

Evaluation of Usen clay deposit in Edo State, Nigeria, as a drilling mud

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ABSTRACT: This study evaluates the suitability of the Usen clay deposit in Edo State, Nigeria for use as drilling mud through comprehensive mineralogical, chemical, and rheological analyses. Elemental characterization was conducted using Instrumental Neutron Activation Analysis (INAA) at the Nigerian Research Reactor (NIRR-1), revealing that the clay is predominantly siliceous, with high SiO₂ (74.55%) and moderate Al₂O₃ (11.72%) concentrations, but deficient in Na₂O (0.02%) and MgO (below detection limit). Rheological properties were assessed following API diagnostic procedures, including Marsh funnel viscosity, plastic viscosity, apparent viscosity, and mud density. Results showed that the formulated mud exhibited poor rheological performance, with viscosities far below API standards (e.g., apparent viscosity of 1.0 cP vs. API minimum of 15 cP), attributable to low sodium and magnesium contents. However, mud density values (8.55 lb/gal) were within acceptable limits, suggesting potential for modification. Comparative analysis with API bentonite confirmed weak correlation ($R^2 = 0.288$), highlighting the need for beneficiation strategies such as sodium activation, polymer treatment, and barite addition to enhance performance. Overall, while the Usen clay demonstrates favorable density characteristics, its poor rheological behavior necessitates chemical modification before industrial application as drilling mud.

Keywords: Bentonite comparison, drilling mud formulation, Instrumental Neutron Activation Analysis, Rheological properties, Usen clay deposit.

INTRODUCTION

Drilling mud also called drilling fluid refers to a heavy viscous fluid mixture that is used in oil and gas drilling operations to carry rock cuttings to the surface and also to lubricate and cool the drill bit. The drilling mud, by hydrostatic pressure, also prevents the collapse of unstable strata into the borehole and the intrusion of water from water-bearing strata that may be encountered (Falode *et al.*, 2008; Afolabi *et al.*, 2017). Drilling muds are traditionally based on water either fresh water, sea water, naturally occurring brines or prepared brines. Many muds are oil-based, using direct products of petroleum refining such as diesel oil or mineral oil as the fluid matrix. In addition, various so-called synthetic-based muds are prepared using highly refined fluid compounds that are made to more-exacting property specifications than traditional petroleum-based oils. In general, water-based muds are satisfactory for less demanding drilling of

conventional vertical wells at medium depths, whereas oil-based muds are better for greater depths or in directional or horizontal drilling, which places greater stress on the drilling apparatus. Synthetic-based muds were developed in response to environmental concerns over oil-based fluids, though all drilling muds are highly regulated in their composition, and in some cases specific combinations are banned from use in certain environments (Agwu *et al.*, 2015; Chaanda *et al.*, 2026).

A typical water-based drilling mud contains clay, usually bentonite, to give it enough viscosity to carry cutting chips to the surface, as well as mineral such as barite (barium sulfate) to increase the weight of the column enough to stabilize the borehole. Smaller quantities of hundreds of other ingredients might be added such as caustic soda (sodium hydroxide) to increase alkalinity and decrease corrosion, salts such as potassium chloride to reduce

(infiltration of water from the drilling fluid into the rock formation, and various petroleum-defined lubricants. Oil and synthetic-based mud contain water (usually brine), bentonite and barite for viscosity and weight, and various emulsifiers and detergents for lubricity (Ogbu, 2024; Afolayan, 2021).

Clay refers to a fine-grained soil that combines one or more clay minerals (hydrous aluminium phyllosilicates, sometimes with variable amount of iron, magnesium, alkali metals, alkaline earths and other cations found on or near some planetary surfaces) with traces of metal oxides and organic matter. Geologic clay deposits are mostly composed of phyllosilicate minerals containing variable amounts of water trapped in the mineral structure. Depending on the academic source, there are three or four main types of clay: kaolinite, montmorillonite-smectite, illite and chlorite. Chlorites are not always considered clay, sometimes being classified as a separate group within the phyllosilicates (Eyankware *et al.*, 2021; Onyekuru *et al.*, 2018). Clay minerals are typically formed over long periods of time by the gradual chemical weathering of rocks (usually silicate-bearing) or shales by low concentrations of carbonic acids and other diluted solvents. These solvents usually acidic, migrate through the weathering rock after leaching through upper weathered layers. In addition to the weathering process, some clay minerals are formed by hydrothermal activity. Clay deposits may be formed in place as residual deposits, but thick deposits usually are formed as the result of a secondary sedimentary process after they have been eroded and transported from their original location of formation. Clay deposits are usually associated with very low energy depositional environments such as large lakes and marine deposits (Iraor *et al.*, 2023; Omoruyi *et al.*, 2022). Clays are distinguished from other fine-grained soils by various differences in composition. The distinction between silt and clay varies by discipline. Geologists and soil scientists usually consider the separation to occur at a particle size of 2 μm (clays being finer than silts), sedimentologists often use 4–5 μm , and colloid chemists use 1 μm . Petroleum engineers distinguish between silts and clays based on the plasticity properties of the soil, as measured by the soils Atterberg limits. ISO 14688 grades clay particles as being smaller than 0.063 mm, and silts larger (Uwaezuoke *et al.*, 2022; Oyedoh *et al.*, 2023).

There are three or four main groups of clays depending on the academic source: the Kaolin group made up of five minerals which are Kaolinite, Halloysite, Dickite, Nacrite and Endellite; the Bentonite group made up of Montmorillonite-smectite, Endellite, Beidellite, Nontronite and Saponite; the Hydrous mica group represented by the mineral Illite; and Chlorites, which are not always considered clay, sometimes being classified as a group within the phyllosilicates. Instrumental characterization of clay can be performed by different techniques such as Nuclear Activation Analysis (NAA), X-ray fluorescence (XRF), X-ray diffraction (XRD), Fourier Transform Infrared

(FT-IR), Atomic Absorption Spectroscopy (AAS). XRF shows the chemical compositions of the clay whereas XRD confirms the presence of these materials in the clay. FTIR studies show the presence of mineral matters and carry out vibrational analysis. Physicochemical analysis is carried out by the AAS and the NAA (Mathias, 2015; Olatunde *et al.*, 2021).

Bentonite is an absorbent aluminum phyllosilicate, impure clay consisting mostly of montmorillonite. They are clays rich in smectite (a group of clay minerals able to expand and contract their structure while maintaining the two-dimensional crystallographic integrity) regardless of their origin, which are valued for their properties such as crystal shape and size, thixotropy, cation exchange capacity (CEC), hydration and swelling, bonding capacity, impermeability, plasticity and tendency to react with organic compounds. The absorbent clay was given the name by Wilbur C. Knight in 1898 after the Cretaceous bentonite shale rock near Rock River, Wyoming in America. There are three different types of bentonite, each named after the respective dominant element, such as potassium (K), sodium (Na), calcium (Ca) and aluminium (Al). Bentonite usually forms from weathering of volcanic ash most often in the presence of water. For industrial purposes, two main classes of bentonite exist: sodium and calcium bentonite. Sodium bentonite expands when wet, absorbing as much as several times its dry mass in water. Because of its excellent colloidal properties, it is often used in drilling mud for oil and gas wells and boreholes for geotechnical and environmental investigations. Bentonite is the most important of all clays used in the preparation of drilling mud. In terms of mud-making properties, it yields about 90 barrels of 15 cP mud per ton (Wilfred & Akinade, 2016; Obioma and Dagde, 2022).

This work is based on characterizing the clay soil in Usen, a town in Edo State, Nigeria, to find out if this particular clay has similar properties to that of bentonite clay so that it can be developed and if possible substituted for the same purpose. If this aim is achieved, we can reduce the country's dependency on imported bentonite for use as drilling mud in our oil companies (Anthony *et al.*, 2020; Otitigbe, 2022). Nigeria being one of the countries that majorly engages in oil and gas production and drilling activities, should aim at utilizing its local clays for use as a substitute for bentonite clay which is consumed in extremely large quantities as drilling mud in our oil industries. Unfortunately, Nigeria imports this clay from countries like the United Kingdom, USA and Japan at exorbitant prices despite our present economic state. Kragha M.O. in his research carried out in 1985 observed that more than 15 million is spent annually on importation of drilling clays. However, our petroleum industries continue to make use of these clays, the cost of which could account for over 20% of total operating costs. This over-dependency can be avoided if we characterize the local clays in our communities to determine their suitability for use as drilling mud. If this yields a positive result,

perhaps we could export our local clays for use as bentonite to other foreign countries that major in drilling activities, thereby generating revenue for our country. Characterizing and determining the suitability of our local clays is crucial for the effectiveness of our oil industries. In this work, the steps necessary for characterizing our local clay are elaborated (Osadebe *et al.*, 2011; Oyedoh *et al.*, 2016; Ogbu, 2024).

MATERIALS AND METHODS

Clay identification

Quantitative analysis of clay samples using neutron activation analysis

The elemental composition of the clay samples was determined using Instrumental Neutron Activation Analysis (INAA) at the Nigerian Research Reactor facility. Neutron Activation Analysis is a sensitive and non-destructive analytical technique used for the quantitative determination of major, minor, and trace elements in geological materials. The technique is based on neutron irradiation of stable nuclei, resulting in the formation of radioactive isotopes which emit characteristic gamma radiations used for elemental identification and quantification.

Prior to analysis, the clay samples were dried, homogenized, and pulverized into fine powder using standard laboratory crushing and milling equipment. The powdered samples were sieved to particle sizes finer than 150 mesh in order to ensure uniformity. Aliquots of approximately 5–100 mg were prepared and sealed in irradiation containers before exposure to neutron flux.

The irradiations were carried out using the Nigerian Research Reactor (NIRR-1), a low-power miniature neutron source reactor fueled with highly enriched uranium. The reactor consists of a compact cylindrical core with beryllium reflector and light water serving as moderator and coolant. Both inner and outer irradiation channels were utilized for thermal neutron activation, while the cadmium-lined irradiation channel was employed for epithermal neutron activation analysis.

Gamma-ray measurements were performed using a High-Purity Germanium (HPGe) detector with 30% relative efficiency at the 1332.5 keV gamma-ray line. The detector system was coupled with an ADCAM multichannel analyzer and MAESTRO data acquisition software manufactured by EG&G ORTEC. Detector efficiency calibration was achieved using certified standard gamma-ray sources within the energy range of 59.5–2254 keV.

The gamma spectra obtained from irradiated samples were processed using WINSPAN software developed at the China Institute of Atomic Energy (CIAE), Beijing, China. The software was employed for spectral analysis, peak identification, efficiency correction, and elemental

quantification based on the neutron activation equation. Calibration factors for the elements of interest were established using certified multi-element reference standards subjected to similar irradiation and counting conditions.

Experimental procedure for radioactivity measurement

Radioactivity measurements of induced radionuclides were conducted using plexiglass sample holders designated as H2 for short irradiation and H1 for long irradiation. The H2 holder corresponded to a source-to-detector geometry of 5 cm, while H1 corresponded to geometry of 1 cm. For short irradiation analysis, the first counting session was carried out for 10 min after a decay period of 2–15 min, followed by a second counting session for 10 min after a cooling period of approximately 2–3 h. For long irradiation analysis, the first counting stage was conducted for 30 min after a cooling period of 4–5 days, while the second counting stage was performed for 60 min following an additional cooling period of 9–15 days. The outer irradiation channel was selected to minimize nuclear interference effects associated with threshold reactions involving Mg in the presence of Al, Al in the presence of Si, and Na in the presence of P. This approach reduced analytical errors caused by the relatively high fast-to-thermal neutron ratio associated with the inner irradiation channels located closer to the reactor core.

API diagnostic tests

Measurement of rheological properties

The rheological properties of the formulated drilling mud samples were evaluated in accordance with the American Petroleum Institute (API) recommended procedures. Parameters determined included funnel viscosity, plastic viscosity, apparent viscosity, yield point, shear stress, and shear rate. These properties are essential in assessing the flow behavior, carrying capacity, and hole-cleaning efficiency of drilling fluids. Funnel viscosity measurements were carried out using a standard Marsh funnel viscometer calibrated such that the outflow time of 946 mL of distilled water at $70 \pm 5^\circ\text{F}$ was 26 ± 0.5 s. Plastic viscosity and yield point measurements were obtained using a Fann VG direct-indicating rotational viscometer. The drilling fluids were treated as non-Newtonian fluids and the rheological parameters were calculated using standard API relationships. The equations used for the determination of plastic viscosity, yield point, apparent viscosity, shear stress, and shear rate were adopted as provided by API standard procedures.

The following equipment was used during rheological analysis: Marsh funnel viscometer, Fann VG rotational viscometer Slurry mixer, and Electronic weighing balance.

Experimental procedure for viscosity measurement

A total of 60 g of clay sample was dispersed in 1 L of tap water and mechanically stirred for approximately 30 min to ensure complete hydration and uniform dispersion. Clay adhering to the walls of the mixing container was continuously scraped during mixing to enhance homogenization. For Marsh funnel measurements, the outlet of the funnel was initially covered before the prepared mud sample was poured through the screen into the funnel until the fluid level reached the underside of the screen. The outlet was then released, and the time required for 946 mL of drilling fluid to flow out was recorded in seconds. For rotational viscometer analysis, the mud cup was filled to the calibration mark and mounted on the viscometer platform. The rotor sleeve was immersed to the designated scribed line, after which the sample was stirred at 600 rpm for 15 s. Dial readings were subsequently recorded at 600 and 300 rpm for rheological calculations.

Measurement of mud density

Mud density measurements were conducted using a standard Baroid mud balance in accordance with API specifications. Mud density is an important drilling fluid property required for evaluating hydrostatic pressure control and wellbore stability. The equipment used for mud density determination included: Baroid mud balance, Electronic weighing balance and Slurry mixer

Experimental procedure for mud density determination

For each mud formulation, 60 g of clay sample was added to 1 L of tap water and mixed thoroughly for approximately 30 min using a slurry mixer to obtain a homogeneous suspension.

The cup of the Baroid mud balance was filled completely with the prepared mud sample, ensuring that trapped air bubbles were eliminated by gentle tapping. The lid was then fitted firmly onto the cup, allowing excess mud to escape through the vent hole. The exterior surfaces of the balance were cleaned to remove residual mud before measurement.

The balance beam was placed on the fulcrum, and the rider was adjusted until equilibrium was achieved as indicated by the spirit level. The mud density value was then read directly from the calibrated scale at the position nearest the fulcrum.

RESULTS AND DISCUSSION

Elemental composition of the Usen clay deposit

The average elemental composition of the Usen clay samples determined through Neutron Activation Analysis

is presented in (Tables 1 and 2). The results revealed that silicon (Si) and aluminum (Al) are the dominant constituents of the clay samples, while calcium (Ca), titanium (Ti), manganese (Mn), sodium (Na), vanadium (V), and dysprosium (Dy) occur in relatively lower concentrations. Magnesium (Mg) was below the detection limit in both samples.

The high silicon concentration recorded in both samples, with values of 74.8% and 74.3% respectively, indicates that the Usen clay deposit is predominantly siliceous in nature. The predominance of silica is characteristic of many sedimentary and residual clay deposits in Nigeria and confirms the aluminosilicate nature of the material. Similar high silica concentrations have been reported in several Nigerian clay deposits by Eyankware *et al.* (2021), who observed that silica-rich clay minerals are widespread in southern Nigeria due to prolonged weathering and sedimentary enrichment processes. Comparable results were also documented by Onyekuru *et al.* (2018) for southeastern Nigerian clays and by Anthony *et al.* (2020) for clay deposits evaluated for drilling mud applications in southwestern Nigeria.

The aluminum concentrations of 10.420% and 13.030% for Samples A and B respectively further confirm the clayey and aluminosilicate characteristics of the deposit. Aluminum-bearing minerals are major constituents of bentonitic and kaolinitic clays and play significant roles in determining plasticity, swelling potential, and adsorption properties. The Al concentrations obtained in this study are consistent with values reported by Uwaezuoke *et al.* (2022), who identified appreciable alumina content in Nigerian clay deposits suitable for industrial applications. Similarly, Irabor *et al.* (2023) reported moderate alumina concentrations in Lokoja clay deposits and attributed such compositions to the abundance of aluminosilicate minerals within the clay matrix.

Calcium concentrations of 5903 mg/kg and 3294 mg/kg were observed for Samples A and B respectively. The presence of calcium may indicate the occurrence of exchangeable cations and carbonate-associated minerals within the clay structure. According to Ogunro *et al.* (2023), calcium-bearing minerals commonly occur in Nigerian clay deposits and can influence ion-exchange properties and drilling fluid stability. The relatively moderate calcium concentration observed in this study may contribute positively to mud density characteristics.

Titanium concentrations of 6638 mg/kg and 5830 mg/kg were recorded for Samples A and B respectively. Titanium is commonly associated with accessory minerals such as rutile and ilmenite in sedimentary formations. Similar titanium occurrences in Edo State clay deposits were reported by Omoruyi *et al.* (2022), who associated Ti enrichment with the provenance and depositional history of clay-bearing sediments in the Niger Delta region.

Manganese concentrations of 2302 mg/kg and 1540 mg/kg were also identified in the samples. The occurrence of manganese within clay minerals has been linked to secondary weathering processes and geochemical

Table 1. Average (short-listed) chemical composition of the clay samples in ppm (parts per million) or mg/kg(milligram/kilogram)..

Elements	Sample A (MG/KG)	Sample B (MG/KG)
Mg	Below detection limit	Below detection limit
Al (%)	10.4200±1.355	13.0300± 1.303
Ca	5903±1216	3294± 860
Ti	6638± 876	5830± 659
V	137± 7	142± 8
Mn	2302± 12	1540± 9
Na	133± 14	172 ±13
Dy(%)	3.30 ± 0.67	4.35± 0.55
Si(%)	74.8± 7.2	74.3± 6.2

Table 2. Average chemical composition of samples in percentage (%).

Elements	Sample A (%)	Sample B (%)
Mg	Below detection limit	Below detection limit
Al	10.420 ± 1.355	13.033 ±1.303
Ca	0.5903 ± 0.1216	0.3294± 0.0860
Ti	0.6638 ±0.0876	0.5830 ± 0.0659
V	0.0137 ± 0.0007	0.0142 ± 0.0008
Mn	0.2302 ± 0.0012	0.1540 ± 0.0009
Na	0.0133 ± 0.0014	0.0172 ± 0.0013
Dy	3.30 ± 0.67	4.35 ± 0.55
Si	74.8 ± 0.72	74.3 ± 6.2

enrichment during sediment deposition. Studies by Eigbike *et al.* (2013) similarly identified trace metallic elements, including manganese, in Edo State clay deposits and suggested that such elements may influence the physicochemical properties of the clay materials.

The sodium concentrations obtained in the present study were relatively low, with values of 133 mg/kg and 172 mg/kg for Samples A and B respectively. Sodium is a critical component in bentonitic drilling clays because it enhances hydration, swelling capacity, and viscosity development. The low sodium content observed therefore suggests poor swelling potential and low rheological performance. This observation agrees with findings by Agwu *et al.* (2015), who reported that most Nigerian clays possess insufficient sodium content and consequently require beneficiation before they can satisfy API drilling mud specifications. Similar conclusions were reached by Falode *et al.* (2008) and Afolabi *et al.* (2017), who emphasized that sodium activation significantly improves the rheological performance of locally sourced Nigerian clays.

Vanadium concentrations of 137 mg/kg and 142 mg/kg were recorded for Samples A and B respectively. Although vanadium occurs in relatively small quantities, its presence may be associated with detrital minerals and organic-rich sedimentary environments. Trace metals such as vanadium are commonly reported in Nigerian sedimentary clay deposits and may serve as indicators of depositional environment and parent rock composition.

Dysprosium concentrations of 3.30% and 4.35% were also observed in the samples. Rare earth elements such as dysprosium are often associated with accessory mineral phases and may reflect the geochemical evolution of the clay deposit. According to Kashim (2011), the occurrence of trace and rare earth elements within Nigerian mineral deposits demonstrates the economic and industrial significance of the country's solid mineral resources.

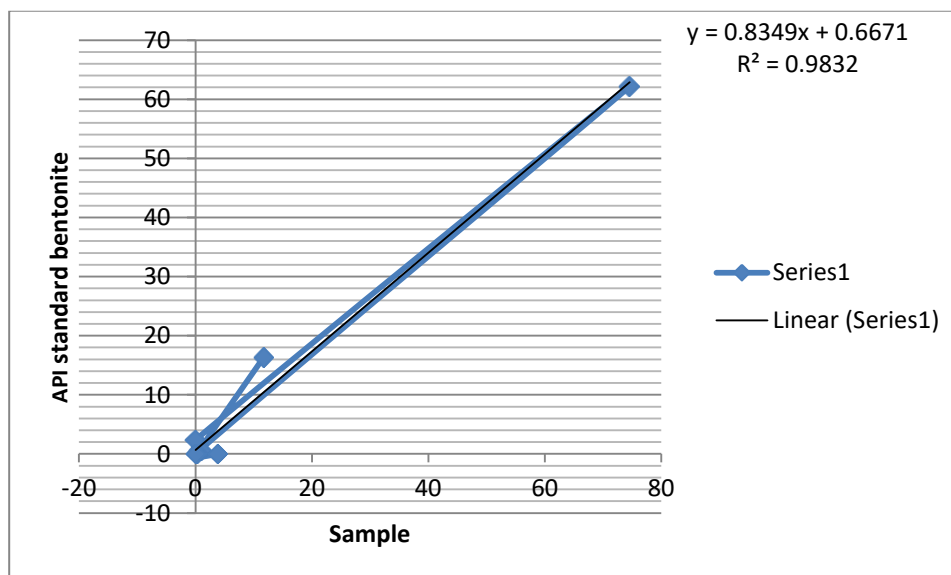
The absence of detectable magnesium in both samples may indicate low concentrations of magnesium-bearing clay minerals such as smectites and montmorillonites. Since magnesium-rich smectitic minerals contribute significantly to swelling behavior and drilling mud viscosity, the absence of Mg may partially explain the poor rheological properties observed in the formulated drilling mud. Similar relationships between mineral composition and rheological performance were reported by Nweke *et al.* (2015a) and Olatunde *et al.* (2021).

Oxide composition of the Usen clay compared with API bentonite

The oxide composition of the Usen clay samples and their comparison with API standard bentonite are presented in (Table 3 and Figure 1). The results indicate that the clay samples are predominantly composed of silica (SiO₂) and alumina (Al₂O₃), with smaller quantities of calcium oxide

Table 3. Average chemical composition (oxides) as compared to bentonite in percentage(%).

ELEMENT	SAMPLE A (mean values)(%)	SAMPLE B (mean values)(%)	Average Sample values(%)	API BENTONITE (%)
MgO	Below detection limit.	Below detection limit	Below detection limit	3.26
Al ₂ O ₃	10.40	13.03	11.72	16.35
CaO	0.83	0.46	0.65	0.63
TiO ₂	1.11	0.97	1.04	0.65
MnO	0.33	0.22	0.28	0.03
Na ₂ O	0.02	0.02	0.02	2.38
SiO ₂	74.80	74.30	74.55	62.2
VnO	0.02	0.03	0.03	–
Dy	3.30	4.35	3.82	–

**Figure 1.** Average chemical composition of sample as compared to standard bentonite.

(CaO), titanium oxide (TiO₂), manganese oxide (MnO), sodium oxide (Na₂O), vanadium oxide (VnO), and dysprosium (Dy). Magnesium oxide (MgO) was below the detection limit in both samples.

The predominance of SiO₂ and Al₂O₃ confirms that the Usen clay belongs to the aluminosilicate group of clay minerals. The average SiO₂ content of 74.55% was significantly higher than the API bentonite value of 62.2%, while the average Al₂O₃ concentration of 11.72% was lower than the API value of 16.35%. High silica concentrations in Nigerian clay deposits have been widely reported in previous studies and are generally associated with the presence of quartz-rich sedimentary materials and weathered feldspathic minerals. Similar observations were reported by Eyankware *et al.* (2021), Onyekuru *et al.* (2018), and Anthony *et al.* (2020), who identified silica as the dominant oxide in several Nigerian clay deposits evaluated for industrial and drilling fluid applications.

The elevated silica content obtained in this study suggests that the Usen clay contains substantial quantities of non-clay siliceous materials, which may adversely affect

swelling behavior and rheological performance. According to Falode *et al.* (2008) and Afolabi *et al.* (2017), excessive silica content in drilling clays tends to reduce hydration capacity and viscosity development because quartz particles are largely non-swelling in nature.

The Al₂O₃ concentration obtained in the present study indicates the presence of alumina-bearing clay minerals such as kaolinite and montmorillonite. However, the lower alumina concentration relative to API bentonite suggests reduced montmorillonitic content and limited swelling potential. Similar findings were reported by Mathias, (2015) and Nweke *et al.* (2015b), who observed that Nigerian clays with lower alumina contents generally exhibit weaker rheological properties and require beneficiation prior to drilling applications.

The CaO concentration of the Usen clay averaged 0.65%, which closely approximates the API bentonite value of 0.63%. This similarity suggests that calcium-bearing minerals are moderately represented in the clay matrix. Calcium oxides are important in determining cation exchange capacity and mud density characteristics.

Comparable CaO values have been reported for Edo State and southwestern Nigerian clay deposits by Oyedoh *et al.* (2023) and Ogunro *et al.* (2023).

Titanium oxide concentrations of 1.11% and 0.97% were recorded for Samples A and B respectively, yielding an average value of 1.04%, which exceeded the API bentonite value of 0.65%. The enrichment of TiO₂ may be attributed to the presence of accessory minerals such as rutile and ilmenite derived from the parent rock materials. Similar TiO₂ enrichments in Edo State clay deposits were reported by Omoruyi *et al.* (2022), who associated titanium enrichment with provenance signatures and depositional processes within Niger Delta sediments.

The MnO concentration averaged 0.28%, which is substantially higher than the API bentonite value of 0.03%. Elevated manganese oxide concentrations may indicate secondary geochemical enrichment during weathering and sedimentation processes. According to Eigbiki *et al.* (2013), trace metallic oxides such as MnO are commonly encountered in Edo State clay deposits and may influence physicochemical behavior and industrial performance.

One of the most significant observations from (Table 3) is the extremely low Na₂O concentration of 0.02% compared to the API bentonite value of 2.38%. Sodium oxide is one of the most critical components responsible for swelling, hydration, and viscosity generation in drilling mud systems. The low Na₂O content therefore confirms that the Usen clay is predominantly calcium-based rather than sodium-based bentonite. This explains the poor rheological performance observed during drilling mud evaluation. Similar low sodium concentrations have been reported for several Nigerian clays by Agwu *et al.* (2015), Oyedoh *et al.* (2016), and Obioma and Dagde, (2022). These studies emphasized that most locally sourced Nigerian clays require beneficiation with sodium carbonate and polymers before meeting API drilling fluid specifications.

The absence of detectable MgO in the analyzed samples further indicates low concentrations of magnesium-rich smectitic minerals. Magnesium-bearing clay minerals are important contributors to swelling behavior and viscosity development in drilling mud systems. Similar observations were reported by Osadebe *et al.* (2011), who noted that deficiencies in magnesium-bearing minerals negatively affect the drilling performance of locally sourced clays. The presence of vanadium oxide and dysprosium in trace concentrations suggests the occurrence of accessory and rare earth minerals within the deposit. According to Kashim (2011), the occurrence of trace and rare earth elements within Nigerian mineral deposits reflects the complex geological history and mineralization processes of the sedimentary basins.

Rheological properties and mud weight evaluation

The rheological properties and mud density of the formulated drilling mud samples are presented in (Table

4), while the comparative relationship between the clay samples and API standard bentonite is illustrated in (Figure 2). The evaluated rheological parameters include Marsh funnel viscosity, viscosity at 600 rpm and 300 rpm, plastic viscosity, apparent viscosity, and mud weight. These properties are critical in determining the suitability of drilling mud for cuttings transport, wellbore cleaning, suspension capacity, and overall drilling efficiency.

The Marsh funnel viscosities obtained for Samples A and B were 33.7 sec/quart and 38.6 sec/quart respectively, with an average value of 36.15 sec/quart. These values are considerably lower than the API recommended range of 52–56 sec/quart for standard drilling bentonite. The low funnel viscosity indicates inadequate flow resistance and poor carrying capacity of the drilling fluid. This suggests that the formulated mud may not effectively transport drill cuttings from the borehole to the surface during drilling operations. Similar observations were reported by Wilfred and Akinade (2016), who observed that locally sourced Nigerian clays generally exhibit lower funnel viscosities compared to imported bentonite due to poor swelling characteristics and low sodium content.

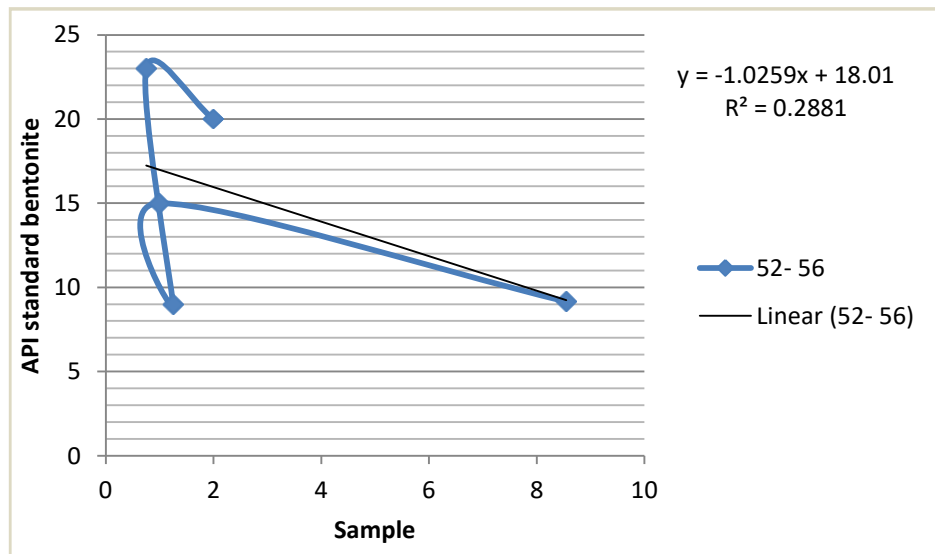
The viscosity values obtained at 600 rpm were 3 cP and 1 cP for Samples A and B respectively, while the average value was 2.00 cP. These values are extremely low when compared with the API minimum requirement of 20 cP. Similarly, the viscosity values at 300 rpm were 1 cP and 0.5 cP respectively, with an average value of 0.75 cP, which is substantially below the API minimum specification of 23 cP. The low dial readings indicate poor rheological strength and insufficient colloidal dispersion within the mud system. According to Mathias, (2015), drilling muds with low rheological values are generally incapable of maintaining drilled cuttings in suspension, especially under low circulation conditions.

The extremely low rheological values obtained in this study may be attributed to the low sodium oxide concentration and absence of magnesium oxide previously identified in the clay samples. Sodium-bearing montmorillonitic clays possess high swelling and hydration capacities, which are essential for viscosity development. The low Na₂O concentration of 0.02% observed in the oxide composition analysis therefore explains the poor rheological performance of the formulated mud. Similar relationships between sodium deficiency and poor drilling mud performance were reported by Falode *et al.* (2008), Agwu *et al.* (2015), and Afolabi *et al.* (2017).

The plastic viscosity values of 2 cP and 0.5 cP obtained for Samples A and B respectively, with an average value of 1.25 cP, are significantly below the API recommended range of 8–10 cP. Plastic viscosity represents the internal resistance to fluid flow caused by friction between suspended particles. The low values obtained indicate weak inter-particle interaction and poor suspension characteristics. This suggests that the clay lacks sufficient active colloidal materials necessary for effective drilling mud performance. Similar findings were reported by

Table 4. Results for Rheological properties and Mud Weight as compared to standard bentonite.

Test	sample A	sample B	Sample (average values)	API standard
Marsh Funnel viscosity (sec/quart)	33.7	38.6	36.15	52- 56
Viscosity at 600rpm(cp)	3	1	2.00	20cp minimum
Viscosity at 300rpm(cp)	1	0.5	0.75	23cp minimum
Plastic viscosity(cp)	2	0.5	1.25	8cp-10cp
Apparent Viscosity(cp)	1.5	0.5	1.00	15 cp minimum
Mud weight (lbs/gal)	8.5	8.6	8.55	8.7- 9.60

**Figure 2.** Results for rheological properties and mud weight as compared to bentonite.

Nweke *et al.* (2015b), who observed that several Nigerian clays exhibit low plastic viscosity due to low montmorillonite content and poor hydration properties.

The apparent viscosity values of 1.5 cP and 0.5 cP recorded for Samples A and B respectively, with an average value of 1.00 cP, are also substantially lower than the API minimum requirement of 15 cP. Apparent viscosity reflects the overall resistance of the drilling fluid to flow under dynamic conditions and is directly related to the mud's ability to transport cuttings efficiently. The low apparent viscosity obtained therefore confirms the poor rheological quality of the formulated mud. Similar low apparent viscosities have been reported for untreated local clays by Udie *et al.* (2006), Otigbe, (2022), and Obioma and Dagde (2022).

The poor rheological properties observed in this study imply that the formulated drilling mud would exhibit inadequate hole-cleaning efficiency and poor carrying capacity if deployed directly in drilling operations. According to John, (2018), drilling fluids with insufficient viscosity are unable to suspend cuttings effectively, thereby increasing the risk of pipe sticking, poor borehole cleaning, and formation instability. Despite the poor rheological properties, the mud weight values obtained for Samples A and B were 8.5 lb/gal and 8.6 lb/gal

respectively, with an average value of 8.55 lb/gal. These values are relatively close to the API recommended range of 8.7–9.6 lb/gal, with deviations of only 0.2 and 0.1 respectively. This suggests that the clay possesses favorable density characteristics that may support drilling fluid formulation after suitable modification. Similar observations were reported by Oyedoh *et al.* (2016) and Anthony *et al.* (2020), who noted that many Nigerian types of clay possess acceptable mud density values despite poor rheological behavior.

The relatively favorable mud density suggests that the formulated drilling fluid could be improved through the addition of weighting materials such as barite. According to Ogbu, (2024), Nigerian barite has proven effective in improving drilling fluid density and reducing dependence on imported weighting agents. Similar beneficiation approaches involving sodium carbonate, polymers, and starch additives have also been recommended by Odeh *et al.* (2022) and Udo *et al.* (2025) for improving the rheological performance of locally sourced Nigerian clays.

The regression coefficient ($R^2 = 0.288$) obtained from the comparative plot shown in (Figure 2) indicates a very weak correlation between the rheological properties of the User clay mud and API standard bentonite. Since the regression value falls far below the acceptable correlation range of

0.75–1.0, it confirms that the drilling performance of the formulated mud differs significantly from standard commercial bentonite. Similar poor correlations between untreated local clays and API bentonite standards have been reported by Osadebe *et al.* (2011), Olatunde *et al.* (2021), and Oyedoh *et al.* (2016).

Conclusion

The characterization of the Usen clay deposit revealed that it is predominantly siliceous, with high silicon and moderate aluminum content, but critically deficient in sodium and magnesium oxides. These compositional features directly influenced the performance of the formulated drilling mud. While the mud density values were close to API standards and suggest adequate hydrostatic pressure control, the rheological properties including funnel viscosity, plastic viscosity, and apparent viscosity were significantly below the required thresholds. The implication of these findings is that Usen clay, in its raw state, cannot be directly applied as drilling mud due to poor swelling and hydration capacity. However, its favorable density characteristics indicate potential for industrial use once properly beneficiated. Chemical modification through sodium activation, polymer treatment, or the addition of weighting materials such as barite could transform the clay into a viable substitute for imported bentonite. In practical terms, this study underscores the importance of beneficiation in unlocking the economic value of local clay deposits. For the oil and gas industry, successful modification of Usen clay would reduce reliance on costly imports, lower drilling fluid expenses, and promote sustainable utilization of indigenous resources. This positions Usen clay as a promising candidate for future development in drilling mud applications, provided that targeted enhancement strategies are implemented.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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