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Impact of Soil Geochemistry on the Stability of Engineering Structures in the Tropics

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Abstract

Stability and durability response of expansive soils are important in engineering structures, hence the need to examine its mineralogy and geochemical composition. Ten samples were collected at varied locations in south eastern Nigeria from devastated infrastructures and were investigated using XRD, XRF and relevant preliminary tests (particle size distribution and Atterberg limits) in consonance with American Society for Testing and Material (ASTM) Standards. Major elements detected were Si, Al, Fe, K, Ti, Ca, Ag, Li, Ba and Cr, while oxides of Al_2O_3 and SiO_2 from different sources (clay minerals in clay size particles and quartz mineral in sand fraction respectively) influenced the soil engineering behavior. Result showed that Fe, Ca, Li, Ba, Ag, Zn and Cr could substitute for Al. However, when present as either substitution for Al or as adsorption on the clay minerals, soil swelling potential is enhanced but if it exists as components of the cementing material such as ZnO, MnO and $CaCO_3$, swelling potential diminishes. Ratios of the oxides indicate that the soils in our study area contain swelling clay minerals (montmorillonite, illite and kaolinite) in varied proportion which corresponds with the XRD results. Values of liquid limit, plasticity index and free swell were 60.7, 41.3 and 82.3% respectively, indicating medium to high swelling potentials, capable of causing serious engineering problems on wetting at construction sites.

Keywords: Swelling potential, Clay minerals, Substitution, Correlation, Heavy metals, Active elements

Introduction

Swelling soils is central in most researches due their poor performance when utilized in its pristine state for construction work (Priyanthiet al. 2012; Maduka et al. 2016; 2017) because of poor drainage characteristics (Mitchell 1976; Seco et al. 2011; Mohantyet al. 2016). In south eastern Nigeria, swelling soil covers a vast section (Aghamelu 2011) and engineers have tried to maximize its prevalence against the high cost incurred in transporting alternative materials (Mohamedzein et al. 2005). Regrettably, most engineering structures carried out on shale are bedeviled with varying categories of structural damages (Okagbue 1988; Ezeribe 1994; Okogbue and Aghamelu 2010) leading to colossal economic wastes, expensive remediation involvements (Okogbue and Aghamelu 2011; Far and Flint 2017) and a palpable neglect of most areas prone to such occurrences.

Staving our trust on facts from cognate literature, Mishra (2012), Mir et al. (2014), Kang et al. (2015) and Kolay (2016) opined that durability assessment, suitability analysis and mineralogical evaluations offers one the scope of determining the best option for the stabilization of expansive soils because the swelling and shrinking phenomenon is a function of mineral content and type of clay (Ito and Azam 2010). We therefore, reinforce the need to integrate an analysis of the mineralogy of the clayey soils in southern Anambra Basin using XRD and XRF technique since it has been alluded in the previous researches (Okogbue and Aghamelu 2010; Aghamelu 2011).

Approvingly, Jandardhan et al. (2017) notified that an assessment of mineralogical composition is the support for successful construction works in any clayey environment. They established that a linear relationship exists between swelling potential, swelling pressure and the amount of montmorillonite in a soil. In same vein, Yaya et al. (2012) described montmorillonite as having a high absorbing capacity between its crystalline sheet which makes it highly vulnerable to swelling and shrinking processes. Similarly, Dhakal (2001) reported that the slake durability and other geotechnical behaviors of argillaceous rocks are strongly influenced by mineralogy. The presence of montmorillonite or high-activity smectite clays is an indication for distress -cracks on the soil surface (Fig. 1a), consequent upon the damages to structures (Fig. 1b) because the strength and stiffness characteristics were profoundly shaped by its mineralogy (Nicholson et al. 1994).

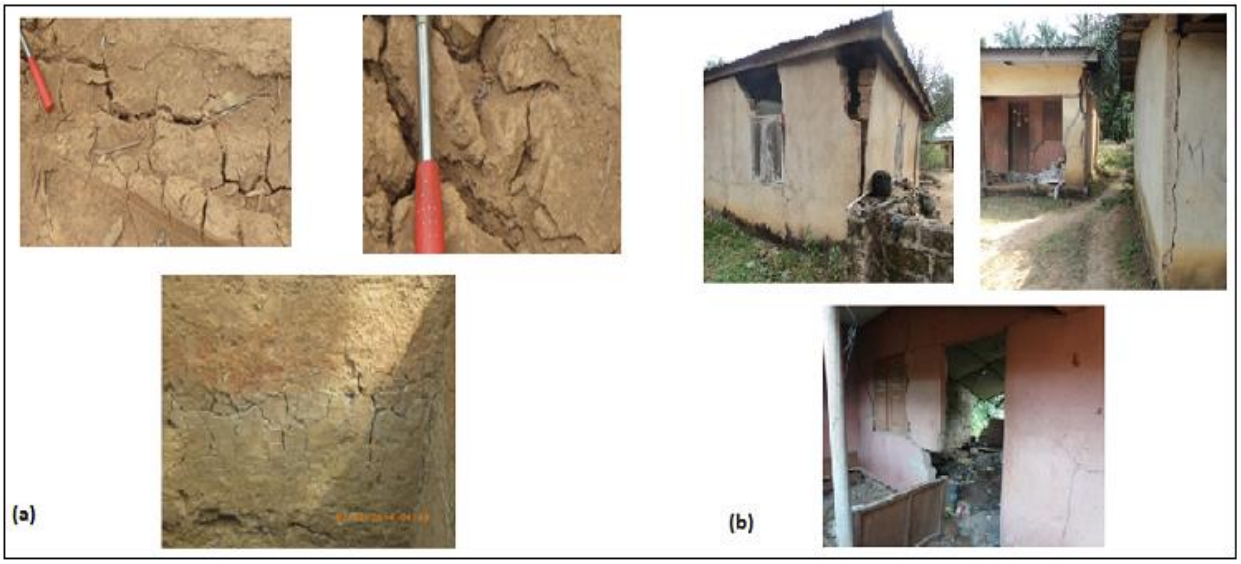


Fig. 1: Expansive soil evidences

Concurrently, volumetric shrinkage is mostly recorded during drying (Arora 2008; Lew 2010). Mitchell (1976) reconciled kaolinite with expansiveness especially when it is existing in extremely fine particle sizes (less than a few tenths of micron) whereas Velde (1995) and Lutenegger (2000) recognized that smectite and clay soil has a high affinity for the adsorption of heavy metals which influences consolidation, stability and durability pattern (Ohtsubo et al. 1995).

Aptly, Thomson and Ali (1969) and Davis (1976) noted that swelling characteristics of soil is also a function of its exchangeable ions. In extension, Mitchell (1976) disclosed that in soils with same mineralogy, increased swelling would occur on soil sample with exchangeable Na cation than in a sample with Ca or Mg cations. Principally, soils with adsorbed Na cation are relatively more plastic at low water contents and possess smaller shear strength than the soils with adsorbed Ca cation (Murthy 1977). Thus, ascertaining the geochemical composition of the swelling soils in the study area is timely and appropriate. Such knowledge would be relevant in forestalling the structural encumbrances associated with dominant soils in the study site and provide suitable guidelines suitable for addressing associated challenges in similar environments.

The impact of surfacial fluvio-geomorphic processes in the study area remains unbeatable (Ofomata and Umeuduji1994) and its apparent location in the humid tropical region characterized with high rainfall regime -cum-temperature extremes (Monanu and Igbozurike1975) facilitates swelling-shrinking processes (Weihen 1999; Chinwokwu 2000; Windapo 2006; Opara 2007). Such pronounced challenge in the study area necessitated this study

which hosts Turonian clay deposits that outcropped at Agwu, Nara, Agbani, Amagunze, Owo, Obugu and Akpugo of Enugu Sate, as well as other states in southeastern Nigeria. With this in mind, this work focused on determining the mineralogy and geochemical contents, and evaluate their potentials as subgrades and aggregate materials.

1.1 Geological and Geographical Setting of the Area

The study area is located at latitude 6º 15ˈ N to 6º 20ˈ N and longitude 7º 35' ˈE to 7º 40ˈ E (Fig. 2) within the Benue Trough. It belongs to the first sedimentary phase (Obi et al 2001), characterized with the deposition of about 3000m of rocks comprising the Asu-River Group and Eze-Aku spanning to Agwu Formations and Agbani Sandstone in the Abakiliki-Benue Basin of the Southern Benue Trough from the Albian to Coniacian ages (Catchely and Jones 1965; Benkhelil 1986). However, the Awgu Shale is of the Turonian age (Reyment 1965). Awgu Shale and Agbani Sandstone are the major geologic rocks outcropped in the study area (Fig. 2). They are characterized by bluish grey, well-bedded shales with intercalations of fine-grained sandstones, thin marshy and shelly limestones and medium–coarse grained bio-turbated pebbly sandstones, with laminated brownish clays and pyritic carbonaceous shales respectively. Awgu Shale is rich in ammonite and mollusks (Kogbe 1981) being an indication of a marshy, deltaic and shallow marine deposit (Obaje1994).

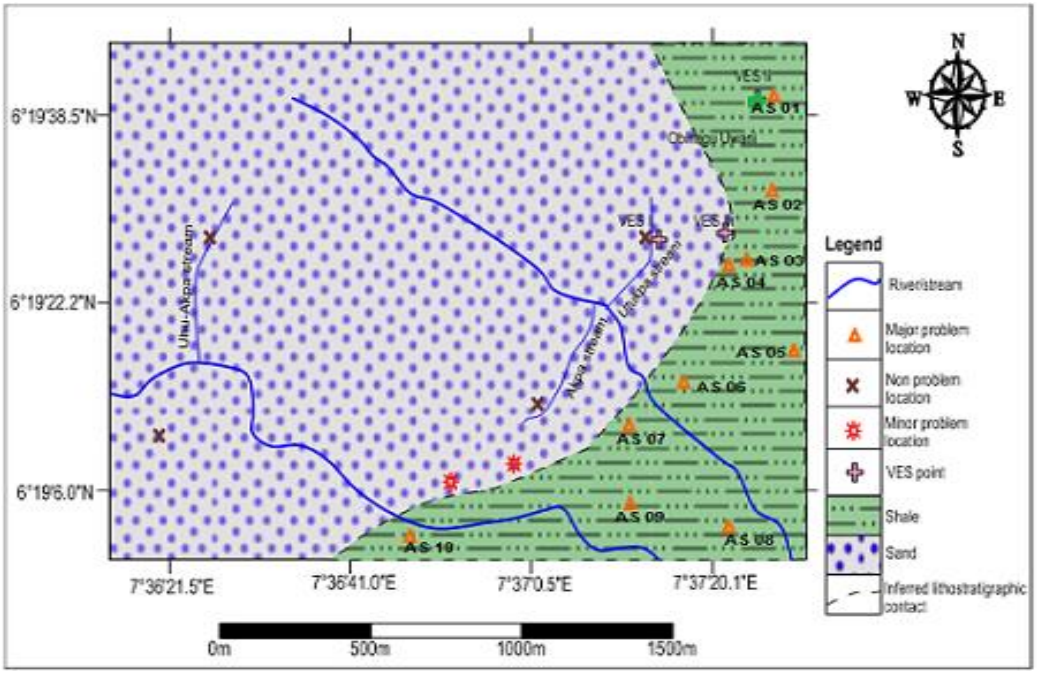


Fig. 2 Map showing sample collection points

The climatic type is the humid tropical characterized with two seasons-wet and dry seasons. The dry season starts from November and ends in March while the wet season, which lasts for seven (7) months begins in April to October. The total annual rainfall in the area ranges from 1,500mm to 2,000mm with a significant short dry period in the month of August unusually called "little dry season". Temperature range could be as high as 27ºC to 28ºC (Monanu and Inyang 1975). The relief of the study area is low and it is poorly drained.

Methodology

Ten soil samples labeled AS 01 – 10 (Fig.2), were collected from the foundations of some devastated engineering structures (Fig.1) at depths between 0.5 – 1.0m. The samples were highly weathered and typical of horizon A and B of southeastern Nigeria soil. Samples were placed in black sample bags and transported to the laboratory (within 48 hours of collection to hinder microbial activities on soil components) for analysis of the selected geotechnical parameters-particle size, Atterberg limit and free swell tests in line with the ASTM (American Society for Testing and Materials) standards. The survey involved the detailed description of outcrops within the area based on their lithology, texture, structure and color (Table 1).

Table 1: Samples physical properties and mineral compositions

Sample no	Physical properties	Clay minerals	Non clay minerals
AS 01	Light Brown with yellowish mottles, massive, smooth feel with fine sand	Illite, Smectite, Kaolinite	Calcite, Hematite, Quartz, Osumilite
AS 02	Whitish grey, fissile, very fine smooth feel	Smectite, Illite, Kaolinite	Hematite, Albite, Quartz, Calcite
AS 03	Brownish grey with yellow mottles, massive, slightly gritty	Kaolinite Sapiolite	Hematite, Quartz, Calcite
AS 04	Light brown, massive, fine smooth feel	Kaolinite, Illite Smectite	Feldsper, Albite, Muscovite, Quartz,
AS 05	Yellowish brown with orange stains, massive slightly gritty	Kaolinite,Chlorite, Sapiolite	Quartz, Mica, Quartz, Anthrophylite

AS 06	Light brown, massive, fine smooth feel	Smectite, Illite, Kaolinite	Quartz, Muscovite, Albite, Anthrophylite
AS 07	Brownish grey with yellow mottles, massive, smooth feel with fine sand	Smectite, Illite, Kaolinite	Hematite, Muscovite, Calcite, Quartz
AS 08	Yellowish brown with orange stains, massive smooth feel with fine sand	Smectite, Illite, Chlorite	Anthrophylite, Quartz, Feldsper, Calcite, Osumilite
AS 09	Light Brown with yellowish mottles, massive, gritty feel	Illite, Chlorite, Kaolinite,Sapiolite	Albite, Muscovite, Quartz, mica, Calcite
AS 10	Light Brown with yellowish mottles, massive, slightly gritty feel	Chlorite, Illite	Quartz, Calcite, Mica, Hopeite, Feldsper

The shale and clay samples were sun dried, pulverized and each of the samples were treated with about 100 ml of hydrogen peroxide –cum- diluted hydrochloric acid per 100 g of each sample, and heated to a temperature of 40°C to remove the organic matter contents and carbon compounds in the samples. Each of the samples were dried again, and passed through the sieving machine to separate the sand size particles. Particles (silt + clay) passing the sieve were collected and passed through sedimentation analysis as outlined by Ketiler et al. (2001) to determine the clay percentage in samples.

X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) was employed to analyze the mineral and chemical (major and trace oxides) compositions at the National Steel Raw Materials Exploration Agency, Kaduna, Nigeria using the Seimens D5000 diffract meter. Data processing of each sample scanned were done using eleven (11) scan points and thirty (30) repeat times. For the soil engineering characteristics, investigations were performed on whole samples without going to separation methods. However, XRD and XRF were performed on separated clay fractions.

Results

The samples exhibited variability in their geotechnical characteristics (Table 2). The PSD result revealed that the range of sand, silt and clay in the Agwu Shale unit are 3 – 49% (4.76 – 0.074mm grain size), 1.3 – 3.7% and 48.7 – 95.2%, respectively. The Atterberg Limits indicated that liquid limit (LL) ranges from 44.5 to 78.0%, plastic limit (PL) ranges between 16.5 and 21.9% and plasticity index (PI) ranges from 23.1 to 56.1% (Table 2). The free swell (FS) of the soil ranges between 30 and 145% while natural moisture content (NMC) and bulk density (BD) range from 7.2 to 14.6% and 1.5 to 2.2 Mg/m^2, respectively (Table 2). The XRF results portrayed the major oxides in the soil-

SiO_2 (46.0 – 68.0%), Fe_2O_3 (17.1 – 29.7%), Al_2O_3 (9.4 -15.0%), K_2O (1.3 – 3.6%), Ag_2O (1.5 – 3.0%), TiO (1.2 – 2.5%), CaO (0.1 -1.7%), ZnO (0.02 – 0.10%), MnO (0.01 – 0.08%) and CuO (0.03 -0.06%) as was presented in Table 3. The clay minerals recorded by the XRD scan were smectite, illite, kaolinite and chlorite while the non-clay minerals are quartz, hematite, calcite and feldspar (Table 1).

Discussion

4.1 Sub-grade chemical component interactions

The summary of the grain size distribution and representative curves are presented in Table 2 and Figure 3. The fines and sand contents of the samples range from 51 – 97% and 3 – 49%, respectively. The soil grading denotes a predominantly clay soil with inclusions of sands. Soils of equal uniformity of grain size distribution exhibit the same engineering properties and act the same way during earthworks.

Table 2: Summary of geotechnical analysis

Soil properties	AS 01	AS 02	AS 03	AS 04	AS 05	AS 06	AS 07	AS 08	AS 09	AS 10	Average
2.0 - 4.76 (mm)	3.0	-	2.0	-	1.0	1.0	-	2.0	1.0	2.0	1.2
0.42 - 2.0 (mm)	9.0	2.0	4.0	5.0	2.0	1.0	8.0	1.0	6.0	3.0	4.1
0.074 - 0.42 (mm)	37.0	1.0	21.0	20.0	29.0	24.0	7.0	28.0	35.0	24.0	22.6
0.002 - 0.074 (mm)	2.3	1.8	3.7	2.2	2.7	1.8	1.8	1.3	1.9	1.5	2.1
< 0.002 (mm)	48.7	95.2	69.3	72.8	65.3	72.2	83.2	67.7	56.1	69.5	70
LL (%)	62	78	48	55	44.5	68	74	54.6	63.2	60	60.7
PL (%)	18.4	21.9	17.1	16.5	21.4	17.7	20.6	19.3	20.1	21.1	19.4
PI (%)	43.6	56.1	30.9	38.5	23.1	50.3	53.4	35.3	43.1	38.9	41.3
FS (%)	30	110	60	135	45	145	83	75	50	90	82.3
NMC (%)	13.2	14.6	14	7.2	9.6	10.4	12.3	13.5	11	8.5	11.5
BD (Kg/m^3)	2.1	2.12	2.09	1.97	1.96	2.18	1.5	2.1	1.9	2.11	2.0

However, from the XRF result (Table 3), there were noticeable large variations in the content of the principal oxides. Al_2O_3 ranges from 9.40 – 15.00 with an average of 13.08% while SiO_2 ranges between 46.20 – 67.90% with an average of 54.1%. K_2O has an average of 2.7% with its quantity ranging between 1.25 – 3.71% within the samples. TiO_2 and Ag_2O have quantities ranging from 1.68 – 2.45% and 1.73 – 2.79% with averages of 2.7 and 2.2% respectively, and Fe_2O_3 has values between 17.13 – 29.52% with 24.3% as average.

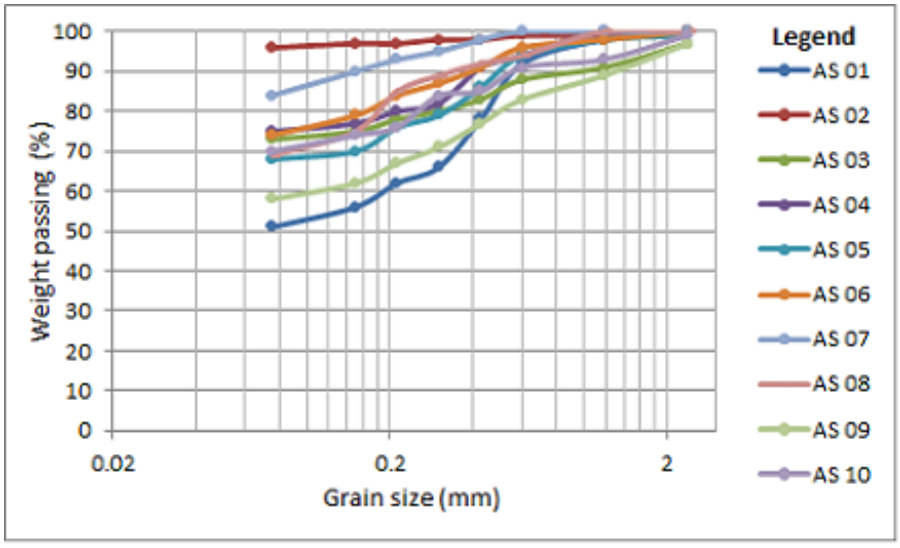


Fig. 3: Particles size distribution curves

The major oxides noted were Al_2O_3 and SiO_2. The correlation coefficient (r) between SiO_2 and Al_2O_3 showing negative (r = -0.8782) indicated that both oxides were derived from different sources (Fig. 4a). The SiO_2 contents are mainly derived from quartz minerals in sand fraction, whereas the main source of Al_2O_3 is the clay minerals in the fines. The variations of the contents of SiO_2 when compared to Al_2O_3 in all samples presented a reduction in the SiO_2 when there is an increase in Al_2O_3 content (Table 3).

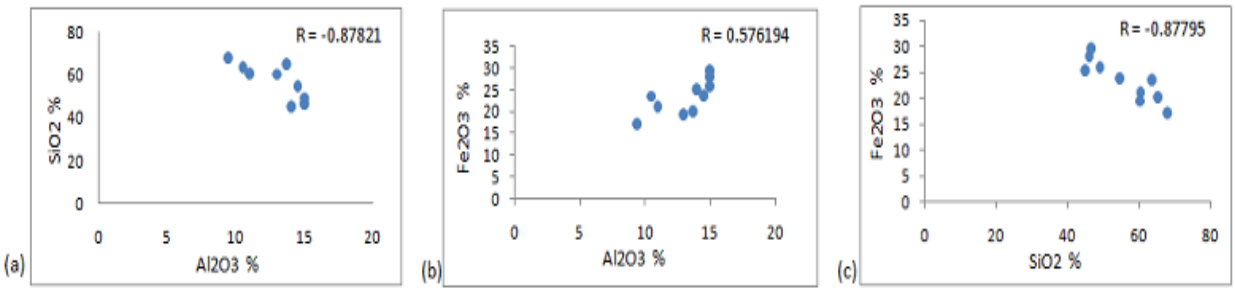


Fig.4 Bivariant plots between some of the major oxides.

Table 3: Samples chemical analysis result

Chemical composition	Al2O3 (%)	SiO2 (%)	K2O (%)	CaO (%)	TiO2 (%)	V2O5 (%)	Cr2O3 (%)	MnO (%)	Fe2O3 (%)	NiO (%)	CuO (%)	ZnO (%)	Ag2O (%)	BaO (%)
AS 01	15	55	3.57	1.66	2.15	0.2	0.04	0.06	19.41	0.03	0.05	0.1	2.29	0.43
AS 02	15	47	3.14	0.67	2.03	0.12	0.05	0.01	29.72	-	0.04	0.04	2.06	-
AS 03	11	60	1.64	1.39	2.45	0.21	0.04	0.05	21.12	-	0.03	0.03	1.97	-
AS 04	15	49	3.71	1.67	1.17	0.1	0.05	0.04	25.86	-	0.06	0.03	2.97	0.25
AS 05	9.4	68	1.25	0.53	1.68	0.08	0.06	0.03	17.13	0.04	0.03	0.02	1.73	-
AS 06	14.5	54.4	2.27	0.58	2.05	0.13	0.03	0.08	23.79	-	0.05	0.05	2.15	-
AS 07	13	60.2	1.78	0.88	2.23	0.1	0.05	0.07	19.51	0.03	0.03	0.03	1.78	0.1
AS 08	15	46	3.32	0.78	1.98	1.21	0.03	0.05	28.33	-	0.04	0.04	2.53	0.56
AS 09	9.5	61.5	1.78	0.12	2.24	0.13	0.05	0.06	23.05	0.05	0.03	0.03	1.46	-
AS 10	10.7	60.1	2.33	0.79	1.66	0.08	0.03	0.03	22.2	-	0.04	0.03	2.01	-
Average	12.81	56.12	2.45	0.9	1.96	0.24	0.04	0.05	23.01	0.02	0.04	0.04	2.1	0.13

Graph of variation of both oxides always present linearity (Laraba 2006). However, the non-linear relationship (Fig. 5) might have been caused by a reduction of Al_2O_3 in samples (AS 03, 05, 07, 09 and 10) due to a reduction in Al through ionic substitution by other more active elements - Fe, Li, Ca, Ba and Cr (Table 3).

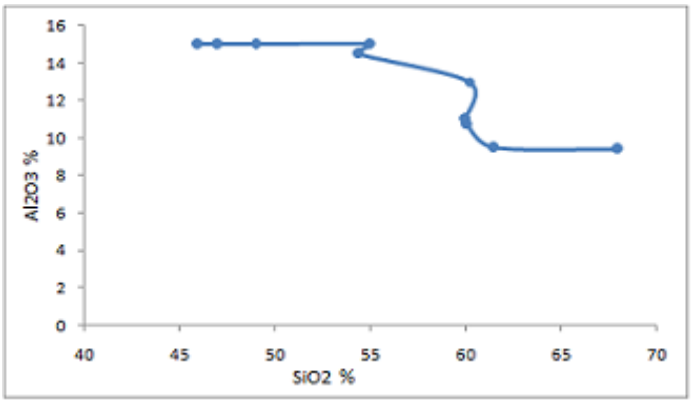


Fig. 5: Graph of percentages of SiO_2 and Al_2O_3

Samples AS 01, 02, 04 and 08 have relatively high content of Al_2O_3 (15%) and high clay contents (48.7%, 95.2%, 72.8% and 67.7) respectively, while sample AS 03, 05, 07 and 10 have low Al_2O_3 content (11.0%, 9.40%, 13.0% and 10.7%) with high amount of clay fraction (69.3%, 65.3%, 83.25% and 69.5%) respectively as shown in Tables 3 and 2. This may also support the ionic substitution for Al in the clay mineral structures. However, the elements in the exchange complex are low, which resulted in low cation exchange capacity (CEC) in the clays. Thus, monovalent and divalent cations control the final swell index.

In the study of clay minerals for their structural formulae, elements such as Si, Al, Fe, Mg, Ti, Mn, P, Ca, K and Na are essential (Mermut and Cano 2001). Some elements such as Fe, Mg, Mn, and Ca could be present in clays either as constituents of soil materials or as cations proxy for Al (Velde 1995). In line with the report of Velde (1995), clay minerals-smectite, illite and chlorite show ionic substitution of Fe^{2+}, Fe^{3+} for Al^{3+}. In the present study, our results showed direct positive correlations (r = 0.5762) between these cations (Fig. 4b). Consequently, the Fe is strongly related to Al and clay minerals. The negative correlation (r = -0.8780) between SiO_2 and Fe_2O_3 (Fig. 4c) is in agreement with Dogan (2009) which stated, that negative correlation exist between iron and clay variables. This implies that the dominant clay minerals are smectite, illite, kaolinite, and chlorite, having little or no iron content.

Fe^{2+} must have existed as cementing material, evidenced by the presence of hematite in spite of the fact that Mn, can occur as a substitute for Fe (Velde, 1995) or as MnO cement on the rock surfaces. Ca which is usually found

in cementing material might have existed as a substitute for Al, in the form of CaO which is commonly formed from the dissociation of calcite ($CaCO_3$) (Singh, 2008). From our analysis, most of the samples examined have potassium (K) contents indicating the presence of illite as a mineral constituent of the clay (Table 3).

Furthermore, CuO and ZnO are more related to the clay contents since they have strong positive relationship (r = 0.7253 and 0.5398) and negative (r = -0.2650 and -0.2921) correlations with Al_2O_3 and SiO_2 respectively (Fig. 6a-d).

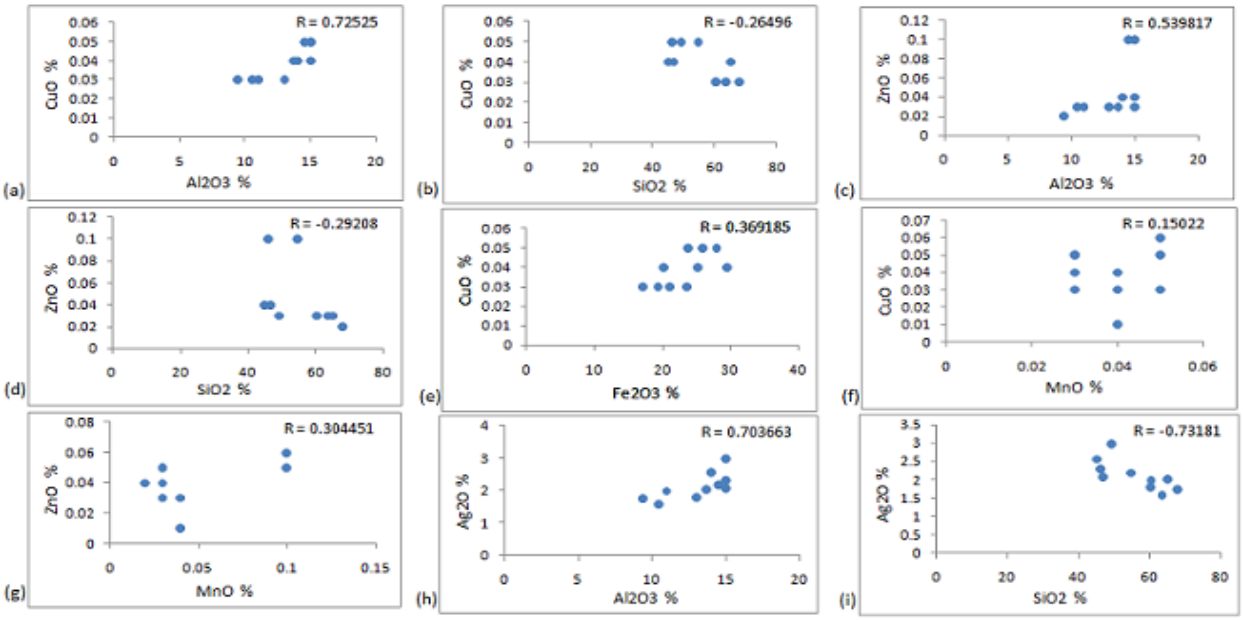


Fig. 6: Bivariant plots between major oxides

Clay minerals in relation with Fe_2O_3 and MnO, also showed a positive correlation with CuO and ZnO (Fig. 6e-g). Therefore, heavy metals such as Cu and Zn have similar adsorption behavior on the surfaces of clay minerals as also seen in the positive (r = 0.7037) and negative (r = -0.7318) correlation co-efficient of Ag_2O with Al_2O_3 and SiO_2 respectively (Fig. 6h-i) (Abd-Allah et al, 2009). Clay particles are generally composed of platelets having negative electrical charges on their surfaces and positively charged edges (Velde, 1995). This results in a high chemical activity on clay surfaces and a consequence interaction with ions in aqueous solution. The negative charges are balanced by cations such as Zn^{2+}, Cu^{2+}, Ag^{2+}, V^{2+}, Ti^{3+} and others (Abd-Allah et al. 2009). These cations could have been present in the groundwater and/or in the basin's water during their deposition, and they are attached to the surfaces of the platelets by electrical forces.

Figures 7a and 7b shows three ratios SiO_2/Al_2O_3, Fe_2O_3/TiO_2 and K_2O/TiO_2, and SiO_2, Al_2O_3 and other oxides percentage contents in samples, and typical illite, kaolinite and smectite minerals (Model from Weaver & Pollard 1975). For samples AS 01, 02, 04, 06 and 08, the SiO_2/Al_2O_3 ratio, remain relatively stable at 1.9 – 3.3 being an indication of typical illite, kaolinite and smectite. Fe_2O_3/TiO_2 ratios for all the samples show the presence of illite and kaolinite within these iron-rich clays samples with iron as the dominant element. This might explain the brownish color of most samples (Fig. 1a). All samples showed that the ratio K_2O/TiO_2 is almost stable for Kaolinite rich soils, and far below a typical illite (Fig. 7a).

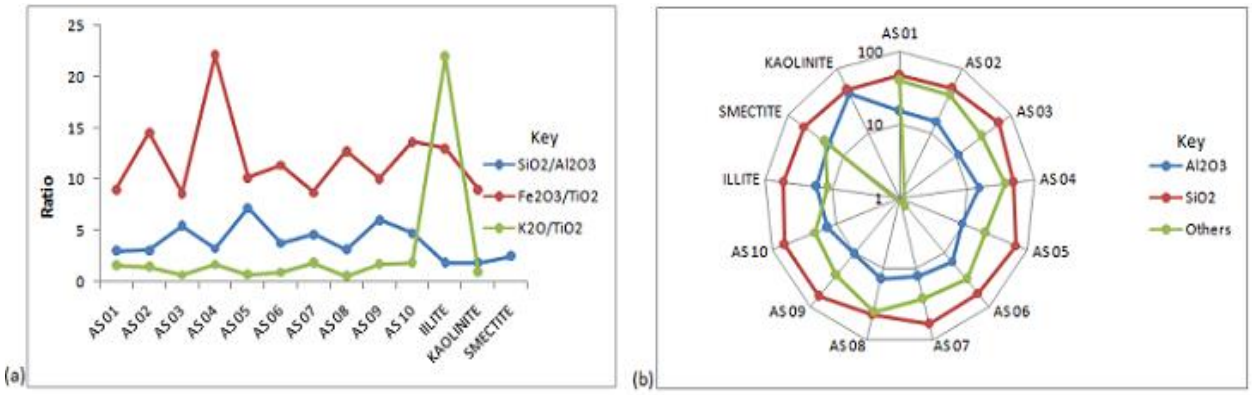


Fig. 7: Comparison of major oxides with typical smectites

Figure 7b, shows a web-plot presented in a log-scale. Iron assumed to be in Fe_2O_3 form only, was combined with TiO_2, K_2O and other oxides category. In terms of SiO_2contents, all the samples with exception of AS 05, 09 and 10 showed stable percentage for illite, kaolinite and smectites. However, in terms of Al_2O_3 and other oxide contents, all the samples showed lower and higher contents than a typical kaolinite. Thus, the soil has stability closer to smectite and illite. These observations might be attributed to the higher fines content in the samples, as indicated by the smooth (non-gritty) feel of the samples. Thus, the samples likely contain mixtures of smectite, illite and kaolinite in different proportions. Obiora and Umeji (2004) had earlier observed the dominance of expansive minerals in the order of smectite>illite> kaolinite in the Awgu Formation, Ezeaku Formations and the Abakaliki Shale.

The clay mineralogical assemblage in the soil samples from the XRD analysis (Table 1) is in conformity with spectrally dominant chemical contents from the XRF analysis. The XRD test results revealed that the soil samples contain clay minerals such as montmorillonite (smectite), illite, kaolinite (kaolinite – serpentine group such as

Lizardite and chrysotile), clinochlore (chlorite) and sepiolite as shown in Fig. 8, which could significantly influence the engineering behavior of the expansive soil due to their high activity.

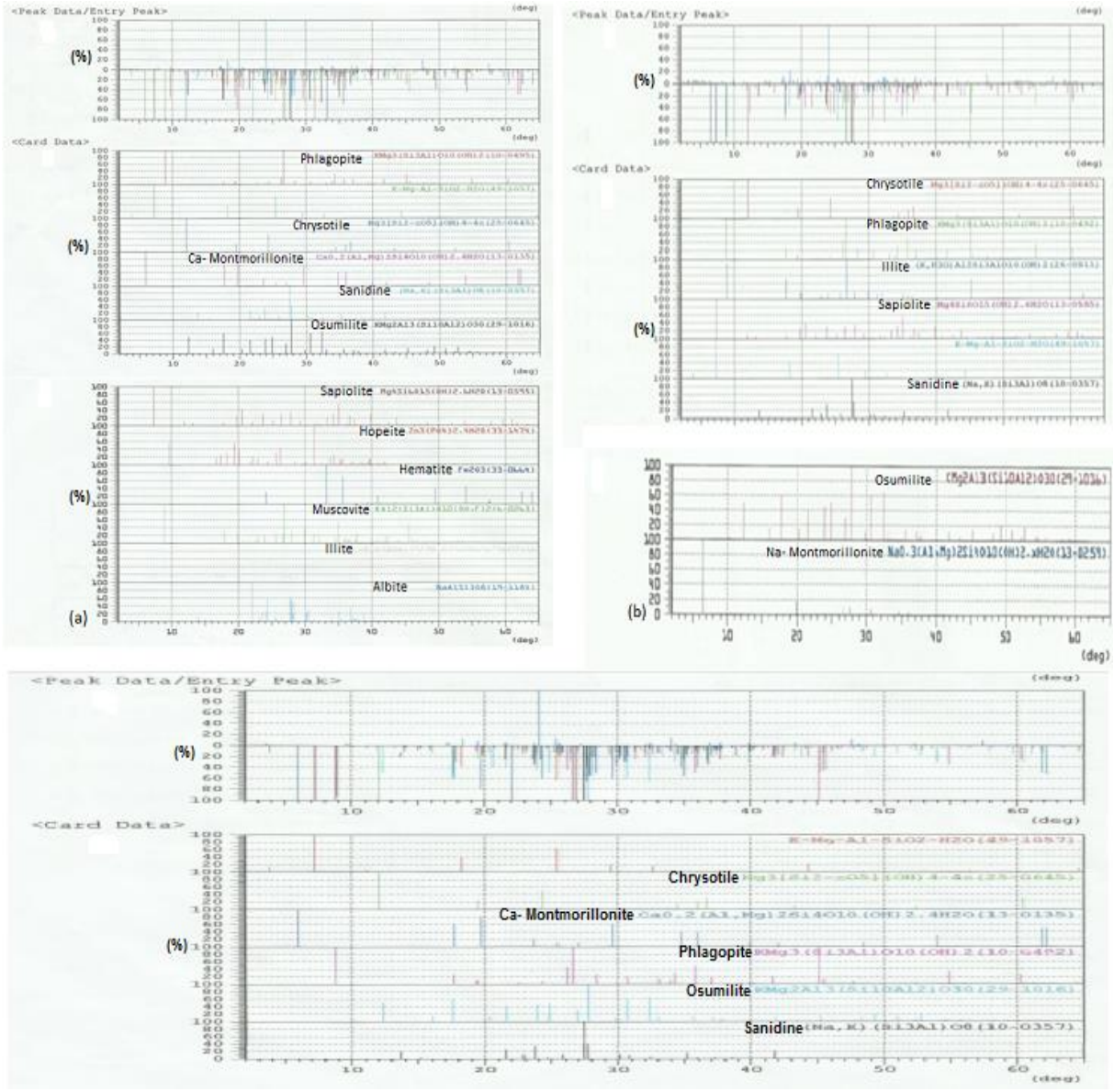


Fig. 8 XRD scan results

Figure 9a shows montmorillonite (cornflake or oak leaf-like structures) and illite (ribbon-like filament structures with curve ends) clay minerals in a mixed-layered sample, which could cause swelling behavior in Awgu Shale. However, the effects of the swelling minerals could be reduced by the flocculated arrangement of other non-swelling clay mineral within the clay as seen in Fig. 9b. The clays with this structural arrangement are light weight

with high void ratio and water content; though moderately strong to resist external forces (Arora 2008). This could be the reason for the moderate water content and shear strength recorded by the Awgu Shale (Una et al. 2015). Thus, the shale could withstand foundation stresses until the behavior of the swelling minerals takes effect.

Other minerals such as quartz, hematite, feldspar (sanidine), mica (Muscovite), albite, phlagopite, osumilite, hopeite and anthophyllite were also present (Table 1). However, these minerals do not contribute to the expansiveness of the soil due to their low activity but some, for example, feldspar, could be weathered, to form the clay minerals.

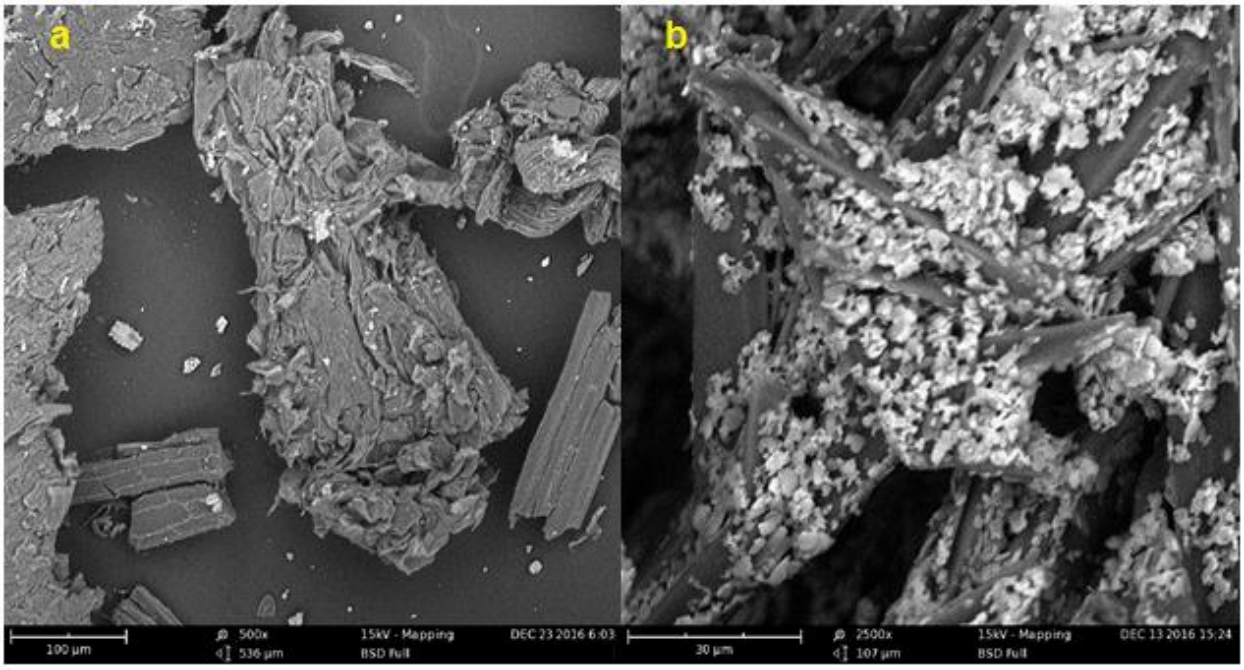


Fig. 9: SEM photo of some of the clay samples

4.2 Subgrade Geotechnical Properties

Atterberg limit test was done to substantiate soils' swelling nature. The result of the consistency limit tests and the plasticity chart are presented in Table 2 and Fig. 10a. From the chart, the soil is classified as medium to high plastic clayey soils (Tadanier and Nguyen 1984; Chen 1988). Moreover, all the samples plotted above the A-line and within the montmorillonite mineral zone, thus indicating an expansive soil (Van der Merwe1964).

All the samples with exception of AS 03 and 05 plotted on the right of the vertical line crossing LL equals 50% implying highly compressible soil (Lew 2010). Following the Unified Soil Classification System (USCS) and soil plasticity chart, the samples are classified as inorganic clay of high plasticity (CH) and/or inorganic clay of

medium to high plasticity (ML) (Garg 2011). The samples exhibited a great tendency for water absorption and swelling which increases activities of clay minerals in soils (Gidigasu 1980). Furthermore, the observed high plasticity could be attributed to the presence of montmorillonite and other swelling clay minerals. Thus, the samples are unsuitable for sub-base and subgrade foundation materials. In proposition for describing expansive soils as highly active (Fig. 10b), Skempton (1954) asserted that such clays have high water-holding capacity causing volume change during swelling and shrinking (Lew 2010).

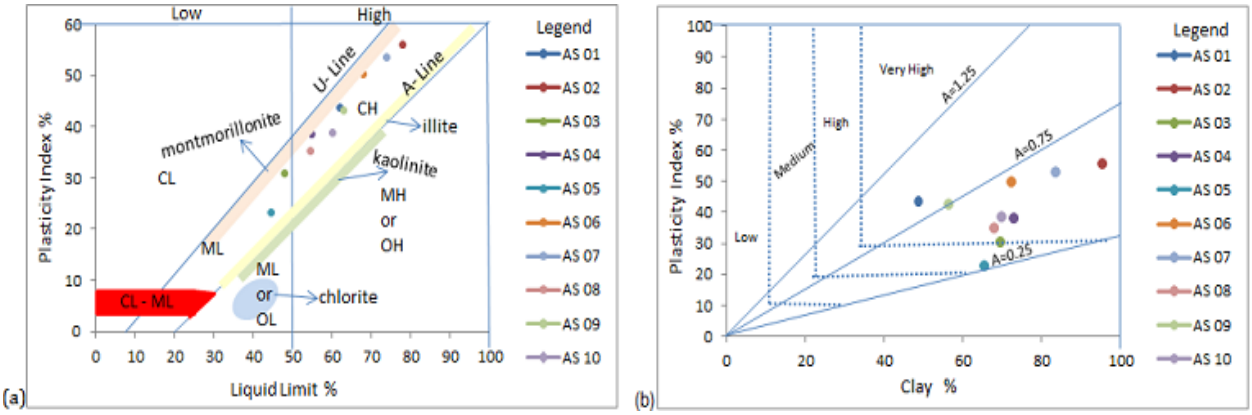


Fig. 10 Soil plasticity and activity chart

The tested samples presented moderately high free swell (FS) with an average of 82.3% (Table 2). The FS results agreed with the PI values. The values indicated that the samples are likely to pose significant field compaction problems. Such soils usually have the ability to retain appreciable amount of moisture in the diffuse double layer of the clay minerals by means of adsorption (Olayanju, 2011). This is supported by a significant mean value of natural moisture content of 11.5% recorded by the samples (Table 2) (Aghamelu and Okogbue 2011). Garg (2011) and Holtz and Gibbs (1956) reported that soils having free swell values as low as 100% may show considerable volume change under light loads when wetted and hence should be viewed with caution. However, a soil having free swell values below 50% are not normally expected to present any serious problems under light loads (Garg, 2011).

The wide variation of these swelling parameters could be attributed to several factors such as clay type and percent, primary structures (massive, laminated and fissile), type and quantity of the cement materials and the fine sands content present as fine laminas. These laminas act as cushions diminishing the swelling potentiality (Abd-Allah et al 2009). The sand and fines contents of the samples were correlated with the swelling properties (Table 4). It was

observed that the swelling properties of the studied samples correlated positively with the clay content and negatively with the silt and sand fractions.

Table 4: Correlation coefficient (R) between aggregate chemical components and its geotechnical properties

Properties	**LL %**	**PL %**	**PI %**	**FS %**
Clay %	0.5220	0.3172	0.4875	0.6195
Silt %	-0.5557	-0.3932	0.4652	-0.3480
Sand %	-0.4966	-0.2988	-0.4160	-0.6062
Al_2O_3%	0.4353	0.3954	0.6051	0.4918
SiO_2 %	-0.3583	-0.1945	-0.3888	-0.5166
Fe_2O_3 %	0.3645	0.3923	0.5123	0.4467
CuO %	0.1014	0.1107	0.2621	0.2628
TiO_2 %	0.2610	0.1699	0.2631	0.2393
AgO_2 %	0.1951	0.2913	-0.0289	0.1497
ZnO %	0.1685	-0.3683	0.3904	0.1279
MnO %	0.1121	-0.4860	0.1697	-0.0809
CaO %	-0.2312	-0.6450	-0.1406	-0.0382

This implies that the swelling potential could be enhanced by increasing the clay percentages and vice versa or reducing quartz minerals which constitutes the main component of sand size particles. Thus, volumetric shrinkage strain increases with increasing plasticity index and clay content.

The very high activity of smectite minerals enhances their ability to absorb water in the form of adsorbed water on its surfaces and increases the natural moisture content. The clay samples have natural moisture content (NMC) and bulk density (BD) range between 7.2 – 14.6% and 1.50 – 2.18 kg/$m^{3,}$ respectively. Natural moisture content shows a general direct correlation with bulk density of sediments until the optimum limit of moisture content (Abd-Allah et al. 2009) and it applies in this study because a positive correlation existed between NMC and BD which could be attributed to high clay content (Fig. 11d). However, clay structure, cement materials and grain size distribution could explain the non-significant positive relationship (r = 0.0670) between the natural moisture content and bulk density.

NMC also influences clay bulk density and consistency (Bell 2000, Nelson and Miller 1992). In this study, NMC showed positive correlations (r = 0.2943 and 0.1441) with liquid and plastic limits respectively and a negative correlation (r = -0.3537) with the free swell (Figure 11a-c). Similar correlation values have been reported for expansive soils in Egypt (Abd-Allah et al. 2009). This means that water content has an important impact on mechanical behavior of argillite. Moreover, the XRF results showed that the clay samples contain very low mean percentage (about 0.97%) of CaO (Table 3) which is largely responsible for soil stabilization. This suggests the possibility of low shear strength of the samples due to poor cementation and high swelling potential (Fada 1995; Cheng et al. 2004). Increase in PI denotes loss in strength and decrease in load bearing capacity as moisture increases (Emesiobi 2002).

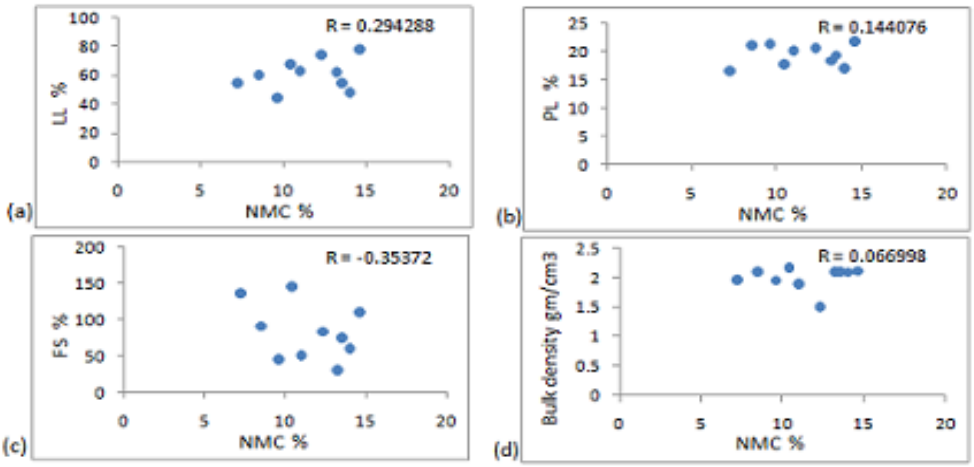


Fig. 11 Correlation between NMC and PL, LL, BD and FS

4.3 Influence of Geochemistry on Geotechnical Properties

Chemical composition exerts a lot of influence on the physical behavior of clays, especially the main minerals, cementing materials, absorbed cations and anions. In this research, Al_2O_3 showed positive correlations (r = 0.4353, 0.3954,0.6051and 0.4918) with LL, PL, PI and FS, respectively, while SiO_2 content is negatively correlated (r = -0.3583, -0.1945,-0.3888 and -0.5166) with clay content parameters such as LL, PL, PI and FS respectively (Table 4). This supports that SiO_2 is mainly derived from granular (sand) particles while Al_2O_3 is derived from clay particles. The sources of $Al_2O_3$and $SiO_2$are further upheld by a positive correlation noted between clay and swelling properties (LL, PL, PI and FS) while negative correlation existed between sand, silt and swelling properties (Table 4). It affirms that the swelling properties of the studied samples could be increased by increasing the clay percentages and decreased by increasing the non-clay minerals, mostly quartz.

Elements such as Fe, Mn, and Ca could be present in clays either as constituents of cement materials or as cations proxy for Al (Velde 1995). In this study, the presence of Fe as proxy for Al is more dominant than being a component of cement materials as obtained from the behavior of the oxide of this element and Al_2O_3 with respect to the relationship with geotechnical parameters. Fe_2O_3 contents show positive correlations with Al_2O_3 content (Figure 4b) and with LL, PL, PI and FS (Table 4). The substitution of Al^{3+} by Ca^{2+} and other divalent cations will result in a negative charge in the crystal lattice of the clay minerals, which is balanced later by a monovalent cation such as K^+ present during diagenesis process or its availability in the groundwater. The process of substitution-balance is supported by the considerable K_2O present in samples (Table 3).

Cu, Ti and other heavy metals have similar behavior with Fe as regards their relationship with geotechnical parameters. CuO, Ag_2O and TiO_2 also presented positive correlations with LL, PL, PI and FS as shown in Table 4. This reflects the common property of clay minerals especially smectite to adsorb heavy metals from the surrounding solutions (Velde, 1995). Comparing MnO to Fe_2O_3, the Mn could have existed partly from the substitution for Al in the clay minerals structure of the studied samples as revealed from its slight positive correlations with LL and PI (r = 0.1121 and 0.1697) respectively. MnO recorded a negative and non-significant correlation (r = -0.4860 and -0.0809) with PL and FS respectively thereby supporting that MnO could feature as cementing material (Table 4). The observed negative correlation of CaO with all the swell parameters (Table 4) connotes that the main sources of Ca in the studied clays are calcite and other cements. Thus, Ca from cement materials becomes more active when exposed to groundwater and dissolution processes to form CaO.

Conclusion

This study exposed the construction hazard potential of shale subgrades and aggregates. The major chemical contents of the clay samples detected in the study were Si, Al, Fe, K, Ti, Ca and Ag. Fe, Ca, Li, Ba and Cr, and these could substitute for Al in the clay mineral crystal lattice. Since exchangeable ions plays significant role in enhancing the processes of soil expansive properties and methods of clay stabilization that applies in tropical environment, caution must be exerted in the type of chemical wastes released or agricultural additives allowed in similar environment. The Atterberg limits indicated that the shale is medium to highly expansive with high water-holding capacity due to the presence of swelling clay minerals such as montmorillonite and illite. The variation of the swelling

potentials of the samples is attributed to clay type and percent, clay structure, cement material and presences of non-clay minerals.

This study opines that stabilizations based on soil plastic properties are likely to have limitations and it is essential to modify stabilizer by including clay mineralogy of the soil and its interactions with chemical additives. The use of calcium admixtures to enhance performance-stability and durability of swelling soils in problematic soils is therefore recommended. The use of potassium and sodium fertilizers on clayey environments should be discouraged to reduce the formation of smectite minerals. Soil experts such as geologists, geomorphologists, and geotechnical engineers should be involved in engineering structure projects to provide the needed insights.

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