14%), Silicon (15.79%), Aluminium (7.53%), Carbon (5.96%), Magnesium (2.11%), Ferrous (1.96%), Calcium (0.82%) and Nitrogen (0.68%) with traces of Sodium (0.00%) and Sulphur (0.00%). The ratio of the exchangeable cation Calcium / Magnesium is less than 0.5 indicating an unstable soil. The EDS chemical analysis by SEM detected eleven (11) elements. The distribution of the chemical elements by atom% in descending order is: Oxygen (63.67%), Silicon (18.66%), Aluminium (10.36%), Ferrous (3.44%), Carbon (1.66%), Calcium (0.6%), Potassium (0.52%), Tin (0.37%), Sodium (0.36%), Magnesium (0.25%), Phosphorous (0.13%), with traces of Sulphur and Barium. The Percentage Atomic concentration of carbon and aluminium given by XPS are much higher than that given by SEM (atomic %) while that of Oxygen is similar.

The soil index properties: high liquid limit (68%), low plastic limit (25.3%), high plasticity index (41.7%) and free swell (50%) indicate a high swelling and highly compressible soil with an estimated uplift pressure of 151.8kN/m^2. This is due to the presence of clay minerals. The soil strength characteristics: Maximum Dry Density (1708.9 Kg/m^3); Un-soaked CBR (36%) and the soaked CBR (17%) fall below the minimum requirement for sub-base and base course. The frequent damages to road pavements and foundations in the area can be attributed to the chemical composition and mineral assemblage of the soil in the area. The characterization and knowledge of the chemical assemblage will make possible the effective stabilization as chemical stabilization will be directed at the different chemical compounds in the soil.

Keywords: *Atomic Absorption Spectroscopy, X-ray Diffraction, X-ray Photoelectron, Soil Index,Scanning Electron Microscopy, Strength Test, Chemical composition, Clay minerals*

1. INTRODUCTION

All structures and infrastructures are founded on soil which is a geological material. Soil properties are controlled by the minerals present in their mineralogy. The knowledge of minerals present in a particular soil formation is therefore important to the safety and success of the infrastructure on it.

The Maiduguri-Gamboru Road is of significant and economic importance to Nigeria and the North Eastern states of Nigeria in particular: it is the main international road between Nigeria and the neighboring North African countries thereby promoting international trade, tourism, foreign investment and income. The road is frequently subjected to severe pavement deformation and distortion resulting in frequent rehabilitation, loss of lives, economic losses and under-development. The cause of the premature failure and performance can be attributed to the presence of expansive clays. But the characteristics of this clay vary from place to place and on its mineralogy (Ola, 1983 and NIBBRI 1993).

Failure of road pavement is common in most parts of the world. A number of causes have been identified which includes poor construction, poor pavement design, over-use and overloading. Adeyemi and Oyeyemi (2000) and Meshida (2006) however attributed the majority of road failures to geotechnical factors. Most Nigerian roads are flexible pavement, hence they have little tensile strength and any change in the shape of the subgrade is followed by a change in the shape of the subgrade (Sutton, 1985). Since the road surface sits on the subgrade and depend on the strength of the subgrade, then there is need to know the strength and geotechnical characteristics of the subgrade and the underlying soil.

Clay soils are prone to swelling and shrinkage which may be excessive thereby causing severe damages to road pavements, foundations and infrastructures founded on it. The mechanism of swelling and shrinkage in soils can best be explained and solved by the knowledge and understanding of the mineralogical and chemical composition of the soil and its effect on the strength characteristics of the soil. This is essential to the development of chemical stabilizer for each type of soil. A lot of stabilizers and admixtures like cement, lime, pozzolanic and wastes have been developed to stabilize and improve the properties of expansive clays (Ogundalu et al 2013). These have achieved limited success because the improvement in the properties of a soil depends on the chemical reaction and bonding between a soil stabilizer/admixture and the soil mineral and chemical composition.

Bell (1996) reported that many of the important engineering properties of clay soils are improved by adding lime. When lime is added to clay soils, calcium ions initially combine with or absorb clay minerals. But the addition of lime contributes towards the improvement of soil workability but not to the strength increase (Ramadas et al, 2011). The effectiveness of lime stabilization is independent on the development of reaction products formed from the attack of lime on the minerals on a deposit of clay (Bell, 1996). Effective stabilization depends on a cation exchange between the clay soil and the stabilizer. The case with which a cation can be replaced by another depends mainly on the valency, relative concentration of the different types of cations and the cation size (Singh 2010).

1.1. Geology, Physiographical and Climatic conditions of the study area

Clay soils investigated in this work were collected along Dikwa-Marte Road, off the Maiduguri-Gamboru Road, Borno State, Nigeria at Latitude 12^0 04'.513''N, Longitude 13^0 55'.143''E. This is the main international road between Nigeria and the neighboring North African countries. The area falls within the Lake Chad Basin and partly within the River Benue trough. This is a sequence of lacustrine and fluviatile clays and sands of the Pleistocene age laid down during the Tertiary and Quaternary periods (Ola, 1983). The formation sequence is made of weathered shaly and clayey sediments as well as basaltic rocks (Osinubi 2006). It is believed that the soils derive their origin in Nigeria from basic igneous rocks such as basalts of the upper Benue trough and from quaternary sediments of lacustrine origin from the Chad basin which consists mainly of shales, clays and sandy sediments (NIBBRI, 1993).

The physiographical features and climatic conditions of the Chad basin is a flat, poorly drained area. It is an area of high temperature and humidity with alternating wet and dry season and an annual rainfall less than 100cm. Sediments are deposited as the lake expands during raining season and shrinks during dry periods. These conditions are conducive to leaching, alkaline environment and the retention of calcium and magnesium in the soil. The process of formation compares favourably with formation of similar tropical volcanic soils generated from volcanic parent rocks and weathered under conditions of high temperature and humidity with alternating wet and dry seasons (Chen, 1975; Nicholson et al, 1994).

2. MATERIALS AND METHODS

2.1. Clay Soil

Clay soils investigated in this work consist of samples collected along the Maiduguri-Dikwa-Gamboru Rd, Borno State, Nigeria. All were collected and investigated in their natural states. The samples are dark grey in colour. Three main types of analyses were performed on the soil samples: oxide and metallic composition by X-ray Power Diffraction (XRD) tests for mineral identification, X-Ray Photoelectron Spectroscopy (XPS), Scanning Electron Spectroscopy (SEM) and soil index analysis. The clay soils classified as A-7-6 in the AASHTO Soil Classification System (AASHTO 1986) and CL in the United Soil Classification System (ASTM 1992).

2.2. X-ray Power Diffraction (XRD)

The clay minerals present in the soil samples were identified using the X-ray Power Diffraction (XRD). 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 power diffraction was performed on the various soil samples at the Cornel Center for Material Research, Cornel University, Ithaca, USA.

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 instrument is used extensively for phase identification, which is done by comparing diffraction scans with the JCPDS database of ~250,000 patterns. Additional information that can be obtained through X-ray diffraction includes crystallite size, % crystallinity, quantification of phases in a sample, and lattice parameter determinations. Data analysis is performed using Materials Data Incorporated's JADE 7.0 software package with whole pattern fitting. Phase identification is possible using ICDD's PDF-4 database. 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 was displayed on the computer monitor. Minerals present were identified by comparison with established data and patterns available in the Mineral Power Diffraction File Data Book (ICDD 2001). A summary of the minerals present in the clay soils is presented in Tables 3.

2.3. X-ray Photoelectron Spectroscopy (XPS)

The X-ray Photoelectron Spectroscopy was done at Cornell Center for Material Research, CCMR, Cornell University, Ithaca, USA. The elemental analysis of the surface was carried out using a Surface Science Instruments (SSI), Model: X-Probe (SSX-100) with X-ray kV and mA emission: 1486.6eV (200W), 1.5 to 22.5 mA (spot-size dependent). The X-ray Energy is 1486.6 eV (8.3393 Å) with 180-degree hemispherical Analyzer type. The System Base Pressure is < 10-9Torr while the Normal Operating Pressure is 1.6 x 10-9 Torr. The Angle of X-ray incidence and emission is 55 degrees from sample normal while the angle between x-rays and analyzer, a=71^0 (relative to sample normal). Photoelectrons were collected at Standard Electron emission angle: = 55° (relative to sample normal). The analyzer is a 180-degree hemispherical-type analyzer with an electronically defined, 128 active channels, 40 mm x 40 mm resistive anode SSI Position Sensitive Detector, which has a maximum count rate of 1,000,000. A pass-energy of 150V was used for survey scans. The test data result is plotted using a CasaXPS software.

2.4. Scanning Electron Microscopy (SEM)

The Scanning Electron Microscopy was done at Cornell Center for Material Research, CCMR, Cornell University, Ithaca, USA, on the JEOL JXA-8900 Super Probe. The JXA-8900 Super Probe is a high resolution SEM and a WD/ED Combined Electron Probe Micro-analyzer (EPMA). The combination of up to 5 wavelength dispersive X-ray spectrometers (WDS) and an energy dispersive X-ray spectrometer (EDS) assures the most efficient and accurate analysis. Computer input analyzes data from the two types of X-ray spectrometers and presents the data as a unified analysis. The WD/ED combined system can simultaneously analyze up to 13 elements (5 WDS, 8 EDS). The backscattered electron image, provided by a highly sensitive solid state detector, and the secondary electron image, brings the total obtainable signals to 15. The WD/ED combined micro-analyzer provides for higher detection sensitivity for trace elements, higher accuracy of quantitative analysis, higher resolving power (resolution) for adjacent X-rays and higher accuracy of quantitative analysis for light elements. Using the microprobe, only standard-less quantitative analysis was done with EDS, no WDS.

2.5. Soil Index Properties

Bulk samples were taken for laboratory tests to determine the necessary classification tests. Fresh soil samples collected and tested within 3 months were used in order to prevent alteration of the properties of the residual soil. All the samples were air-dried for 1-day before testing in order to simulate field conditions. Laboratory tests were conducted to determine the index properties of the natural soil according to British Standard, BS 1377 (1990). The soil was characterized and classified by the following tests: Atterberg limits, compaction, California bearing ratio (CBR) and unconfined compressive strength (UCS). A summary of the soil index properties is presented in Table 8. The results are in agreement with those obtained by Ola (1983) and Osinubi (2006) for soils from the study area.

2.5.1 Compaction Tests

Tests involving the compaction tests and strength tests of CBR and Unconfined compressive strength were carried out using the West African Standard (WAS) energy levels. If the BS (Proctor) compaction mould is used, the compactive effort for the WAS consists of the energy derived from a 4.5kg rammer falling through 45cm onto five layers, each receiving 10 blows. When the CBR mould is used, the WAS compactive effort is also derived from a 4.5kg receiving 25 blows (Osinubi 1998a,). WAS compaction is commonly used in West Africa region.

2.5.2. California Bearing Ratio (CBR) Tests

California Bearing ratio (CBR) tests were done in accordance with the Nigerian General Specifications (1997) which stipulates that specimens are to be cured in the dry for 6 days and then soaked for 24 hours before testing. Two tests of CBR tests were conducted on each soil sample, one at the Optimum Moisture content, compacted to the Maximum Dry Density (as per the West African Standard of Compaction) and the other test on a similarly compacted under soaked conditions. A four-day soaking period was adopted. During soaking of the sample, the amount of swelling was also measured.

3. RESULTS AND DISCUSSION

3.1 Mineralogical Characterization by X-Ray Diffraction (XRD)

Four (4) minerals including one clay mineral (Kaolinite) were detected by XRD in the soil samples. The names of the minerals, their chemical names, chemical formula, structure and colour are given in Table 1. The spectrum and main diagnostic peaks used for their identification are shown in Figures 1 and 2. The XRD analysis revealed that Quartz, Kaolinite, Calcite and Larnite are the main mineral occurring in the soil sample. The soil samples are within the Lake Chad basin where the land is almost flat with extremely poor drainage conditions. The physiographical features and climatic conditions of the Chad basin is a flat, poorly drained area of high temperature and humidity with alternating wet and dry season and an annual rainfall less than 100cm. Sediments are deposited as the lake expands and shrinks during alternating wet and dry periods.

Table 1: Minerals identified by XRD in soil samples

Name of Mineral	Chemical Name	Chemical formulae	Structure	Colour
Quartz	Silicon oxide	SiO_2	Hexagonal	White
Kaolinite	Aluminium Silicate Hydroxide	$Al_2Si_2O_5(OH)_4$	Triclinic	White/Cream
Calcite	Calcium carbonate	$CaCO_3$	Trigonal	White
Larnite	Calcium Silicate	Ca_2SiO_4	Monoclinic	

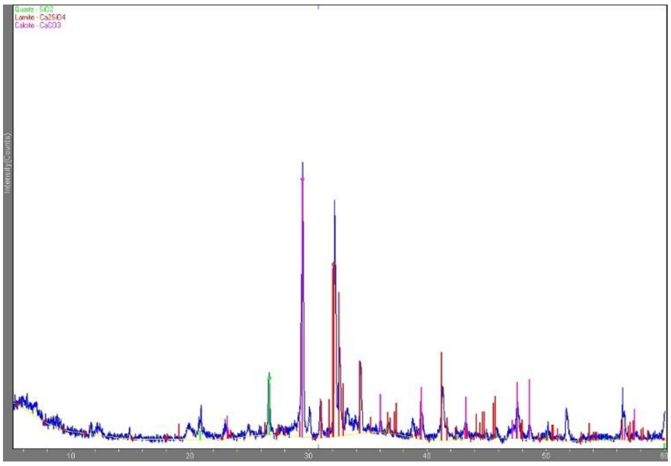

Figure 1: XRD Diffractogram of the soil sample indicating Quarz, Larnite and Calcite

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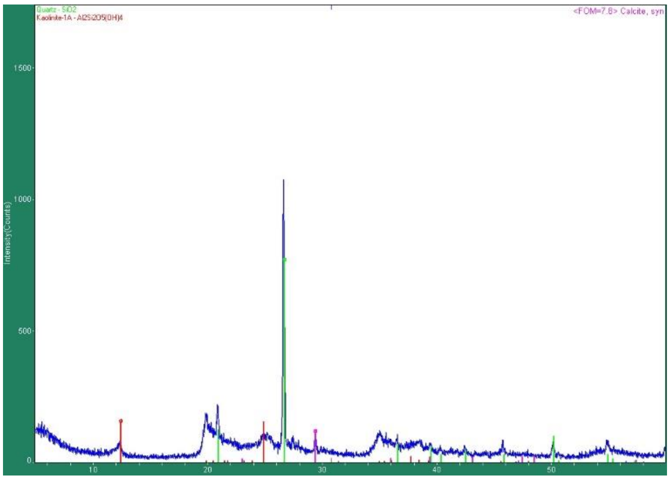

Figure 2: XRD Diffractogram of the soil sample indicating Quarz and Kaolinite

3.2. X-Ray Photoelectron Spectroscopy (XPS)

The elemental composition of the surface of the soil was carried out by X-ray photoelectron spectroscopy. The peak analysis using the CasaXPS curve fitting software attached to the spectrometer gave the name, position, full with at half maximum (FWHM) and Percentage Atomic Concentration of each element (10), present in the clay sample (Figure 3). The XPS phase patterns and peak analysis by CasaXPS software confirmed the availability of eight (8) elements and traces of two (2) elements. The Percentage Atomic Concentration of the various elements in descending order is: Oxygen (65.14%), Silicon (15.79%), Aluminium (7.53%), Carbon (5.96%), Magnesium (2.11%), Ferrous (1.96%), Calcium (0.82%) and Nitrogen (0.68%) with traces of Sodium (0.00%) and Sulphur (0.00%), Table 2. The Silicon and Oxygen constitute over 80% of the percentage atomic composition of the soil sample. The ratio of the exchangeable cation Calcium / Magnesium (0.82/2.11=0.39) is less than 0.5, this shows that the soil is unstable as the ratio of Calcium / Magnesium must be higher than 0.5 for a soil to be considered to be stable. The higher this ratio, the more stable the soil. Calcium tend to form ionic compounds with very strong bonds while Magnesium compounds are mainly ionic compounds but show characteristics of covalent bonds which is less stable.

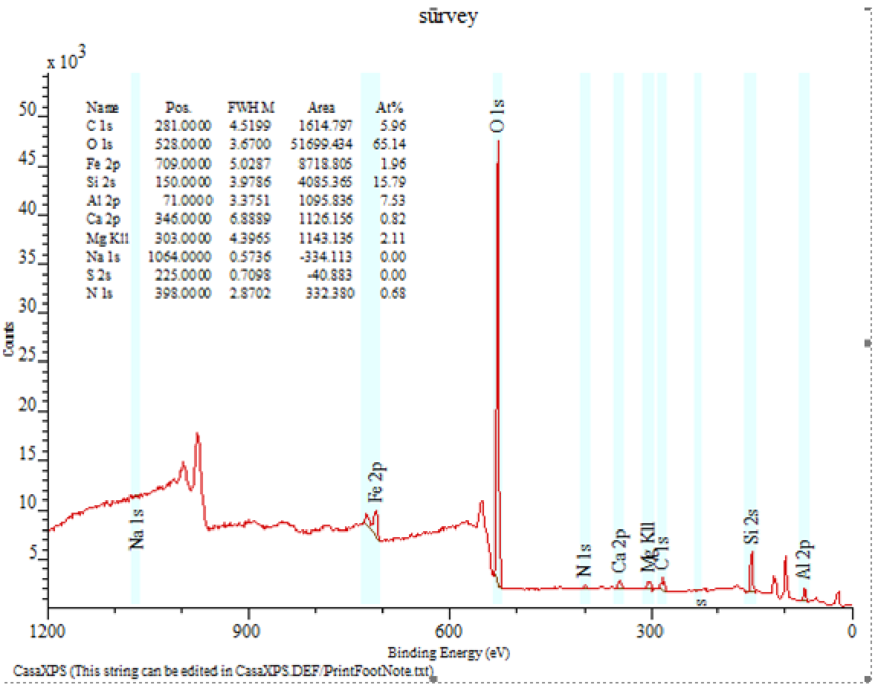

Figure 3: XPS Spectrum of surface elemental composition

Table 2: XPS Percentage Atomic Composition of Soil elements

Name	Percentage Atomic Concentration (%)
Carbon (C 1s)	5.96
Oxygen (O 1s)	65.14
Ferrous (Fe 2p)	1.96
Silicon (Si 2s)	15.79
Aluminium (Al 2p)	7.53
Calcium (Ca 2p)	0.82
Mg K11	2.11
Sodium (Na 1s)	0.00
Sulphur (S 2s)	0.00

Nitrogen (N 1s)	0.68
Total (%)	99.99

3.4. Scanning Electron Microscopy (SEM)

The EDS chemical analysis by SEM detected that eleven (11) elements abound in the clay soil. These are Carbon, Oxygen, Sodium, Magnesium, Aluminium, Silicon, Phosphorous, Potassium, Calcium, Tin and Ferrous with traces of Sulphur and Barium. The distribution of chemical elements by weight, atom and compound are listed in Table 3. Figure 4 provides the details of the EDS analysis data and Figure 5 show the SEM image of the various mineral particles.

Table 3: SEM Quantitative Analysis of Elements detected

Element Line	Weight (%)	Atom (%)	Compound (%)
C K	0.94	1.66	3.45
O K	48.18S	63.67	---
Na K	0.39	0.36	0.52
Mg K	0.29	0.25	0.48
Al K	13.22	10.36	24.98
Si K	24.79	18.66	53.03
Si L	---	---	---
P K	0.18	0.13	0.42
P L	---	---	---
K K	0.96	0.52	1.15
K L	---	---	---
Ca K	1.14	0.60	1.59
Ca L	---	---	---
Ti K	0.83	0.37	1.39
Ti L	---	---	---
Fe K	9.08	3.44	12.98
Fe L	---	---	---
Ba L	---	---	---
Ba M	---	---	---
Total	**100.00**	**100.00**	**99.99**

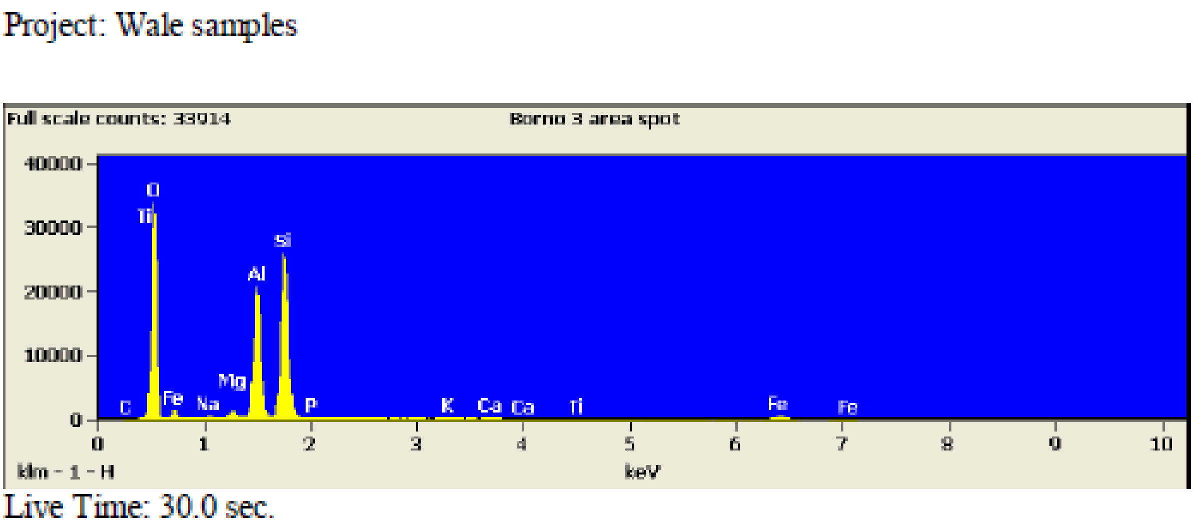

Figure 4: Scanning Electron Microscopy of details of the EDS analysis data of soil sample

Ten (10) elements were detected in the elemental composition by compound (excluding Oxygen). This is because oxygen is very reactive and forms compounds with other elements. The percentages by atom of carbon and oxygen in the soil are higher than the percentages given by their weight by 76.6% (carbon) and 32.2% (oxygen) respectively. All other elements have a reduction in their percentages by atom compared with their respective percentages by weight. The composition by compound appear to be the sum of the percentages by weight and atom (±8 to ±33) %. The Oxygen was calculated stoichiometrically in SEM to get the percentages and may be responsible for this difference

XPS analysis indicated the presence of eight (8) elements and traces of two (2) elements (sodium and sulphur) while SEM analysis indicated the presence of eleven (11) elements. All the elements detected in the XPS analysis were detected by the SEM; in addition Phosphorous, Tin and Barium were also detected by the SEM. This shows that the SEM can detect more elements. However, it should be noted that clay mineral surface usually comprises of a layer of either oxygen or hydroxyls so that hydrogen bonding of water molecules can easily occur (Singh 1990). XPS is more surface sensitive than the SEM microbe, heavier elements like Tin and Barium may not be detected by it. The distribution of chemical elements by Atom in the SEM analysis compares favourably with Percentage Atomic Concentration of XPS for oxygen (±2.3%) and silicon (±18%). The Percentage Atomic concentration of carbon and aluminium given by XPS are much higher than that given by SEM (atomic %). In addition, the differences for some of the elements could suggest that they are part of mineral coatings on the surface of other mineral grains.

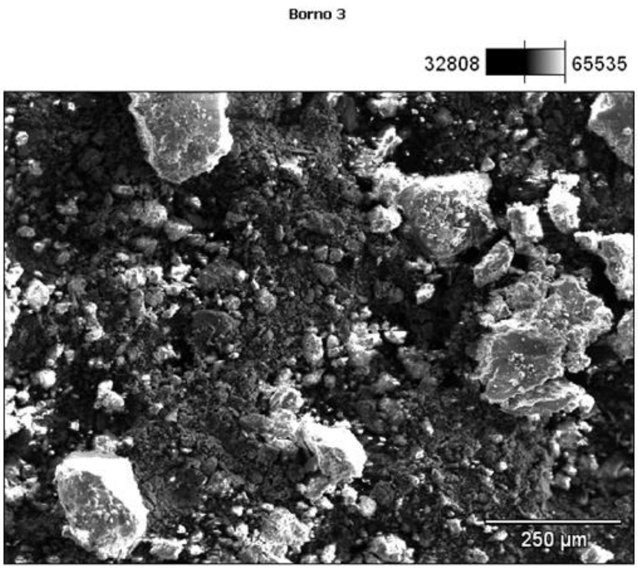

Figure 5: SEM image of the various mineral particles

3.5. Geotechnical Characteristics

3.5.1 Index Property of Soils

The Index properties of the soil samples are summarized in Table 4. Classification test indicate that the soil lie above the A-line (Figure 8) and can be classified as A-7-6 soil under the AASHTO Soil Classification System (1986) or CH in the United Soil Classification System. The soil is clayey. The Liquid Limit and Plasticity Index of the soils do not meet the Nigeria Federal Ministry of Works specifications for sub-base and base course, Table 5. The soils require soil improvement and stabilization.

Table 4: Index properties of soil samples

Property	Borno 3
Liquid limit, %	67.0
Plastic limit, %	25.3
Plasticity Index, %	41.7
Shrinkage limit, %	9.4
Free Swell, %	50
Uplift Pressure (kN/m^2)	151.78
Optimum moisture content (WAS), %	18.9
Maximum Dry Density, MDD (Mg/m^3), WAS	1.709
Unsoaked CBR (%)	36
Soaked CBR (%)	17
CBR Swelling Potential	39.4%
UCS(KN/m^2)	26.7
Swell potential	High
Free Swell	High
Compressibility	High

Table 5: General Requirements for Subgrade, Sub-base and Base Course in Nigeria

Property	Subgrade	Sub-base	Base Course
Fines content (%)	35	35	35
Liquid Limit (%)	80	35	35
Plasticity Index (%)	55	12	12
Soaked CBR (24Hrs), (%)	NA	30	80
Relative Compaction (%)	100	100	100

Source: Federal Republic of Nigeria Highway manual (1992)

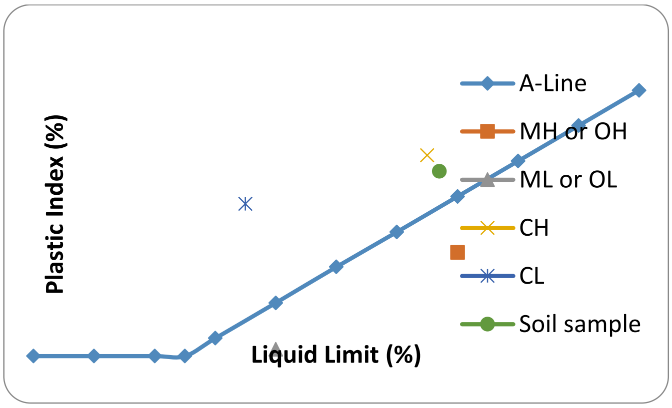

Figure 6: Plasticity Chart for Soil Classification

The soil has a high liquid limit (68%), low plastic limit (25.3%) and a high plasticity index (41.7%) indicating a high swelling and high compressibility. The difference in the plasticity index, amount of swelling and compressibility may be due to the presence of montmorillonite clay minerals in the mineralogy of the soil samples. But only kaolin clay mineral was detected by XRD while montmorillonite clay mineral was not detected. Kaolinite mineral does not swell as much as montmorillonite mineral. Clay samples derived from lagoon clay deposits show high swelling tendencies (Nwaiwu and Nuhu, 2012).

3.5.2 Strength Characteristics

Compaction test

The result of the compaction test using the West African Standard (WAS) is shown in Figure 7. The Maximum Dry Density, MDD, is 1708.9 Kg/m^3 at an Optimum Moisture Content, OMC of 18.86% using the West Africa Compaction. Although results of MDD obtained using the West African Standard Compaction method (WAS) is always higher than that obtained using the Standard Proctor compaction method, the MDD of 1708.9 Kg/m^3 obtained for the soil sample is outside the range of 1720 to 1920 Kg/m^3 which is considered satisfactory to excellent. The MDD does not meet the basic requirement.

California Bearing Ratio test

The CBR test was carried out using the results of the West Africa Standard (WAS) compaction test. Two tests of CBR tests were conducted on each soil sample, one at the Optimum Moisture content, compacted to the Maximum Dry Density (as per the West African Standard of Compaction) and the other test on a similarly compacted under soaked conditions. The results of the CBR test and swelling potential measured during the test are presented in Table 6. The Unsoaked CBR for the soil sample is 36% while the soaked CBR is 17%. Both the Un-soaked CBR and the soaked CBR fall below the minimum soaked CBR of 80% for base course (Table 5). The soaked CBR also fall below the minimum soaked CBR requirement of 30% for Sub-base course. Hence the soil sample does not meet the requirements for both road sub-base and base courses. The reduction in the Soaked CBR compared to the Un-soaked CBR is an indication of a significant loss in strength in the presence of water or on increase of water content.

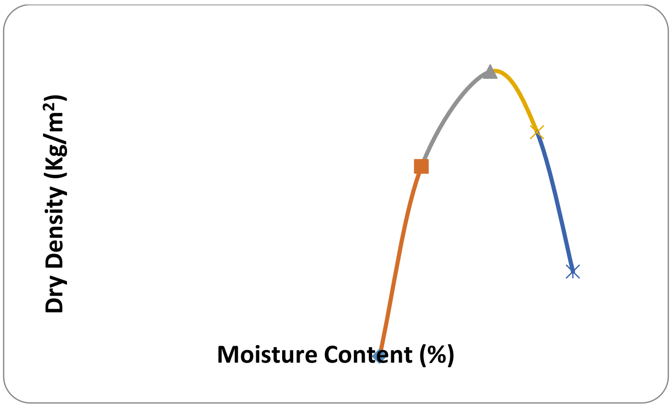

Figure 7: Moisture - dry density relationship for the soil sample

3.5.3 Swelling

The soil sample has a free swelling potential of 50% and a CBR swelling potential of 39.4% indicating a high swelling and shrinkage potential which will result in excessive road pavement deformation and foundation problems. The high plasticity index also shows that the soil will develop high swelling pressure resulting in severe road upheaval and up thrust on structures. This may also point to the presence of montmorillonite clay mineral which was not detected in the XRD analysis. However, the mineral kaolinite detected has a low-shrink swell capacity and is associated with montmorillonite.

3.5.4 Stabilization

The high plasticity index and high free swell (50%) are indications of instability, significant loss of strength in the presence of water and swelling which may lead to road upheaval, severe road pavement distress and deformation, and foundation problems. There is therefore a need to stabilize the soil. Clay minerals control important soil chemical and physical properties which affect design and construction of infrastructures (Ola 1980; Ola 1981; Azam et al 2012; Nwaiwu et al 2012), therefore chemical stabilization will be directed at the different chemical compounds in each clay soil to achieve effective soil stabilization to mitigate the present economic losses. The knowledge of the chemical assemblage is essential for the necessary stabilization reactions that will take place.

4. CONCLUSION

i. The study established the qualitative and quantitative mineral and geotechnical characterization of Maiduguri Black Cotton Soil.

ii. X-ray powder diffraction analysis detected the presence of four minerals: Quartz, SiO_2; Calcite, $CaCO_3$; Larnite, Ca_2SiO_4; and a clay mineral Kaolinite, $Al_2(Si_2O_5)(OH)_4$.

iii. XPS peak analysis confirmed the presence of eight (8) elements with Percentage Atomic Concentration as: Oxygen (65.14%), Silicon (15.79%), Aluminium (7.53%), Carbon (5.96%), Magnesium (2.11%), Ferrous (1.96%), Calcium (0.82%) and Nitrogen (0.68%) with traces of Sodium (0.00%) and Sulphur (0.00%). The ratio of the exchangeable cation Calcium / Magnesium is less than 0.5 indicating an unstable soil.

iv. The EDS chemical analysis by SEM detected eleven (11) elements. The distribution of the chemical elements by atom% in descending order is: Oxygen (63.67%), Silicon (18.66%), Aluminium (10.36%), Ferrous (3.44%), Carbon (1.66%), Calcium (0.6%), Potassium (0.52%), Tin (0.37%), Sodium (0.36%), Magnesium (0.25%), Phosphorous (0.13%), with traces of Sulphur and Barium. The Percentage Atomic concentration of carbon and aluminium given XPS are much higher than that given by SEM (atomic %) while that of Oxygen is similar.

v. The soil index properties: high liquid limit (68%), low plastic limit (25.3%), high plasticity index (41.7%) and free swell (50%) indicate a high swelling and highly compressible soil with an estimated uplift pressure is 151.8kN/m^2. This is due to the presence of clay minerals.

vi. The soil strength characteristics: Maximum Dry Density (1708.9 Kg/m^3); Un-soaked CBR (36%)

and the soaked CBR (17%) fall below the minimum requirement for sub-base and base course.

vii. The frequent damages to road pavements and foundations in the area can be attributed to the chemical composition and mineral assemblage of the soil in the area. The characterization and knowledge of the chemical assemblage will make possible the effective stabilization as chemical stabilization will be directed at the different chemical compounds in the soil. The chemical analysis, mineralogical analysis and geotechnical properties appear to be in agreement.

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