academicJournals

African Journal of Environmental Science and Technology

Full Length Research Paper

Comparative evaluation of clays from Abakaliki Formation with commercial bentonite clays for use as drilling mud

Nweke, O. M.*, Igwe, E. O. and Nnabo, P. N.

Department of Geology, Ebonyi State University, Abakaliki, Ebonyi State, Nigeria.

The characteristics of clays from Abakaliki Formation, Southeastern Nigeria was evaluated to establish its suitability as drilling mud when compared with commercial bentonite such as Wyoming bentonite. The chemical, mineralogical and geotechnical properties were employed in assessing the suitability of Abakaliki clay as drilling mud. Mineralogically, the clays were all characterized as dominantly Illite as well as montmorillonite with low percentages of kaolinite. The chemical composition of the clays indicates low percentages of Na_2O when compared with that of Wyoming bentonite with fairly higher percentages of CaO and K_2O than are required for drilling mud clays. The clays are plastic; with liquid limit (LL) of 58.8 to 72.8, plastic limit (PL) of 25 to 30 and plasticity index (API) of 26 to 45.8. They are classified as inorganic clays of high plasticity (CH) according to Unified Soil Classification System (USCS) and as A-7-6 according to American Association of State High and Transportation Official's (AASHTO) classification systems. The natural pH values are greater than 8.10, while the viscosity values varied from 5.9 to 8.0 centipoises for 10 g clay per 350 ml water. Some of these natural properties (Na_2O and CaO contents, LL, PI and viscosity) of these Nigerian clays failed to satisfy the required specifications outlined for clays used as drilling mud when compared with the properties of Wyoming bentonite. This clay will possibly yield low plastic viscosities but with additives such as sodium carbonate and carboxymethyl cellulose, the rheological properties for Abakaliki clay will remarkably improve.

Key words: Abakaliki Formation, drilling mud, geotechnical analysis, Wyoming bentonite, Southeastern Nigeria.

INTRODUCTION

Clay are generally fine-grained materials, with particle size less than 0.002 mm with predominately clay minerals. Other minerals associated with clay minerals in clays may include quartz and feldspar (Grim, 1968), as well as detrital materials that were eroded from the earth's surface. Clay is one of the earliest mineral substances utilized by man. It played an extremely important part in ancient civilizations, records of which were preserved in brick buildings, in monuments and in pottery, and as inscriptions upon clay tablets. Clay is
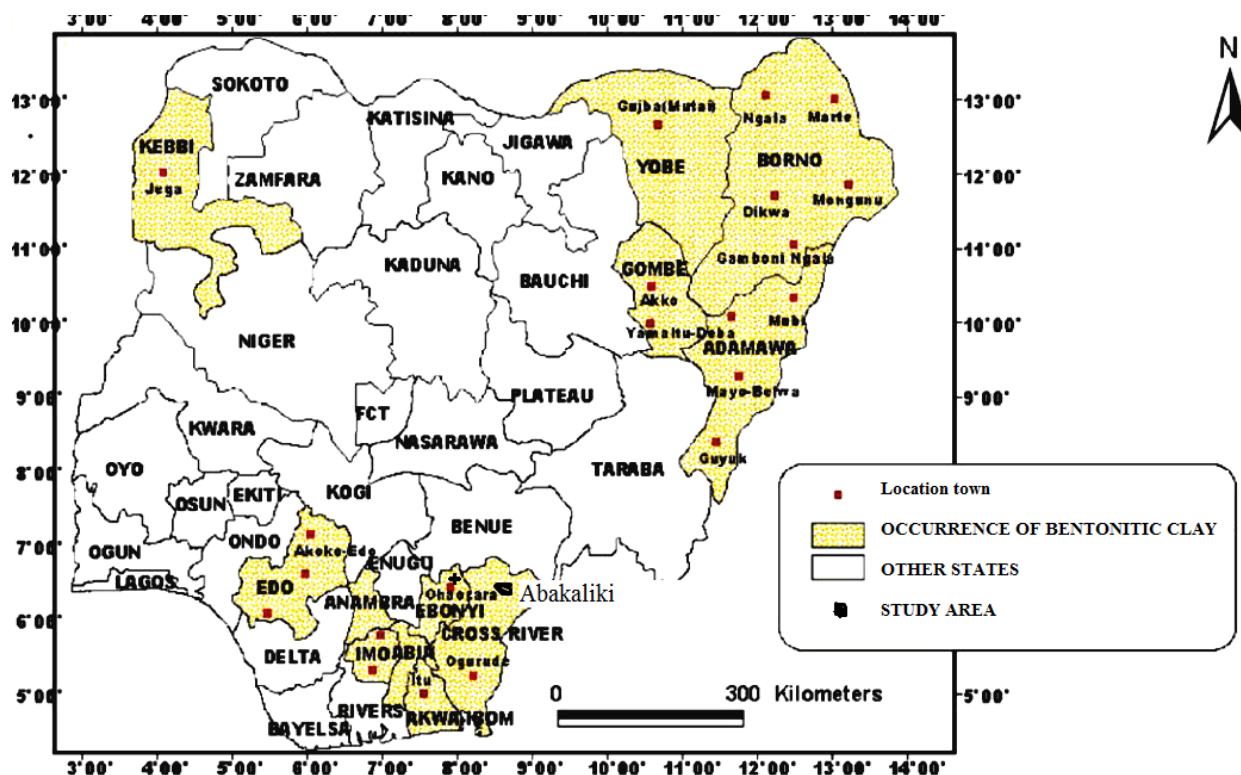
*Corresponding author. E-mail: nwaekeoby@yahoo.com.

Figure 1. Map of Nigeria showing states with occurrence of bentonitic clay (Modified from Apugo-Nwosu et al., 2011).

still an indispensable raw material today. The present uses of clay and clay products are too numerous to list completely. Because of its characteristic plastic property, clay has several industrial uses, which include manufacturing of refractories as well as in drilling mud in the water, oil and gas industries. Several clay occurrences have been investigated and reported in Nigeria (Elueze, 1998). The interest in these studies is hinged on the effective exploitation of the local raw materials for use as drilling mud for sustainable economic growth and creation of employment opportunities

Despite the abundance of clay and its wide industrial uses, it is essential that certain property specifications be met by either the raw or refined clay. The refining of clays usually alters the geotechnical properties of the natural clays, hence, could boost their industrial potentials. Raw materials used for the mud making are usually selected clays with appreciable amount of montmorillonite and are judged by their behavior in water (Nestle, 1944). Their suitability is determined by various criteria, among which are the viscosity, the volumetric yield of given clay and filtration characteristics (Apugo-Nwosu et al., 2011). The raw material which meets most of these requirements for drilling is the bentonite clay. Bentonite is formed by the weathering of volcanic ash. The weathering process, by which the clay minerals are formed from the parent minerals are complex but the main factors are climate,

topography, vegetation, and time of exposure. In addition to montmorillonite, bentonite may also contain feldspar, biotite, kaolinite, illite, cristobalite, pyroxene, zircon and crystalline quartz (Parkes, 1982). By extension, the term bentonite is applied commercially to any plastic, colloidal and swelling clay regardless of its geological origin (Apugo-Nwosu et al., 2011). Such clays are ordinarily composed largely of minerals of the montmorillonite group. Bentonite is clay that expands to many times its original volume when wetted; it is also characterized by a high cation-exchange capacity, by an ability to form viscous suspensions and thixotropic gels when mixed with large amounts of water, by a high adsorption capacity, and by an ability to form an impervious seal (Rath, 1986).

Drilling activities for the development of oil, gas and water resources usually require enormous amount of drilling mud, which is usually imported into the country. Such importation, apart from draining the nation's reserves in hard currency, is also inimical to local content policy being currently promoted for the oil industry in the country. Thus, the need for local sourcing of bentonitic clays or close substitutes has become imperative. Fortunately, clay deposits occur abundantly in the sedimentary basins of Nigeria, especially in Abakaliki area (Figure 1).

This work evaluates, by means of simple but relevant

geotechnical tests, the properties of some clay deposits from Abakaliki area, southeastern Nigeria. The aim was to determine whether the clay deposits meet the specifications for use as drilling mud when compared with that of Wyoming bentonite as well as other commercial bentonite.

Literature review

Research performed in the early 90's by the Bureau of Mines of the U.S.A, showed that the sum of bentonite deposits in the world was about 1.36 billion tons, and the U.S.A. has more than 50.0% of the total (Apugo-Nwosu et al., 2011). Clays of various kinds and grades abound throughout Nigeria's sedimentary basins and on the basement (Falode et al., 2007). Recent investigations by the Nigerian Mining Corporation established the existence of bentonitic clay reserves of over 700 million tonnes in the country, with the largest single deposit at Afuze in Edo State holding 70-80 million tonnes (Apugo-Nwosu et al., 2011).

Although there is a general absence of universally accepted procedure for standardizing industrial specifications of the properties of clays used as drilling mud, the properties of the naturally active Wyoming bentonite which most oil drilling companies use as an effective drilling mud have been employed to evaluate the potential of most clays applied in drilling operations (Rath, 1986). Thus, earlier workers such as Omole et al. (1989) were able to have a pioneering study on the suitability of the black cotton clay soil of northeastern Nigeria as drilling mud. Their work evaluated the nature and geotechnical properties as well as effects of beneficiation on the clay soil. The results of their beneficiation tests showed that the beneficiated clays were still not suitable for direct use as oil drilling mud but could be used for drilling water wells. Later researchers, such as Mihalakis et al. (2004), observed that the rheological properties of the black cotton clays improved with addition of Na_2CO_3, such that the upgraded clay can be used as multipurpose drilling mud.

Other researchers (Ezeribe and Oyedeji, 2005) added lignite to clay mud to improve its rheological and filtration properties. The lignite was activated with sodium hydroxide and added to fresh water mud at different concentrations. The authors concluded that the addition of lignite improved the suitability of the clay with a significant improvement observed when 3% of lignite was introduced. The work of Okogbue and Ene (2008) revealed that some southeastern Nigeria natural clays possess properties that are somewhat similar to those of naturally active bentonitic clays from Wyoming and Texas which are used in the industry as drilling mud. Physical and rheological properties of the clays were however, said to be poor. The characteristics of Abakaliki clay for use as drilling mud have not been evaluated.

Properties required for drilling mud

Chemical properties

The chemical properties of drilling mud are central to the performance and hole stability. Properties that must be anticipated include the dispersion of formation clays or dissolution of salt formations; the performance of other mud products- for example, polymers is affected by pH and calcium; and corrosion in the well. Sodium montmorillonite particles are laminar in shape carrying surface electrical charge not homogeneously distributed. The faces bear a permanent negative charge while the edges are conditionally charged depending on the pH of medium (Kelessidis et al., 2005). It is the imbalance in the electrical charge that characterizes the type of interactions of clay particles with other materials.

Rheology and density

In geology, rheology is defined as the study of how matter deforms the flows, including its elasticity, plasticity and viscosity. Rheology is an extremely important property of drilling muds, work-over and completion fluids, cements and specialty fluids and pills. Mud rheology is measured on a continual basis while drilling and adjusted with additives or dilution to meet the needs of the operation. A high viscosity fluid is desirable to carry cuttings to surface and suspend weighing agents in the mud. However, if viscosity is too high, friction may impede the circulation of the mud causing excessive pump pressure, decrease the drill rate, and hamper the solids removal equipment. Plastic viscosity is a measure of the internal resistance to fluid flow attributable to the amount, type and size of solids present in a given fluid (Garvey et al., 1988). The value expressed in centipoises, is proportional to the slope of the consistency curve determined by the region of laminar flow for materials obeying Bingham's Law of plastic flow.

Geomorphology

Abakaliki which is the study area is made up of villages like Nkaliki, Onuebonyi, Agbaja Unuhu, Ugboloke, Ishieke, Izzi unuhu and Abakaliki urban (Figure 2). The area is geographically located between latitude 6°15'N and 6°20'N and longitude 8°05'E and 8°10'E covering a total area of about 81 km^2. The areas were accessed through Enugu, Ogoja, and Afikpo through a network of tarred roads which include the Abakaliki Enugu Express road, Abakaliki Ogoja Express road and Abakaliki-Afikpo Express road. During the fieldwork, vehicles, motorcycles and footpaths were employed to aid accessibility and
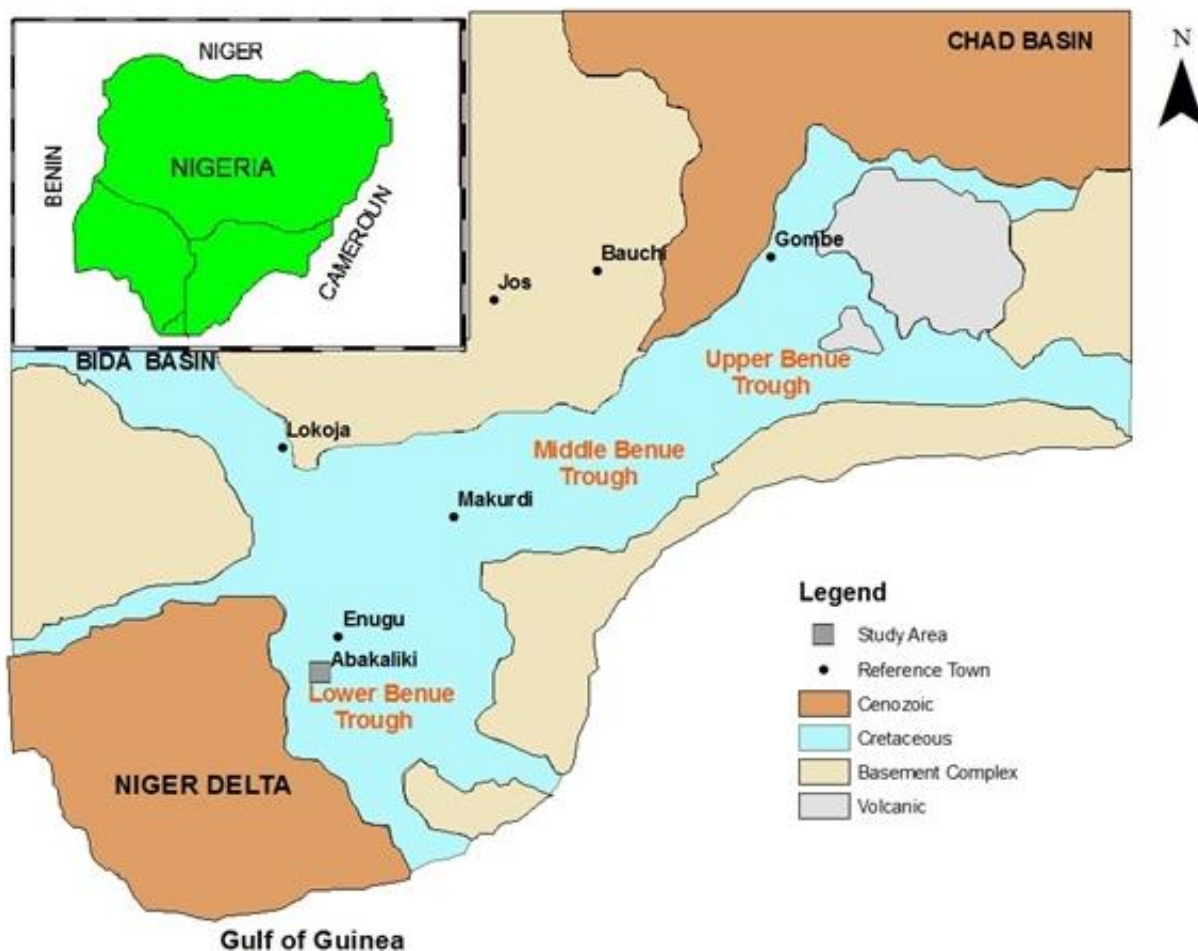
Figure 2. Map of the Benue Trough of Nigeria (Modified from Obaje et al., 1999).

movement through the outcrop locations and sample collections. The vegetation of Abakaliki and its environs is luxuriant vegetation of tropical rainforest.

Its vegetation is densely populated with grasses and trees of different sizes in the area. The area is marked by undulated range of shale outcrops and the shales are either greyish or reddish brown in colour depending on its content and degree of weathering. The area had 400 ft as its highest contour and 100 ft as its lowest contour above sea level. The climate of the study area is of humid tropical climatic region. It experiences one rainy season and one dry season (eight months of rainfall and four months of dryness). Harmattan is felt between December and January. The mean annual temperature stands at 28°C. Humility in this area is about 50-60% P.a. The mapped area has a mean annual rainfall of 2500 mm. Rainfall is highest in September and lowest in January. The drainage system of the study area is dendritic in pattern, as a function of lithologic control. The study area is mainly drained by Iyiokwu River, Iyiudene River and

Ebonyi River with few minor drainage flows. All these, both the major and minor drainage system flow eastward to join the Cross River somewhere outside the study area.

GEOLOGY

Abakaliki area Southeastern Nigeria is underlain by the southern Benue Trough (Reyment, 1965). The origin of the Benue Trough is closely associated with the breakup of western Gondwanaland during the separation of the African and South American Plates, and opening of the south Atlantic Ocean, in the early Cretaceous (Wright, 1976). The Benue Trough has been described as an 'intracratonic rift system' or an 'intercontinental Cretaceous Basin' stretching in a NE–SW direction (Benkhelil et al., 1989).

The southern section of the trough, which underlies most parts of Southeastern Nigeria, has stratigraphic record of deposits represented by sediments of three
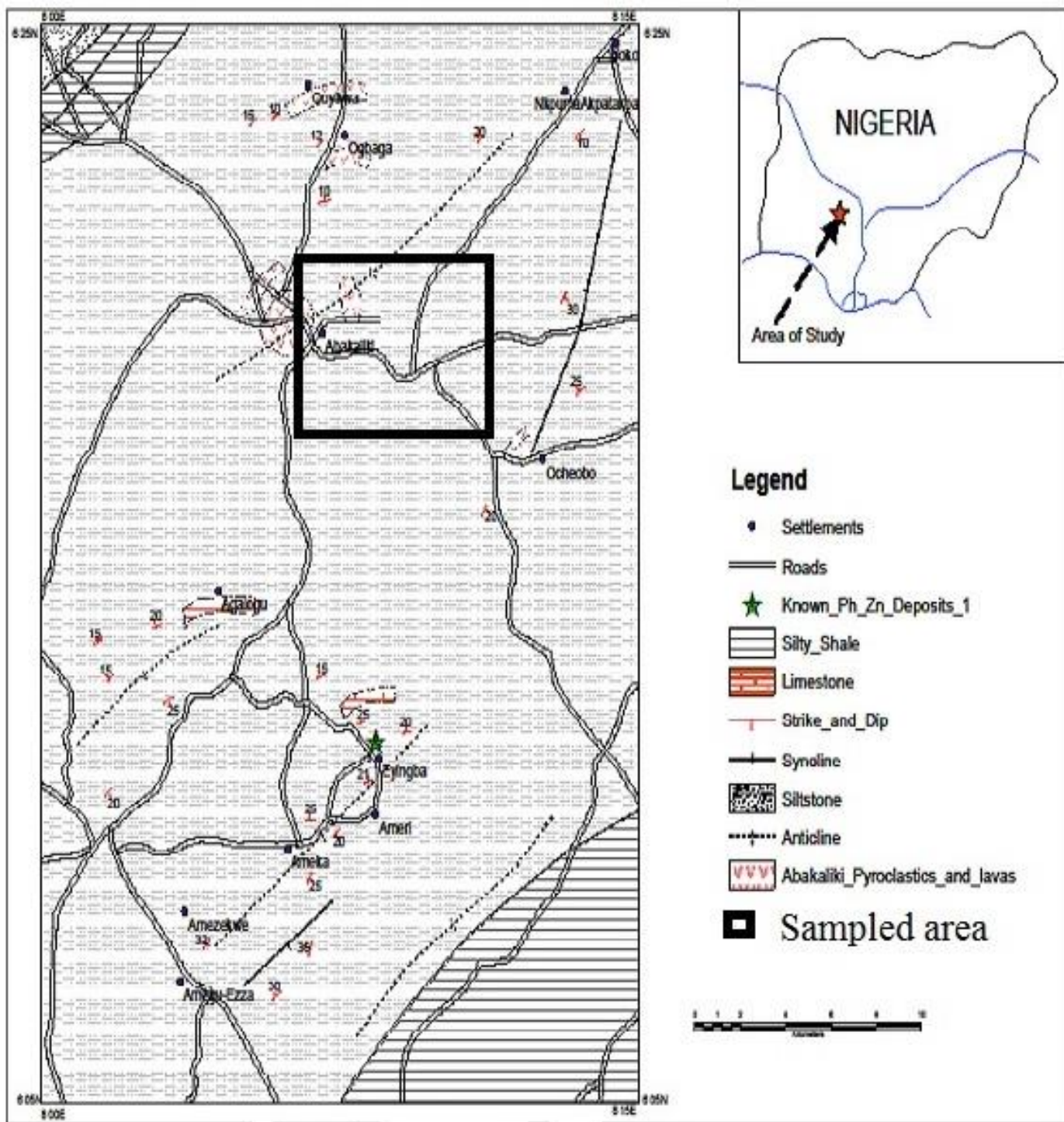
Figure 3. The areas where samples were collected.

main marine depositional cycles, Albian-Cenomanian, Turonian-Santonian and Campano- Maastrichtian (Reyment, 1965). The stratigraphic successions in the Southern Benue Trough and Anambra Basin are presen-

ted in Figure 2. The first marine transgression in the trough is generally believed to have started in the mid-Albian period with the deposition of the Asu River Group made up of predominantly shales and localized develop-
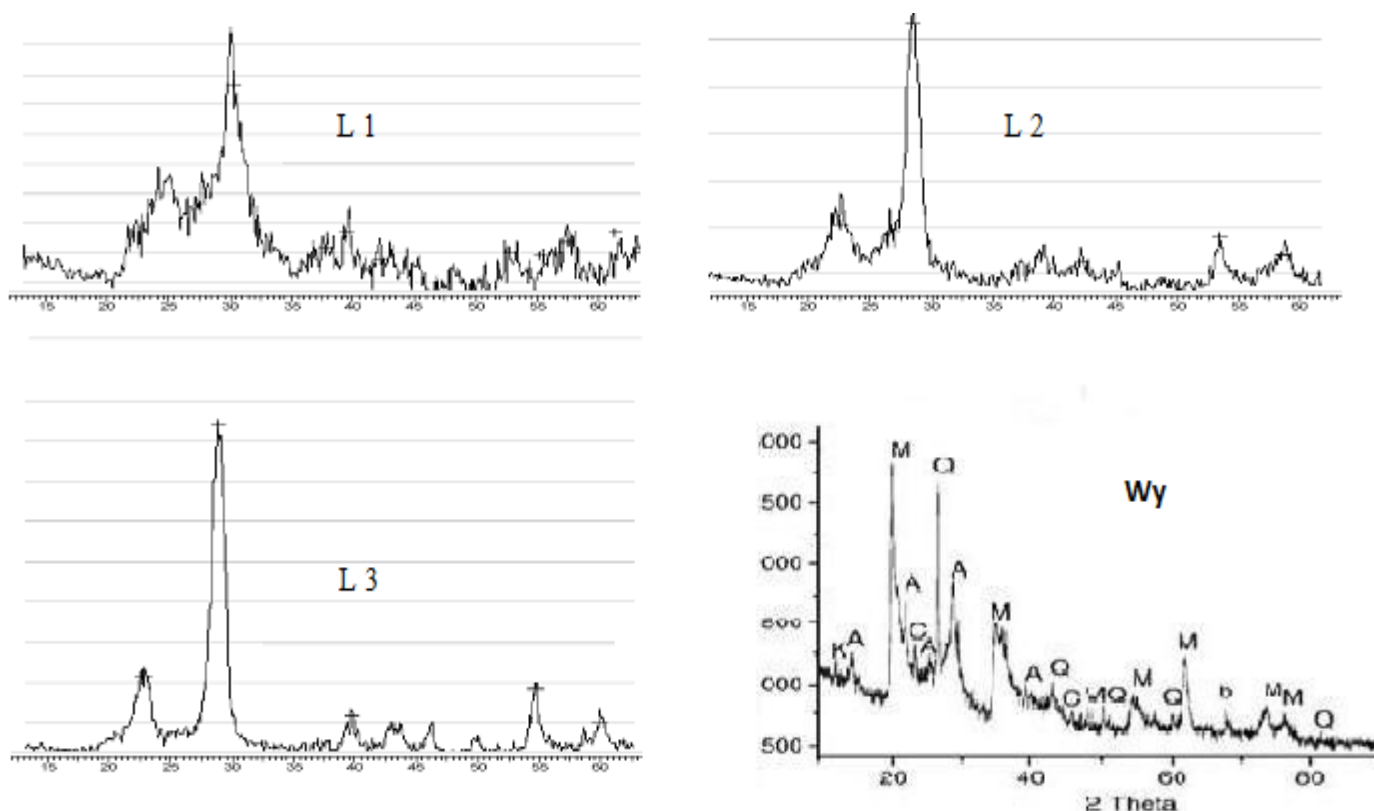
Figure 4. Diffractograms of some of the studied clays and Wyoming clays.

ment of sandstone, siltstone and limestone facies (Hoque and Nwajide, 1988). The study area is covered by sediments of Asu River Group.

MATERIALS AND METHODS

Sampling

Ten (10) fresh samples of clays were taken from Abakaliki area in southeastern Nigeria (Figure 3). The samples are herein designated as L1 to LI0. Care was taken when sampling to ensure that fresh samples were taken and that such samples were representative of the materials to be assessed. The sampling depth ranged from 1 to 2.5 m. Tests on the clay samples were carried out at the material laboratories of the National Steel Raw Material Exploration Agency, Kaduna in Nigeria.

Laboratory tests

Relevant laboratory tests were carried out to determine the properties of the sampled Abakaliki clays. The pulverized clay sample was prepared by creating a highly polished surface in the cavity of the sample holder of the Pw 1800 diffractometer with copper tube anode. This was introduced to the x-ray diffractometer equipment (XRD) which scanned the sample continuously for clay bulk analysis. A generator tension of 40 kv and current of 55 mA were used. From the XRD traces, the clay minerals in the samples were determined by their diagnostic peaks according to diffraction

intensity published by ASTM (1989), in powder diffraction files. An IVT-20 computer-automated X-ray fluorescence (XRF) spectrometer was used for bulk chemical analysis of the clay samples. The clay samples were prepared in accordance with outline given in Kenigan (1971). Cation exchangeable capacity of metallic bases in meq/100 g of dry sample were measured by leaching 50 g of the sample with neutral normal ammonium acetate and the resulting aliquots were analyzed characteristically for Na, K, Ca and Mg cations, following method outlined in ASTM 2354 (1989). The fraction that passed the 75 μm BS (No. 200) sieve was oven-dried, weighed and later dispersed with a solution of sodium hexametaphosphate and sodium carbonate. It was then analyzed using the hydrometer method as specified in BS 1377 (1990). The bulk density and specific gravity were determined using 100 g of oven-dried samples, passing 75 μm BS (No. 200), according to procedures outlined in ASTM (1989). The viscosity and pH were both determined from clay-water suspension with 20 parts water using methods described in L ASTM C97 (1989). The Atterberg limits of the clay samples were determined in accordance with BS 1377 (1990). Free swell test was conducted using methods described by Holtz and Gibbs (1956).

RESULTS

Mineralogical, chemical analysis and cation exchangeable capacity

The diffractograms of the clay samples are as presented in Figure 4. The results of the mineralogical composition

Table 1. Mineralogical composition of Abakaliki clay.

Clay mineral	Wyoming bentonite (%)	Abakaliki clay (%)
Montmorillonite	35.85	20-30
Kaolinite	5.01	15-25
Quartz	23.98	28-30
Calcite	8.32	13-24
Biotite	3.23	
Feldspar	23.98	28-32
Illite	0	30-38

Table 2. Chemical composition of Abakaliki clay.

Composition (w%)		
Chemical oxides	Abakaliki clay (%)	Wyoming bentonite (%)
SiO_2	50.10-58.96	45
Al_2O_3	19.90-25.08	17
Fe_2O_3	3.80-4.67	11.1
TiO_2	1.10-2.10	1.68
CaO	1.00-5.42	1.77
MgO	0.32-2.02	0.33
K_2O	0.52-1.40	0.05
Na_2O	0.68-1.98	2.7
MnO	2.00-3.34	0.15

of Abakaliki clays are summarized in Table 1 and compared with that of Wyoming clay, as reported by Falode et al. (2007).

The results indicate that the clays are composed predominantly of Illite and mixed layer clays, with presence of Montmorillonite which ranges from 20-30% and kaolinite which ranges from 15-25%. Montmorillonite produces "sensitive" clay even where it is present in minute (5% to 10%) amount (Okagbue, 1989). The presence of the montmorlloiite in Abakaliki is significantly low when compared with Wyoming bentonite. The presence of quartz, which acts as an abrasive according to Apugo-Nwosu et al. (2011), could lead to poor physio-chemical performance of the clay. It has been observed (Sowers and Sowers, 1970) that Na-montmorillonite is quite more expansive than the Ca-montmorillonite type. The presence of kaolinite in the Abakaliki clay could lead to poor rheological properties since such type of clay has low swelling capabilities.

Chemical composition

The results of chemical analysis of the clay samples are presented in Table 3. The chemical composition of the Abakaliki clay sample indicated very high alumina (19.90-25.08%) and silica (50.10-58.96%) when compared with the value of Wyoming bentonite that has silica of 45% and alumina of 17% (Table 2). The alkaline earth mineral (CaO) and the alkali mineral (K_2O) of Abakaliki clay are 1.00-5.42% and 0.52-1.40% respectively and that of Wyoming bentonite are alkaline earth mineral 1.17 % and alkali mineral (0.05%), respectively. The bentonite of Wyoming is a high-sodium bentonite and differs from bentonite in the southern United States, which contains much calcium and has different characteristics. The XRF results indicate low content of Na_2O (0.68-1.98%) when compared with that of Wyoming clay which has 2.7 of Na_2O. The fair consistency in the concentrations of oxides may generally indicate similarities in the mineralogy of the studied clays. The relatively high amounts of CaO noted in the clays may possibly be attributed to the occurrence of carbonates such as calcite in the sediments (Reyment, 1965). In all, the enrichment in CaO, as well as depletion in Na_2O, might suggest that the predominant clay mineral is the Ca-rich type. The presence of alkalis and magnesia in the samples suggests presence of clay mineral which may not likely be montmorillonite. Abakaliki clay showed low value of Fe_2O_3, this indicates low laterite concentrations. The very high alumina and silica contents when compared with refractory standards (25-45% alumina and 55-75% silica) as noted by Falode et al. (2007), coupled with the high levels of iron and organic matter would make the Abakaliki clay sample very suitable as a refractory material. The MgO value for Wyoming clay is very close to the value recorded for Abakaliki clay. This compound is normally used to enhance gel strength of mud samples (Falode et al., 2007).

The results of the analysis of the samples for the CEC are presented in Table 3. Ca^{2+} is the main cation in all the studied clays while Na^+ is a minor cation. The CEC recorded for Wyoming bentonite indicates that the values range from 60-65 Na^+ to 15-20 Ca^{2+}. The typical CEC range of pure smectite is from 80 meq/100 g to 150 meq/100 g (Grim, 1968). The presence of Na and Ca ions, among other factors, influences the swell potentials of active clays. While Ca^{2+} limits the swelling of montmorillonite, Na^+ enhances it. Tourtelot (1974) had observed that Ca^{2+} as the main exchangeable cation has a strong depressing effect on the swelling capacity of montmorillonite. Ca-montmorillonites can swell only up to 100% while Na-montmorillonite in bentonite may swell up to 2000%.

Natural clays rich in montmorillonite generally contain a mixture of exchangeable cations, including Mg^{2+}, K^+ and Fe^{3+}, although Na^+ and Ca^{2+} predominate but in varied proportions. Montmorillonite with these mixed proportions of exchangeable cations would be expected to swell in

Table 3. Results of cation exchangeable capacity and hydromteter test.

Parameter	LI	L2	L3	L4	L5	L6	L7	L8	L9	L10	Average
Cation exchangeable capacity (meq/100 g)											
Ca^{2+}	33.2	36.3	38.6	32.3	30.1	32.9	28.8	34.8	35	28.98	33.1
K^+	1.49	2.36	2.07	2.69	3.66	2.12	2.31	2.07	2.67	2.19	2.4
Na^+	12.3	16.6	12.8	11.1	13.5	12.4	16.5	12.3	14.8	12.79	13.5
Mg^{2+}	4.3	5.7	5.3	4.9	5.6	4.9	6.7	5.3	5.4	6.7	5.5
Results of hydrometer analysis (%)											
Sand	18	14	10	8	10	20	29	20	14	11	15.4
Silt	48	46	44	52	48	42	38	48	48	51	46.5
Clay	34	38	46	40	42	38	41	42	38	38	39.7
Viscosity in centipose	7	6	8	6.5	7.8	6.9	8.9	8	8.3	6.7	7.4
Free Swell%	60	63	59	55	62	56	60	50	58	58	58.1
pH	8.1	9	8.25	9.1	8.18	9.3	7.8	7.95	8.12	7.9	8.37

Table 4. Results of Atterberg limit test, specific gravity, bulk density and calculated activity value.

Parameter	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	Average
Specific gravity	2.54	2.56	2.42	2.64	2.6	2.2	2.45	2.6	2.54	2.34	2.48
Bulk density	1.55	1.68	1.67	1.52	1.45	1.7	1.57	1.59	1.45	1.53	1.57
Plastic limit	24.8	24.6	30.1	25	27	34	27	30	32	28	28.25
Liquid limit	66	58.8	70	62.4	72.8	65	62	56	60	63	63.6
Plasticity index	41.2	44.2	39.9	37.4	45.8	31	35	26	32	35	36.75
Activity	1.21	1.16	0.86	0.9	1.09	0.81	0.85	0.63	0.84	0.92	0.92

Table 5. Classification of soils based on activity.

Activity	Soil type	Abakaliki clay
A<0.75	Inactive	
A= 0.75 to 1.25	Normal	0.92*
A> 1.25	Active	

*Average activity value.

amounts intermediate between those of Ca-montmorillonite and Na-montmorillonite end members (Tourtelot, 1974).

Geotechnical properties

The results of the Atterberg limits tests on the natural are presented in Table 4. These results indicate that the clays in their natural states have relatively high plasticity. When compared with Wyoming bentonite which has LL 600-700 (Skempton 1953), the LL values (58.8-72.8) of Abakaliki clay, however, are significantly low. Atterberg plasticity index (API) of 26-45.8 shows that the sample is

plastic over a wide range of moisture content. These also corroborate the alkaline earth mineral of 1.00-5.42% and the alkali mineral of 0.52-1.40% of Abakaliki clay.

The high plasticity index reveals the clay's potential for great volume change characteristics (Figure 5). The silt content makes the sample material unsuitable for wide ceramic applications. The results of the gradation analysis and the calculated Skempton activity values of the clay samples are also presented in Table 4. The results indicate that the samples are characterized by marginally higher proportion of silt-sized particles with average value of 46.5% than the clay-sized particles with average value of 39.7%. The clay fractions, despite being lower than the silt fraction, would be considered significant and are capable of influencing the geotechnical behaviour of the clays, especially if they made of the highly expansive mineral type. Okagbue (1989) had noted that the colloidal (<0.001 mm) content of a soil is an important influencing factor in the absorption of water and in volume changes in the soil depending on the mineral types constituting the colloids.

Activity (A) according to Skempton (1953) of the soil is the ratio of the plasticity index and the percentage of the clay fraction. Activity is a measure of the water-holding
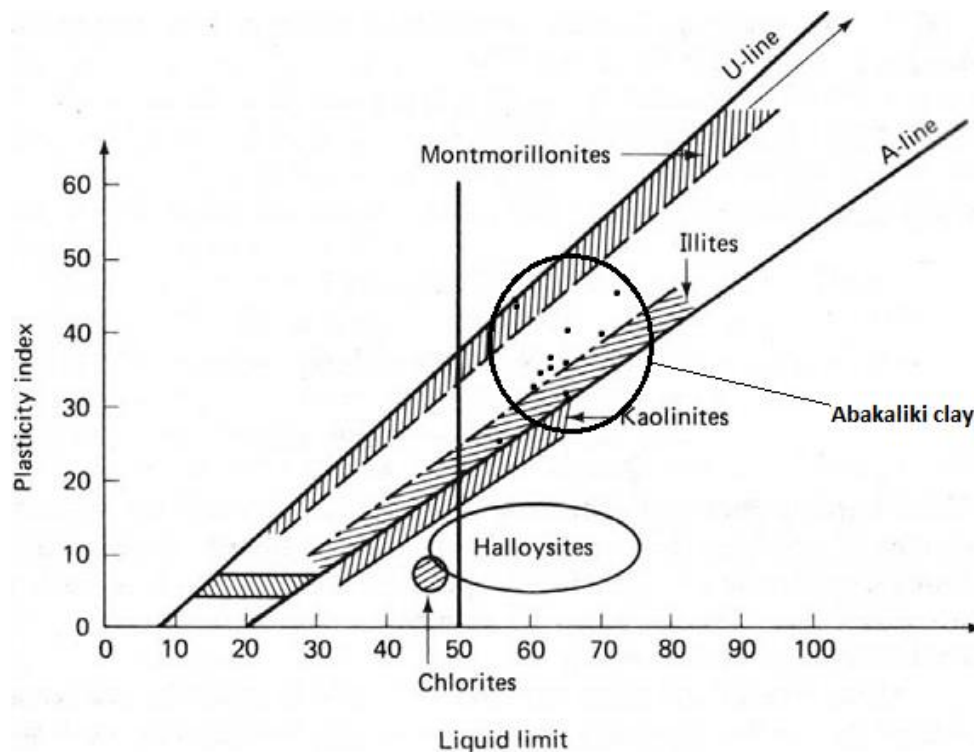
Figure 5. Location of clay minerals on the Casagrande plasticity chart using the Abakaliki clay (Modified from Skempton, 1953).

capacity of the clayey soils. The Activity values of the tested samples which range from 0.63 to 1.21 may suggest that the clays are possibly Ca-rich, rather than Na-rich. Soda rich active clays, according to Skempton (1953) and Tourtelot (1974), have activity values greater than 5. The average activity value for the studied clay is 0.92 (Table 5) indicating normal soil type. Active clays have both high water retaining and high cation exchangeable capacity (Skempton, 1953).

The swelling potential values as indicated from free swell (Table 3) also suggest that the clays are not the very active types. Using LL as one of the swell indicators (Chen, 1988), the free swell test results also indicate that the tested natural clay samples have low swelling potentials when compared with bentonites from Texas with mean LL value of 1110% and free swell range of 397 and 401 (Rath, 1989). As shown in the tables, there is fair consistency in the results of bulk density of all the tested clays, suggesting similarity in the material type; a situation already reflected in the results of mineralogical and chemical analyses. The result suggests that the clays generally have low G_s values (average of 2.48) when compared with that of Texas bentonitic clay which has specific gravity range of 2.50 to 2.80 g/cm^3. Commercial Bentonite sample of China origin according to Abdullahi et al. (2011) has specific gravity of 2.87.

Kearey (2001) noted that a crystal of montmorillonite would have G_s of about 2.74. Since tests have suggested that the tested clays are illite predominated, it may mean that the other fraction that is non-montmorillonite is, most probably the mixed layer fraction, of the low G_s clay mineral type. Attapulgite (or palygorskite) is to be suspected because of its close association with Ca-rich montmorillonitic clays (Kearey, 2001) and its low G_s (mean G_s value of 2.48) (Lambe and Whitman, 1979). The clay needs increase in its density since according to Hall (1993), clays used as drilling mud must be "weighted" by addition of high density solids such as barite or haematite in order to control over pressure.

Rheological properties

The results of the pH measurements of the clay slurries indicate that they are all alkaline. The viscosity of the natural clay slurries, also shown in Table 3, range from 6.0 to 8.9 centipoises. These values are comparatively low when compared with those of drilling mud. Rath (1986) observed that natural bentonitic clays from Wyoming recorded viscosity that ranged between 8.0 and 25.0 centipoises. Bentonites with higher clay percentages (lower non-clay mineral content) as Wyoming

should show high rheological properties. Clay such as montmorillonite that has a high cation exchange capacity swells greatly and forms viscous suspensions at low concentrations of clay, particularly when sodium is in the exchange position. Considering the relative higher swelling volumes of Wyoming bentonite indicated by higher montmorillonite content, it should make better suspensions with water and therefore good rheological properties can be obtained whereas the Abakaliki clay would require some beneficiation to improve the swelling properties. This clay will possibly yield low plastic viscosities but with additives such as sodium carbonate and carboxymethyl cellulose, the rheological properties for Abakaliki clay will remarkably improve.

Performance of the clays as drilling mud

A good drilling mud should have excellent plasticity, lubricity that protects the drilling bit, and viscosity that is required for the transportation of drill cuttings. A comparison of the properties of the Abakaliki clay and the properties of Wyoming bentonite indicates that the recorded viscosity is low against the standard clays that have their viscosity values ranging between 8 and 25 centipoises. With respect to the chemistry, the concentrations of most of the oxides generally compare well with those of the standard clays. Few oxides, such as Al_2O_3, MgO, TiO_2, however are marginally higher. Texas clay recorded bulk density that ranges from 2.50 to 2.80 g/cm^3. The Abakaliki clay has their bulk densities all below 1.73 g/cm^3. A significant inadequacy is also observed in the Atterberg limits, swelling potentials and other properties linked to response of clay minerals to moisture conditions. For example, the free swell values of the Abakaliki clays are generally below 63%, whereas the standard clays all have free swell above 700%. Similar trend is also noticed for PI. While the natural studied clays all have API below 46, the standard clays record PI all above 358. Exchangeable Ca^{2+} is also quite higher for all the samples studied in comparison with that of the standard clays.

Conclusions

This study evaluated the physical and chemical properties of some clays from Abakaliki Formation, southeastern Nigeria and the extent to which sodium carbonate and barite improved these properties for possible use of the clays as drilling mud. X-ray diffraction test on the studied clays from Asu River Group showed that the dominant clay minerals are Illite, kaolinite and mixed layer types. The chemical compositions indicate that the values of Na_2O are lower than would be expected for clays that are used as drilling mud. Ca^{2+} and Na^+ are

the main exchangeable cations with calcium ion as the dominant cation. The clays exhibited presence of high concentration of exchangeable Ca^{2+}. The clays in their natural state possess relatively high liquid and plastic limits and classified as clays of high plasticity (CH), according to Unified Soil Classification System. The weak swelling properties are thought to buttress the presence of low expansive montmorillonite, most probably the calcium variety. A comparison of the chemical composition of the studied clays with that of naturally active bentonite from Wyoming and Texas used in drilling mud showed that the plasticity and swelling properties of the Abakaliki clays are very low. The viscosity values of the clays are also low. This clay will possibly yield low plastic viscosities but with additives such as sodium carbonate and carboxymethyl cellulose, the rheological properties for Abakaliki clays will remarkably improve. However, the G_s and pH values of the clays are close to those of Wyoming and Texas bentonites.

Conflict of interest

The authors did not declare any conflict of interest.

REFERENCES

Abdullahi AS, Ibrahim AA, Muhammad MA, Kwaya MY, Mustapha S (2011). Comparative evaluation of rheological properties of standard commercial bentonite and a locally beneficiated bentonitic clay from a marine deposit in upper Benue basin, Nigeria. British J. Appl. Sci. Technol. 1(4):211-221.1.

American Society for Testing and Material, ASTM C97, 2354 (1989). Annual book. American society for testing and material standard, part 19, philadelphia.

Apugo-Nwosu TU, Mohammed-Dabo IA, Ahmed AS, Abubakar G, Alkali, AS, Ayilara, SI (2011). Studies on the suitability of ubakala bentonitic clay for oil well drilling mud formation. British J. Appl. Sci. Technol. 1(4):152-171.

Benkhelil J, Guiraud M, Ponsard JF, Saugy L (1989). The Bornu – Benue Trough, the Niger Delta and its offshore: tectono-sedimentary reconstruction during the Cretaceous and Tertiary from geophysical data and geology. In: Kogbe, C.A. (Ed.). Geology of Nigeria. 2nd Edition. Rock view Ltd Jos. pp. 213-234.

British Standard Institution (BS 1377) (1990). Methods of testing soils for Civil Engineering purpose, British Standard Institution, London.

Chen, FH (1988). Foundations on expansive soils. 2nd Edition, Elsevier Scientific, Amsterdam.

Ezeribe IE, Oyedeji OA (2005). The suitability of Nigerian bentonites and black cotton soils as drilling mud. Report submitted to Nigerian Geological Survey Agency. Vol. 2B. 244pp.

Falode OA, Ehinola OA, Nebeife PC (2007). Evaluation of Local Bentonitic Clay as Oil Well Drilling Fluids in Nigeria. Appl. Clay Sci. 39:19-27.

Garvey CM, Savoly A, Resnick AL (1988). Fluid loss Control Additives and Drilling Fluids Containing Same, United States Patent 4741843

Grim RE (1968). Clay Mineralogy. 2nd Edition, McGraw- Hill, New York, 596 pp.

Hall PL (1993). Mechanism of overpressuring: an overview In: Manning, D.A.C., Hall, P.L. Hughes, C.R., (Eds), Geochemistry of clay-pore fluid interactions. Chapman and Hall, London. pp. 265-309.

Holtz WG, Gibbs HJ (1956). Engineering properties of expansive clay. Trans. Am. Soc. Civil Eng. 121:641-663.

Hoque M, Nwajide CS (1988). Tectono-sedimentological evolution of elongated intracratonic basin (Aulacogen): the case of Benue Trough Nigeria. J. Mining Geol. 21:12-18.

Kearey P (2001). The new Penguin dictionary of geology. 2nd Edition. Penguin Books, London. 327 pp.

Kelessidis VC, Mihalakis A, Tsamantaki C (2005). Rheology and rheological parameter determination of bentonite-water and bentonite-lignite-water mixtures at low and high temperatures, 7th world congress of chemical engineering, 10-14th July 2005, Glasgow.

Kenigan GC (1971). A sample preparation device for X-ray fluorescence. J. Phy. Earth Sci. Instrument. 5:544-545

Lambe TW, Whitman RV (1979). Soil Mechanics. John Wiley and Sons, New York.

Mihalakis TS, Makhri PG, Kelessidis VC, Christidis GE, Foscolos AE, Papanikolaou CE (2004). Improving rheological and filtration properties of drilling mud with addition of Greek lignite. Paper presented at the 7th National Congress on Soil Mechanics, 24-26 June, 2004, Chania.

Obaje NG (2009). Geology and Mineral Resources of Nigeria, Lecture Notes in Earth Science, Springer-Verlag, Berlin.

Okagbue CO, (1989). Geotechnical and environmental problems of the Niger Delta. Bulletin of the International Association of Engineering Geologists. 27:119-126.

Okogbue CO, Ene E (2008). Geochemical and geotechnical characteristics and the potential for use in drilling mud of some clay bodies in Southeastern Nigeria. J. Mining and Geol. 44(2):121-130.

Omole O, Malomo S, Akande S (1989). The suitability of Nigeria Black soil clays as drilling mud clays. J. Appl. Clay Sci. 4:357-372.

Rath DL (1986). Origin and characteristics of Wyoming bentonite deposits. Public Information Circular No. 25, the Geological Society of Wyoming. pp. 84-90.

Reyment RA (1965). Aspect of Geology of Nigeria. Ibadan University press. Ibadan. 145 pp.

Skempton A (1953). The colloidal activity of clays. Proceedings, 3rd International Conference on Soil Mechanics and Foundation Engineering, Zurich. Vol. 1. pp. 57-61.

Sowers GB, Sowers GE (1970). Introductory soil mechanics and foundations. Macmillan, New York. 556 pp.

Tourtelot HA (1974). Geologic origin and distribution of swelling clays. Bulletin of the Association of Engineering Geologist 1(4):259-273.