Applied Clay Science 143 (2017) 39–49

Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: www.elsevier.com/locate/clay

Review article

Properties and application of Nigerian bentonite clay deposits for drilling mud formulation: Recent advances and future prospects

Richard O. Afolabi [a,*], Oyinkepreye D. Orodu [a], Vincent E. Efeovbokhan [b]

[a] *Department of Petroleum Engineering, Covenant University, P.M.B 1023, Ota, Ogun State, Nigeria*
[b] *Department of Chemical Engineering, Covenant University, P.M.B 1023, Ota, Ogun State, Nigeria*

ARTICLE INFO

Article history:
Received 28 November 2016
Received in revised form 3 March 2017
Accepted 8 March 2017
Available online 16 March 2017

Keywords:
Drilling mud
Montmorillonite
Nigerian clay
Bentonite

ABSTRACT

The vast deposits of Nigerian bentonite clay have many significant uses in different aspects of industrial fields of which the oil and gas industry is a potential consumer of this clay mineral. In this review article, the key mineralogical characteristics and rheological properties of these clay deposits in various locations and their related application for drilling mud formulation were comprehensively reviewed. Various research efforts on these bentonite clay deposits over the past couple of years were summarized with some critical comments and analysis. Attention was given to the clay reserve estimates, mineralogy of the clay deposits, chemical modification of the clays, rheological properties of drilling mud formulated from these clays and its suitability for drilling operations. Moreover, future prospects and key problems to be solved regarding the use of Nigerian bentonite deposits for drilling mud formulation were discussed. This review shed new light on both fundamental and practical studies that are concentrated on the use of Nigerian bentonite for drilling mud formulation.

1. Introduction

The oil and gas industry is majorly seen as the main stay of the Nigerian economy due to its enormous contribution in terms of foreign exchange. While this places the oil and gas sector in a strategic position in the Nigerian economy, the recent global collapse in the price of crude oil has curtailed and limited the earnings of the Nigerian government from crude oil sales while putting some sort of financial constraints on the major players in the oil industry. The most hit of these players are the indigenous oil companies who may not have the financial muscle and resources when compared to their international counterparts. As a result, there is a need to look inward in harnessing the local resources in providing solutions to challenges obtainable in the oil industry. This would help in reducing the importation of materials and conserving financial resources for the indigenous oil companies. The Nigerian Local Content Development Act was signed into law in 2010 with the singular purpose of encouraging the use of Nigerian local resources and content in providing benefits and solutions to the problems confronting the Nigerian oil and gas industry (Ayonmike and Okeke, 2015). The local content act provides a platform not just for Nigerian entrepreneurs in the petroleum industry but also researchers who seek to explore the applicability of the rich and abundant resources of the Nigerian state in solving problems arising in the oil and gas industry. The origin of the local content act can be traced to the formation of the Nigerian National Oil Corporation in 1971 (which later metamorphosed into the present day Nigerian National Petroleum Corporation (NNPC) in 1977) which has since purchased interests in some major International Oil Companies (IOC) even before the local content act was signed into law in 2010 (Balouga, 2012).

One important aspect of the oil and gas sector of the Nigerian economy is the drilling operation. Drilling operation is necessary for the confirmation of oil and gas beneath the earth surface and a major important ingredient for this operation is the drilling fluid which is often called drilling mud. The use of the term *"drilling fluid"* is often preferred to the generic term *"drilling mud"* because it implies that the characteristics, features or attributes are essentially designed into fluid system rather than those that occur naturally in subsurface formations through the mixing of water and formation clays. In addition, the term *"drilling fluids"* relates fluids with differing composition while *"drilling muds"* simply mean a mixture of clay and water. Drilling mud constitutes a large proportion of oil field chemicals consumed annually (Agwu et al., 2015). Prior to the local content development plan of the Federal Government of Nigeria, studies over the couple of years have indicated that drilling operations carried out by oil companies both indigenous and foreign has required the importation of either the ingredients needed for the preparation of the fluids or already tailor made drilling fluid to suit the requirements of the geologic formations in the Niger Delta (Olatunde et al., 2012; Omole et al., 2013; Akinade and Afolabi, 2015a, b). The associated cost of importing such materials for drilling operations is estimated to amount into millions of dollars per annum and this is damaging to the economy. Furthermore, as the search for oil

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* Corresponding author.
E-mail address: richard.afolabi@covenantuniversity.edu.ng (R.O. Afolabi).

http://dx.doi.org/10.1016/j.clay.2017.03.009

and gas reserves shifts from onshore areas to offshore and deep offshore regions, likewise is the associated cost of the overall drilling operation. The cost of drilling operation is also influenced by the performance of the drilling fluid. This in turn makes the design, formulation and maintenance of drilling fluids important.

Nigeria as a nation is blessed with abundant bentonite resources which if well harnessed will reduce the importation of drilling fluid ingredients and specialized drilling fluids. Every region in Nigeria has been reported to have a substantial deposit of bentonite clays. The proven reserve of bentonite in Nigeria has been modestly estimated to be above 700 million metric tons (Aigbedion and Iyayi, 2007a,b; James et al., 2008; Omole et al., 2013; Bilal et al., 2015) with the bulk of it lying in Afuze, Edo State, Mid-Western Nigeria which holds about 70–80 million metric tons of bentonite clay (Nweke et al., 2015; Nweke, 2015). In view of these vast deposits of local bentonite within the Nigerian soil, the Federal Government in 2003 restricted the importation of foreign bentonite clays with a view to tapping into these vast deposits (Oriji et al., 2014). Despite this act, the oil and gas industry is yet to place full confidence in the use of locally sourced bentonite clays for drilling application, as there is little or no reported case of the use of local bentonite clays for drilling operations. Most of the foreign bentonites being used are often smuggled into the country by the multinational companies (Oriji et al., 2014). This singular act has brought about increased research into the use of local clays for drilling mud application in the oil and gas industry. Previous works on the use of strictly Nigerian bentonite in producing drilling fluids have shown that such drilling fluids exhibit high fluid loss. This may be due to the poor quality of bentonite sourced in Nigeria. These clays in its raw form exhibit poor rheological and fluid loss properties hence the need for beneficiation (Olatunde et al., 2012). Furthermore, the use of locally sourced materials and additives like guar gum have not really shown much improvement in the properties of drilling mud in effectively reducing fluid loss (Olatunde et al., 2012). With the rising demand for bentonite clays as oil and gas exploration shifts to deep offshore, there is a growing need to enhance the properties of local Nigerian bentonite clays to meet the American Petroleum Institute (API) standard. These shortcomings and the potential economic implications of the local bentonite reserve make a compelling case for more extensive research in improving the quality of these clay deposits in Nigeria.

This review article looks at:

a) The historical antecedents of the Nigerian bentonite clays. This is based on the early use of Nigerian bentonite clays after the discovery of oil in the Niger-Delta, decline in the use and research of Nigerian bentonite clays and the recent rejuvenation of research interest in the local clays.
b) Scholarly research output done in the area of mineral and chemical characterization of the Nigerian bentonite clays and techniques so far employed in improving the chemical composition in order to meet the API standard.
c) The properties of the locally formulated drilling mud so far investigated and its suitability for drilling operation in the Nigerian petroleum industry.
d) Further research work that needs to be done in improving and properly characterizing Nigerian bentonite clays and drilling mud formulated from it.

2. The Nigerian bentonite clay

A 2012 report of the Nigerian Extractive Industries and Transparency Initiative (NEITI) on the state of solid minerals in the country indicated that there are about 40–50 different types of solid minerals scattered across the country in varying quantities. The commercial and economic value of these mineral deposits has been projected to amount to thousands of trillions of dollars. The northern region of Nigeria holds approximately 65%–70% of these mineral deposits while the remaining are in substantial quantities in the Southern part of the country. These viable natural resources include bentonite clay, ilmenite, columbite, iron ore, barytes, sodium chloride, ephalerite, silica sand, talc, gemstone (tourmaline, aquamarine and sapphire), halcopyrite, topaz, emerald, heliodor, amethyst, quartz, coking coal, marble, and mica. Bentonite clay deposits spans the length and breadth of the Nigerian nation. Some regions of the country may have more deposits than the other. Bentonite clay is predominantly light colored and expands when mixed with water. Bentonite are made up of predominantly the montmorillonite mineral, which is a subset of the smectites group. The general expression for montmorillonite mineral present in bentonite clays is m $(\mathrm{Mg}[\mathrm{Si_4O_{10}}] \times [\mathrm{OH}]_2) \times \mathrm{p}([\mathrm{Al,Fe}]_2 \times [\mathrm{Si_4O_{10}}])$ m:p = 0.8–0.9. The nature of montmorillonite formation brings with it a variety of accessory minerals such as feldspar, quartz, gypsum etc. The principal types of montmorillonite clays are sodium montmorillonite and calcium montmorillonite. There is also potassium, magnesium and lithium montmorillonite clays in which these are the exchangeable cations but they are not too common. Sodium montmorillonite clays are mainly characterized by high swelling capacity and increased thermal stability. Calcium montmorillonite clays are the major constituents of bentonites occurring globally but are mainly characterized by low swelling capacity when compared to the sodium montmorillonite clays. The origin and formation of bentonites is often traced to weathered volcanic ash but there is still the question surrounding the genesis of the numerous clay deposits in Nigeria since there has not been any reported volcanic activity in time past and Nigeria is not a country prone to such geologic activity. This has however necessitated the redefinition of the term "*bentonite*" to mean a clay mineral consisting essentially of montmorillonite irrespective of its occurrence or origin.

2.1. Estimates of clay deposits

According to estimates from the Nigerian Mining Corporation and the Raw Materials Research Development Council (RMRDC), deposits of local bentonite clays in Nigeria has been modestly projected to be above 700 million metric tons (Aigbedion and Iyayi, 2007a,b; Raw Materials Research and Development Council, 2007; James et al., 2008; Omole et al., 2013) with the bulk of it lying in Afuze, Edo State, Mid-Western Nigeria which holds about 70–80 million metric tons of bentonite clay (Nweke et al., 2015; Nweke, 2015). In addition, barite deposits in Nigeria have been identified in Taraba and Bauchi, which holds about 7.5 million metric tons. Other regions with appreciable deposits of bentonite clays are the North-East region which comprises of Borno, Adamawa and Gombe States (Falode et al., 2008; James et al., 2008; Ahmed et al., 2012a,b; Obaje, 2013; Inegbenebor et al., 2014). The Abakaliki Formation in South-East Nigeria is a notable formation with substantial quantities of bentonite clays (Nweke, 2015; Nweke et al., 2015). In addition, deposits of bentonite clay have been reported in Lagos, Anambra and Abia States. It can be said these deposits of bentonite clay cut across almost all the states of the Federation (Inegbenebor et al., 2014). These clay deposits have the potential to be a major source of foreign income earner if properly harnessed. The Niger Delta region of Nigeria has been estimated to hold a probable reserve of about 4 billion tons of clay deposits alone while the North East region of Nigeria has in total 700 million tons in its pure untreated form (Emofurieta, 2001; Agwu et al., 2015). Furthermore, estimation of the Nigerian bentonite reserve has been spearheaded by the Raw Materials Research Development Council (RMRDC) which is a research parastatal of the Federal Government of Nigeria. The RMRDC in 2010 put forward the location and estimated values of proven reserves of bentonite clays in Nigeria (Table 1). Besides the proven reserve of bentonite deposit identified, other locations with bentonite deposits in different parts of Nigeria have been found but needs further investigation for reserve estimation, quantification and characterization (Table 2).

Table 1
Proven bentonite reserve of some clay deposits in Nigeria as at 2010 (Agwu et al., 2015).

Location	Reserve estimate (Tons)
Bende, Umuahia, Arochukwu, Ikwuano, Isiukwuato (Abia State, SE, Nigeria)	5.8 to 7.5 million
Oru, Isu, Orlu, Okigwe (Imo State, SE, Nigeria)	5.8 to 7.5 million
Ngala, Gamboru, Dikwa, Mongunu, Marte (Borno State, NE, Nigeria)	700 million

2.2. Historical antecedents of clay deposits

Early research showed that the mining of Nigerian bentonite clays was first made in Bende local government area of Abia State in the old eastern region of Nigeria in 1961. The production of these clays started at a rate of 3000 tons per day and peaked at 5106 tons per day over a period of 1961 to 1963. Beyond this period, there were few scholarly researches done on Nigerian bentonic clays and this lead to a decline in the use of Nigerian bentonic clays for drilling fluid application (Agwu et al., 2015). The low research into the Nigerian bentonic clays coupled with the rising bentonite need of the Nigerian oil and gas industry lead to importation of foreign bentonite clays to meet their demand. Drilling activities in the Nigerian oil and gas industry started in the early mid-fifties with the employment of local additives in the formulation of the drilling fluid. While the use of locally sourced bentonite clays and additives reduced towards the end of the 1960s, the events of the Nigerian civil war further impeded any research effort towards the development of the Nigerian bentonite reserve. Towards the late 1980s, there was a rejuvenation of research interest in the Nigerian bentonite clays and this brought about the use of sodium beneficiation as a technique in improving the properties of the clays as reported by Omole et al. (1989).

3. Characterization of Nigerian bentonite clays

Previous works done in the area of characterization of Nigerian bentonite deposits was based on a regional study of the locations containing them (Tables 3–5). Moreover, such studies have indicated that the Nigerian bentonite clays are mostly low-grade calcium montmorillonite and would require beneficiation using sodium salt as part of methods to improve its quality. The pioneering characterization study of bentonite clay deposits in Nigeria can be traced to the work of Oyawoye and Hirst (1964). They carried out a mineralogical study using X-Ray Diffraction (XRD) and thermal analysis of clay samples obtained from Ropp in the Plateau Province of the old Northern Nigeria. The number of locations sampled in their study was just one. The clay sample was a calcium montmorillonite with the dominating oxides being silicon oxide (47.38%). aluminum oxide (21.27%) and ferric oxide (10.66%). Other oxides present in the clay samples were <1%.

Bentonite clay samples obtained from deposits in Nigeria has been observed to contain impurities in its raw form hence the need for beneficiation (James et al., 2008; Obaje, 2013). Beneficiation is simply a procedure for removing impurities or associated minerals that are not needed thereby improving the quality of the bentonite clay (Olugbenga et al., 2013). Beneficiation can be done using sodium salt such as sodium carbonate (Na_2CO_3) or sodium hydrogen carbonate ($NaHCO_3$) which allows for the conversion of the mainly calcium montmorillonite clays to sodium montmorillonite via an ion exchange mechanism. It cannot be said precisely if regional distribution of bentonite clays in Nigeria play an important role in the mineralogy, elemental composition and performance of these clays since not all deposits of bentonite clay have been studied. The mineralogy of these clay deposits could be tied to the geology of the environment (basin) from which they were obtained. Marine shale units that are vastly supplemented in montmorillonite occur in all known sedimentary basins in Nigeria. These marine shale units include the Agwu shale unit in Eastern Nigeria, Fika shale unit in North-East Nigeria, Imo shale unit (this forms a belt across the southern part of Nigeria), and the shale units of the Dukamaje and Kalambaina formations in North-West Nigeria. These formations are known to contain over 80% montmorillonite enriched in calcium with little or no section with sodium. Inspite of this, it cannot be conclusively said of the impact of the geology of the environment due to the fact that more still needs to be done as not all locations with substantially proven deposits of bentonite clays have been studied. James et al. (2008) carried out a beneficiation and characterization study of bentonite clay sample obtained from Yola in Adamawa State, North-East Nigeria. Compositional study of this Yola bentonite revealed that the clay sample is a low-grade calcium montmorillonite and this is typical of other samples from regions that have been investigated (James et al., 2008; Obaje, 2013; Nweke et al., 2015). Furthermore, the beneficiation method used in treating the raw bentonite clay does play an important role in enhancing the quality of the resulting clays. James et al. (2008) compared the wet and dry beneficiation methods in treating raw bentonite clay samples obtained from Yola in Adamawa State, North-East Nigeria and observed through material characterization that wet beneficiated Yola clay samples showed improved values in pH, swelling power, cation exchange capacity, apparent viscosity and yield when compared to the dry beneficiated Yola clay samples. However, in terms of bulk density the dry beneficiated Yola clay samples showed higher values than the wet beneficiated Yola clays. This may be attributed to the inefficiency of the dry method in properly removing impurities present in the sample. Some wet beneficiation procedure may also prove ineffective if the bentonite clay is not allowed to properly hydrate and homogenize with the chemicals used for the beneficiation study (Ajugwe et al., 2012a,b).

Table 2
Bentonite clay deposits in Nigeria that requires reserve estimation and quantification as at 2010 (Agwu et al., 2015).

Location	Reserve estimate (Tons)
Ogurude (Cross River State, SS, Nigeria)	Not yet estimated
Ohaozara (Ebonyi State, SS, Nigeria)	Not yet estimated
Awka (Anambra State, SE, Nigeria)	Not yet estimated
Jega (Kebbi State, NW, Nigeria)	Not yet estimated
Itu (Akwa Ibom State, SS, Nigeria)	Not yet estimated

Ahmed et al. (2012a,b) carried out mineralogical studies on bentonic clays obtained from the Pindiga formation in Gombe State, North-East Nigeria. Experimental findings indicate that the clay samples contain montmorillonite, which is predominantly rich in calcium, and this is more stable when compared to Magnesium, Potassium and Sodium based montmorillonite. Compositional analysis of the clay samples showed that it contains oxides of Aluminum, Silicon, Calcium and Iron. Obaje (2013) investigated bentonite clays in Borno State, North-East Nigeria and like previous works done on bentonite clays in that region discovered that it was rich in montmorillonite containing predominantly calcium and requires beneficiation to improve the quality of the clay. Dewu et al. (2011a,b) carried out mineralogical characterization of clay samples obtained from the Fika formation in North-East Nigeria. The mineralogy of the clay samples were mainly calcium-based montmorillonite and would require beneficiation with sodium carbonate to convert it to sodium based montmorillonite via ion exchange. The mineralogical and elemental study of Nigerian bentonite clay deposits carried out by researchers in the 80s, 90s and early 2000s has revealed that beneficiation of these bentonite clays is a necessary step if recourse must be made to it for application in the oil and gas industry. This is important, as most of the clay deposits studied so far do not meet the requirements of the American Petroleum Institute (API) in terms of rheological properties.

Nweke et al. (2015) carried out mineralogical characterization of clay samples from the Abakaliki Formation in the Niger-Delta part of

Table 3
Some previous research work done on Nigerian bentonite clays from different regions.

Researcher(s)	Number of locations	Specific areas studied	Experiment done
Oyawoye and Hirst (1964)	1	Ropp, Plateau Province (Plateau State)	Mineralogical characterization using XRD and thermal analysis
Omole et al. (1989)	20	Bama-Mubi, Maiduguri-Bama, Maiduguri-Gamboru, Dikwa-Marte, Dikwa-Maiduguri, Maiduguri-Bui, Bui-Numan, Yola-Fufore, Numan-Gombe (Borno State)	Sodium carbonate and Trona was used to upgrade the raw bentonite clays; XRD, Rheological, filtration and physio-chemical analysis was carried out.
Ademibawa (1999a,b)	1	Pindiga (Gombe State)	XRD analysis
Onize (2003)	2	Afuze (Edo State) and Maiduguri	CMC, PAC and soda ash was used to improve the properties of the clay. Rheological analysis was done.
Falode et al. (2008)	1	Pindiga (Gombe State)	Rheological and filtration analysis
James et al. (2008)	1	Yola (Adamawa State)	XRF, XRD, rheological analysis. Sodium carbonate was used for beneficiation.
Salam et al. (2010)	2	Ewekoro (Ogun State)	Local gum Arabic and sodium carbonate was used for the beneficiation. Rheological analysis and model development.
Lafia (2010)	1	Nassarawa State	Rheological analysis. Starch was used as beneficiating agent.
Abdullahi et al. (2011a,b)	1	Fika (Benue Trough)	Mineralogical characterization using XRF, XRD. Rheological Analysis
Dewu et al. (2011a,b)	3	Pindiga, Futuk, Arawa River (Gombe Sate)	Mineralogical characterization using XRF, XRD. Use of soda ash and viscosifying agents
Osadebe et al. (2011)	1	Okada (Edo State)	Mineralogical characterization using XRD
Dewu et al. (2012)	3	Ngalda, Maiduwa1, Maiduwa2 (Yobe State)	Mineralogical characterization using XRF, XRD and AAS
Onwuachi-Iheagwara (2012)	2	Akokwa, Akpehe-Olomu (Imo and Delta States)	Rheological analysis
Ahmed et al. (2012a,b)	1	Pindiga (Gombe State)	Mineralogical characterization using XRD, XRF. Acid leaching using concentrated sulphuric acid
Obaje (2013)	2	New Marte, Dikwa (Borno State)	Mineralogical characterization of clay samples using AAS
Imuentinyan and Adewole (2014)	2	Ovia, Ikpoba (Edo State)	Rheological analysis using CMC and tannin as viscosifiers

Nigeria. The minerals present are mainly montmorillonite and illite with traces of kaolinite. Elemental analysis indicates high calcium and potassium oxides. Olugbenga et al. (2013) also characterized bentonite clay samples from the Niger Delta region of Nigeria. Their mineralogical study using X-Ray Diffraction (XRD) on the clay sample indicated that it was a montmorillonite rich in calcium and chemically stable. In addition, beneficiation of the clay samples with sodium carbonate improved the rheological properties of the clay, which gives a promising sign for drilling mud application as per American Petroleum Institute (API) and Oil Companies Material Association (OCMA) recommendation. Apugo-Nwosu et al. (2011) carried out a suitability study of the Ubakala clays in Abia State. Mineralogical analysis of these clays using X-Ray Diffraction showed that it was composed mainly of smectites, kaolin, and albite. Chemical analyses results showed that in the Ubakala clay, the

Table 4
Elemental analysis of some clay deposits in Nigeria.

Researcher(s)	Location	Elemental composition (%)									
		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Na_2O	TiO_2	P_2O_5	LOI
Oyawoye and Hirst (1964)	Ropp	47.38	21.27	10.66	0.42	0.78	0.08	0.12	–	–	9.60
Ademibawa (1999a,b)	Pindiga	53.06	12.09	2.71	1.10	1.30	1.25	6.40	1.53	–	20.19
James et al. (2008)	Yola	61.35	14.09	7.14	0.87	0.12	1.05	1.15	1.453	0.06	12.23
Osabor et al. (2009)	Odukpani	47.52	24.01	2.38	0.188	0.038	–	1.78	–	–	12.00
Akhirevbulu et al. (2010a,b)	Kutigi	66.00	26.87	0.99	–	–	–	–	1.45	–	–
Lawal and Abdullahi (2010)	Lokoja	27.18	13.76	5.82	–	1.17	2.68	–	0.71	–	–
Mark (2010)	Ibere	52.06	27.87	3.25	1.43	0.34	2.92	0.38	–	–	9.2
	Oboro	60.21	19.05	3.78	1.50	0.30	2.16	0.42	–	–	10.2
Olokode et al. (2010)	Ajebo	46.40	34.00	2.49	0.04	0.02	0.08	0.03	–	0.04	17.70
Abdullahi et al. (2011a,b)	Fika	35.17	13.05	7.35	6.17	10.36	1.69	0.06	0.64	0.31	15.73
Dewu et al. (2011a,b)	Pindiga	53.00	18.00	4.68	2.60	0.67	2.28	0.61	0.90	–	15.12
	Futuk	46.76	18.40	8.17	2.34	0.57	2.59	0.45	0.70	–	14.82
	Arawa	52.80	20.80	7.53	2.95	0.77	2.61	0.28	0.67	–	15.63
Dewu et al. (2012)	Ngalda	–	7.32	–	2.71	2.68	–	1.25	0.45	–	9.73
	Maiduwa1	–	4.64	–	3.56	5.59	–	2.43	0.28	–	8.77
	Maiduwa2	–	6.51	–	4.19	5.07	–	2.04	0.28	–	9.24
Osadebe et al. (2011)	Okada	55.77	20.60	0.70	0.20	0.30	0.30	2.0	1.15	0.012	16.80
Apugo-Nwosu et al. (2011)	Ubakala	69.60	16.00	2.99	0.156	0.22	0.59	0.06	2.64	–	–
Ahmed et al. (2012a,b)	Pindiga	46.90	15.00	24.15	–	2.46	3.71	3.52	2.15	–	6.63
Obaje (2013)	New Marte	24.21	60.05	0.03	3.02	0.60	1.01	1.98	–	–	9.10
	Dikwa	26.30	58.40	0.01	3.22	0.45	0.98	2.01	–	–	7.71
Olugbenga et al. (2013)	Niger-Delta	47.40	20.97	5.73	9.48	4.23	0.98	–	1.18	–	–
Nwosu et al. (2013)	Udi	53.20	5.91	0.44	–	0.01	0.12	1.42	–	–	4.00
Aramide et al. (2014)	Ifon	56.77	27.46	1.32	1.96	0.18	0.04	1.62	–	–	10.27
	Ipetumodu	54.82	25.90	1.44	2.08	0.12	0.20	1.57	–	–	11.64
	Iseyin	59.42	35.88	2.42	1.40	0.17	0.04	0.09	–	–	11.66
Nweke et al. (2015)	Abakaliki	58.96	25.08	4.67	2.02	5.42	1.40	1.98	2.10	–	–

Table 5
Mineralogical Analysis of some Clay Deposits in Nigeria.

Researcher(s)	Location	Mineralogical composition
Oyawoye and Hirst (1964)	Ropp	Montmorillonite, Biotite, Quartz and Beidillite
Loto and Omotosho (1990)	Igbokoda	Montmorillonite, Kaolinite and Illite
Falode et al. (2008)	Pindiga	Montmorillonite, Kaolinite, Quartz, Calcite, Biotite, Feldspar
Mark and Onyeamaobi (2009)	Ibere	Montmorillonite, Kaolinite, Quartz, Feldspar, Illite, Chlorite
	Oboro	Montmorillonite, Kaolinite, Quartz, Calcite Feldspar, Illite, Chlorite
	Ohiya	Montmorillonite, Kaolinite, Quartz, Calcite Feldspar, Illite, Chlorite
	Uzuakoli	Montmorillonite, Kaolinite, Quartz, Feldspar, Illite and Chlorite
Osabor et al. (2009)	Odukpani	Kaolinite, Quartz, Feldspar and Illite
Akhirevbulu et al. (2010a,b)	Kutigi	Kaolinite, Quartz, Feldspar and Illite
Abdullahi et al. (2011a,b)	Benue Trough	Montmorillonite, Kaolinite, Dolomite, Ankerite, Quartz and Microcline
Apugo-Nwosu et al. (2011)	Ubakala	Montmorillonite, Kaolinite, Quartz, Biotite, Calcite and Feldspar
Dewu et al. (2011a,b)	Maiduwa	Montmorillonite, Kaolinite, Quartz and Illite
Ahmed et al. (2012a,b)	Pindiga	Montmorillonite, Quartz and Graphite
Omole et al. (2013)	Kaduna & Sokoto	Calcium-Smectites, Illite, Chlorite, Kaolinite, Vermiculite
Akinade and Afolabi (2015a,b)	Abbi	Montmorillonite, Kaolinite, Illite and Chlorite
Nweke et al. (2015)	Abakaliki	Montmorillonite, Kaolinite, Quartz, Calcite, Feldspar and Illite

Al_2O_3/SiO_2 ratio was about 1/4.35. The presence of alkalis and magnesia in the samples suggests significant presence of montmorillonite. Osadebe et al. (2011) also carried out chemical and mineralogical analysis of clay deposits obtained from Okada, Edo State, South-West Nigeria. The analysis was mainly done using X-Ray Diffraction and the results showed that silicon dioxide was more in abundant in the clays followed by aluminum oxide. This was comparable with the works carried out by Ademibawa (1999a,b), James et al. (2008), Abdullahi et al. (2011a,b) and Obaje (2013).

Nwosu et al. (2013) characterized clays samples obtained from Udi in Enugu Sate, South-East Nigeria using X-Ray Diffraction and Fourier Transform Infrared Spectroscopy. The findings from the compositional analysis indicated that silicon oxide (53.2%) was the dominant oxide in the clays samples followed by aluminum oxide (5.906%) other oxides like Fe_2O_3, MgO, CaO, Na_2O, K_2O etc. were <1%. Joel and Nwokoye (2010) also carried out a study on clay samples obtained from the Niger-Delta region. Silicon dioxide and aluminum oxide were both in substantial quantities while other metal oxides were less than a percent. Olugbenga et al. (2013) also investigated the mineralogy and elemental composition of clays obtained in the Niger Delta region using X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD). Analysis of the clay samples revealed the presence of a montmorillonite, which was calcium based and would require beneficiation with a sodium salt in order to improve its properties for drilling mud application. In addition, silicon dioxide was in large quantity (47.4%) followed by aluminum oxide (20.97%) and ferric oxide (5.73%) respectively. Tables 3–5 gives a detailed summary of researchers work on Nigerian bentonite clays from different parts of the country. Oyedoh et al. (2016) carried an experimental investigation into the use of clays obtained from Afuze in Edo State for drilling mud formulation. The mineralogical analysis showed that the clays are mainly calcium montmorillonite and would require beneficiation with sodium salt into order to convert to sodium montmorillonite. The mineralogical and chemical analysis done by most researchers on Nigerian bentonite clays has largely been on the determination of the oxide components of the montmorillonite that make up the clay deposits and quantifying it. Silicon dioxide, SiO_2 and Aluminum Oxide, Al_2O_3 are the major oxide of the clay deposit and the Al_2O_3 to SiO_2 ratio ranges from 0.23 to 2.48 which compares favorably with standard Wyoming bentonite clay ratio of 0.38. A broad characterization of Nigerian bentonite clay deposits is still required as well as the partitioning of the compositional elements and spatial distribution of the elements. This is necessary for subsequent treatment and processing.

4. Properties of locally formulated drilling mud using Nigerian bentonite

The mineral characterization of bentonite clay deposits in Nigeria in its raw form have indicated that the clays are mainly calcium-based montmorillonite and this differs significantly from the industry standard which is a sodium based montmorillonite clay. Beneficiation or activation of these clays with a sodium salt has been largely used by researchers in converting the calcium based montmorillonite clays into sodium based montmorillonite with comparable rheological properties with the API standard Wyoming bentonite clays (Onize, 2003; Falode et al., 2008; James et al., 2008; Salam et al., 2010; Dewu et al., 2011a,b; Udoh and Okon, 2012). The mechanism through which this occurs is via an ion exchange route that involves the substitution of the calcium ions for the sodium ions. The properties of locally formulated drilling mud that has been researched into include Plastic Viscosity (PV), Apparent Viscosity (AV), Yield Point (YP), Mud Density (MD), Fluid Loss (FL), pH and Gel Strength (GS). A summary of the works done on the rheology of locally formulated drilling mud are found in Table 6. Falode et al. (2008) evaluated local bentonite clays obtained from the Pindiga formation in North-East Nigeria for rheological and filtration performance using a Rheometer and an API filter press. The authors considered the rheological properties, free swell volume, gel strength and filtration properties. It was observed that the clay concentration has a direct effect on these properties with noticeable improvement in all of them. Optimum clay concentration was obtained at 80 g bentonite clay/350 ml of deionized water. Beneficiation of the Pindiga clays with 12.5% (potash and starch) and 40 g/350 ml sodium carbonate (Na_2CO_3) resulted in a 64% increase in the swell volume capacity, 750% increase in the plastic viscosity and 3000% increase in the yield point. The starch and potash brought about a 35% and 32% reduction in the amount of fluid loss likewise a 55% and 33% reduction in the size of the mud cake thickness respectively. The authors concluded that optimum concentrations of the clay and additives tend to improve the performance of the local bentonite clays for drilling purpose.

Abdullahi et al. (2011a,b) carried a comparative analysis of bentonic clays obtained from marine deposits in the upper Benue basin of Nigeria with standard commercial bentonite clays. These clay deposits were considered as part of the Fika member of the Pindiga formation and were beneficiated using sodium carbonate in different proportions. The rheological analysis was carried out on the beneficiated clays using an OFITE model 900 viscometer while fluid loss test was done using the API filter press. The analysis were done in comparison with the American Petroleum Institute (API) standard and the European Oil Company Material Association (OCMA) standard. It was observed that the rheological properties of the beneficiated local clays showed values comparable with the standard commercial bentonite (dial reading at 600RPM = 35, fluid loss < 15 ml and yield point = 1–6lb/100ft^2). The studied carried out also discovered that the local bentonite clay had some properties that was in tune with the API standard before beneficiation was done. These properties include the Al_2O_3/SiO_2 ratio, Loss on Ignition (LOI) and moisture content.

Onwuachi-Iheagwara (2012) investigated the rheological properties of clays samples obtained from Akokwa and Akpeherhe-Olomu in Imo and Delta States in the Niger-Delta region of Nigeria. The clays were reported to be suitable for drilling mud application after they have been beneficiated. Dewu et al. (2012) conducted rheological studies on clay

Table 6
Properties of drilling mud made from Nigerian bentonite clays (Agwu et al., 2015).

Researcher(s)	Location	PV[a] (cp)	AV[a] (cp)	YP[a] (Ib/100ft^2)	FL[a] (mL)	pH	MD[a] (ppg)	GS[a] (Ib/100ft^2)
Onize (2003)	Afuze	–	37	–	8.5	10	–	–
	Maiduguri	–	50	–	9.5	10	–	–
Falode et al. (2008)	Pindiga	2–18	–	–	10	–	–	–
James et al. (2008)	Yola	–	1.402	2.74	–	10.2	–	–
Salam et al. (2010)	Ewekoro	1.25–28.83	1.5–52	1–7.83	–	–	–	–
Abdullahi et al. (2011a,b)	Fika	–	–	1–6	<15	–	–	–
Dewu et al. (2011a,b)	Pindiga	7–22	–	–	–	–	–	–
	Futuk	5.7–21	–	–	–	–	–	–
Dewu et al. (2012)	Ngalda	–	–	1.9	–	14	–	–
	Maiduwa	–	–	1.8	–	14	–	–
Osadebe et al. (2011)	Okada	55.77	20.60	0.70	0.20	0.30	0.012	0.02
Apugo-Nwosu et al. (2011)	Ubakala	3–20	–	3–15	–	–	–	4–18
Onwuachi-Iheagwara (2012)	Akokwa	8.30	10.52	4.43	–	9	8.71	0.37–6.13
	Akperhe	13.90	16.75	5.70	–	12	8.60	0.37–0.47
Udoh and Okon (2012)	Uyo	7	11.50	9	–	9.60	9.20	3–5
Nwosu et al. (2013)	Udi	–	–	–	49.58	5.63	1.67	–
Oyegoke (2013)	Yola	17.30	26.59	18.56	13.35	9.50	–	–
Imuentinyan and Adewole (2014)	Ovia	10	–	7	11.40	8	8.60	–
	Ikpoba	12	–	10	19.60	8	8.40	–
Nmegbu (2014)	Oboboru	1.06–15.55	1.42–22.61	0.88–15.22	14–40	10	8.47	1.99–56.55

[a] Note: PV = Plastic Viscosity, AV = Apparent Viscosity, YP = Yield Point, FL = Fluid Loss, MD = Mud Density and GS = Gel Strength.

samples from Ngalda and Maiduwa in Yobe State, North-East Nigeria. The rheological properties of the beneficiated samples of the bentonite clays were reported to improve considerably with the addition of a polyanionic cellulose under the trade name of "Drispac". Omole et al. (2013) investigated the rheological properties of drilling mud that was formulated from local clay samples obtained from the Northern part of Nigeria and beneficiated with sodium carbonate. The clay samples in their natural state showed no comparable rheological properties with the standard bentonite clay. However, as the concentration of the clay and beneficiating agent increased so was the plastic viscosity, apparent viscosity and yield point. Abdulkadir et al. (2013a,b) evaluated the use of Kaolinite based clay sourced from Kankara, Katsina State, North-East Nigeria. The clay was used in conjunction with bentonite clay in different proportions. The bentonite clay samples were also sourced from Nigeria. The kaolinite clay on its own showed poor swelling capabilities but when used with the bentonite clay, there was an increase in the swelling capacity with the highest obtained with the combination with the highest bentonite content. Based on the work of the authors, Kaolinite clay can act as a weighting material in drilling mud preparation. This largely supports the work of Adebayo and Ajayi (2011) who worked on Kaolinite clay samples obtained from Ota, Ogun State, South-West Nigeria.

Nmegbu (2014) investigated clay deposits from three different areas of Rivers State, South-South Nigeria. These areas include Egbamini (Emolga), Afam (Phalga) and Oboboru (Onelga). It was discovered that the clays from these areas are essentially calcium-based montmorillonite and exhibited poor rheological properties, which were below the standard API requirements for drilling mud material. The plastic viscosity, apparent viscosity and yield point ranged from 1.06–15.55cp, 1.42–22.61cp and 0.88–15.22Ib/100ft^2 respectively. The fluid loss of the clay samples were between 14.6 and 39.27 ml while the pH and mud density were 10 and (8.28–8.47) respectively. Oyegoke (2013) studied the rheological properties of clay samples obtained from Sangere (Yola) in Adamawa State, North-East Nigeria. The clay samples were essentially a low-grade calcium based montmorillonite and had to be beneficiated to meet the API specification. This was in accordance with the work of James et al. (2008) who also worked on clay samples from Yola and discovered that the clay samples were low-grade calcium montmorillonite. The author used POLYPAC which was a low viscosity polyanionic cellulosic polymer as a fluid loss agent. The rheological and fluid loss results after beneficiation and addition of POLYPAC were 17.3cp, 26.59cp and 18.56Ib/100ft^2 for the plastic viscosity, apparent viscosity and yield point respectively. The fluid loss and pH were 13.35 ml and 9.5 respectively. Wilfed and Akinade (2016) carried out a research in evaluating the properties of drilling mud prepared using bentonite clays obtained from Abbi in Delta State, Mid-West Nigeria. Beneficiation of the locally sourced mud was done in order for the prepared mud to have favorable and comparable properties with drilling mud prepared with foreign (Wyoming) clay. The pH of the mud was between 9.5 and 12.5 after beneficiation but the viscometer reading at 600RPM was slightly below 30 which is the standard API requirement but was seen to appreciate to this with further treatment with Drispac. Based on the work of the authors, the Abbi clay showed good viability for drilling mud application with very low sand content if sourced from the right depth and strata.

Not much is known about the viscoelastic behavior of the locally formulated drilling mud under challenging downhole environment such as High Temperature High Pressure (HTHP), deep offshore etc. In addition, the thermal stability of these beneficiated clays has not been well researched into and as a result is still an area of major concern. Furthermore, the beneficiated local clays have most often been used primarily for teaching purpose in institutions of higher learning due to the cost implications of importing foreign grade bentonite clays. Looking beyond the technique of beneficiation, acid activation and calcination of local bentonite clays have been reported (Ahmed et al., 2012a,b). This technique was applied during the mineralogical and elemental study of clay deposits obtained from Pindiga, North-East Nigeria but the impact of this procedure on the rheological behavior of the bentonite-based mud was not reported, as the authors did not investigate this. The calcination of clays is often used to enhance the solubility of alumina present in the clay and increase the alumina content (Ahmed et al., 2012a,b; Zulfiqar et al., 2016). This calcination step is critical as it makes the dealumination of the clay by acid leaching easy. Acid is often preferred to alkalis as the residue is easily separated from the filtrate after the process. The use of sulphuric acid has been reported to bring about a dealumination of the clay and likewise a reduction in the Fe_2O_3 content while using HCl predominantly attacks the alumina present. The study into the acid activation of bentonite clays has largely been limited to its use in heavy metal removals in the environment and not much is known of its impact on bentonite clays used for drilling mud formulation. This approach may also serve as another way of improving the rheological properties of locally sourced bentonite clays but more research needs to be done in that area for enhancing the rheology of locally formulated mud.

5. Additives for locally formulated drilling mud using Nigerian bentonite

Various additives have been researched into towards improving the rheology and fluid loss characteristics of drilling mud formulated from local Nigerian clays. These additives include both local and conventional additives. The locally sourced additives comprises of materials sourced within the Nigerian environment while the conventional additives are those that are globally recognized within the oil and gas industry. Olatunde et al. (2012) investigated the use of local materials such as guar gum and Arabic gum as additives in the formulation of local drilling mud. Guar gum and Arabic gum are available in substantial quantities in the Northern part of Nigeria. It was observed that the guar gum acts primarily as a viscosifying agent and tend to improve the rheological properties of the locally formulated drilling mud. The Arabic gum was more of a stabilizing agent than a viscosifying agent due to its fizzing property. It was also reported to have good fluid retaining properties and this makes it a good fluid loss control agent. This was also buttressed by the work of Salam et al. (2010) who worked on bentonite clay samples obtained from Ewekoro in Ogun State, South-West Nigeria using Arabic gum as an additive.

Adebayo and Ajayi (2011) investigated the use of unprocessed Kaolin obtained from Ota, Ogun State, South-West Nigeria as a weighting additive in the formulation of local drilling mud. The use of the local Kaolin tends to decrease the apparent and actual mud viscosities by as much as 85%. The mud density was observed to increase with a 25% and 27.25% increase respectively at 100% kaolin. The research work showed that the natural Kaolin was a good weighting material likewise a colloidal additive. A secondary viscosifier would be needed to improve on the viscosity of the drilling mud. Okorie (2009) examined the use of ash of burnt palm head sponge and a rich potash base mineral known as Trona as additives for controlling pH of locally formulated drilling mud. From the work carried out, it was concluded that the local pH mud additives could increase the mud pH of the drilling mud from 7.0 to well over 12.90. The Burnt Palm Head Sponge Powder gave the higher mud pH impartation of pH 7.0 to 12.90, followed by the Trona, which gave mud pH impartation of 12.88 and 12.86 respectively.

Nwosu and Ewulonu (2014) carried out a study on the use of three well-known biopolymers used in the industry: carboxyl methylcellulose (CMC), xanthan gum polysaccharide, and polyanionic cellulose (PAC). These biopolymers were used as additives on locally formulated drilling muds. The viscosity of the prepared water based mud was more pronounced with PAC than the other two. In addition, the PAC produced the highest shear stress values under increasing shear rate and acted as a better viscosifying agent than CMC and the Xanthan gum. This could be attributed to the open chain structure of the PAC and its ability to interact with water molecules thereby enhancing the viscosity of the mud. Akeju et al. (2014) carried out a study on the use of oyster seashells (*Crassostrea virginica*) as a lost circulation material in locally formulated drilling mud. Analysis of the experiment carried out indicated that the oyster sea shells were a good lost circulation material as a result of its fine size but did not improve the viscosity to the drilling mud. Samavati et al. (2014) investigated the use of *Manihot esculenta* derivative (*igebu garri*) as a fluid loss inhibitor in the formulation of water based mud. The results of the work indicated that the use of the cassava derivative enhanced the viscous properties of the mud with minimum fluid loss. Under high temperature conditions (250 °F), the fluid loss was still minimal (1.4 ml) compared to other additives like potato (3 ml) and corn starch (10 ml). Akintola and Isehunwa (2015) reported the use of starch obtained from cassava and *Zea mays* as additive in locally formulating bentonite based drilling mud. Under ambient conditions, the starch additive was observed to improve the rheological properties of the prepared mud (PV, AV, and YP) but under elevated temperature, it was observed that these properties tend to decrease with temperature (>62 °C). The observed decrease in the properties could be attributed to the thermal degradation of the starch molecules. At low and gradually increasing temperature values, the molecules of starch become thermally agitated leading to a break in the intramolecular association between them and allowing for the starch molecules to associate with the water molecules thereby increasing the rheological properties of the mud. Beyond the particular temperature of 62 °C, there is a complete loss of starch crystallinity because of thermal degradation leading to a decrease in the properties of the prepared drilling mud.

6. Suitability of Nigerian clay for drilling mud formulation

The only major use of Nigerian bentonite for drilling oil wells was made during the period of the early discovery of crude oil in the 1950s and more recently by Shell Petroleum Development Company, Nigeria in 2001 where over 600 wells were drilled with it (Agwu et al., 2015). In recent years, Nigerian researchers have been actively pursuing the study of using Nigerian clay in drilling muds and finding potential markets for it. Many of these studies have focused on characterizing and beneficiating the clays to the American Petroleum Institute (API) standard. Previous research works on the use of strictly Nigerian bentonite in its raw form in producing drilling fluids have shown that such drilling fluids exhibit high fluid loss (Olatunde et al., 2012). While the use of locally sourced materials like guar gum have not really shown much improvement in the properties of drilling mud in effectively reducing fluid loss (Olatunde et al., 2012).

Despite the significant reserve of bentonite clay in Nigeria, there has not been any report on the significant exploitation of these clays for drilling mud preparation. While these clays in its raw natural form may not provide the required attributes for drilling mud application, subjecting them to certain treatment might improve the quality of these clays. The local bentonite in its raw form and concentration makes it unsuitable for drilling mud applications. However, when these local clay samples were subjected to beneficiation with starch, sodium carbonate and potash, there was an improvement in the rheological and filtration properties in line with the API and OCMA recommendation. Furthermore, it was observed that starch beneficiated mud gave the best filtration characteristics while potash beneficiated mud had the most improved rheological properties. It could also be said that a combination of potash and starch would improve the properties of locally produced drilling mud thereby enhancing its suitability. It was also discovered that beneficiation with chemical additive, such as the polymer “drispac” lead to an improvement in the rheological properties of the locally sourced bentonite clays (Dewu et al., 2011a,b; Ajugwe et al., 2012a,b). Furthermore, the measured parameters were in line with API specifications. This goes to further show that Nigerian bentonite clays are largely suitable for drilling mud applications when beneficiated with the right chemical additives.

It can be said from the reviewed works of Falode et al. (2008); James et al. (2008); Abdullahi et al. (2011a,b); Dewu et al. (2011a,b); Ajugwe et al. (2012a,b); Udoh and Okon (2012); Olugbenga et al. (2013) and Omole et al. (2013) that the mainly rich calcium montmorillonite clays of Nigeria need to be effectively beneficiated to a sodium rich montmorillonite clay via ion exchange as none of these clay samples in their raw state showed any appreciable swelling properties that may warrant its application for drilling mud preparation. Such beneficiated bentonite clays have shown remarkable swelling and rheological properties comparable with standard commercial foreign bentonite. While this may be seen as breakthrough in enhancing the applicability of local bentonite clays, more still needs to be done as highlighted in the next section. The Nigerian bentonite reserve has the potential to become an income earner for the country. As a result more study needs to be done in evaluating and enhancing its applicability both within and beyond the shores of Nigeria. With the shift from conventional to unconventional oil resources, questions still remain if the local bentonite clay can be efficiently used in such regions. Improving the properties of the local bentonite clays must not be restricted to the Nigerian context alone. Looking beyond the Nigerian context in enhancing the characteristics of the locally sourced bentonite clays would allow for a marketable product for foreign use thereby generating foreign exchange earnings.

7. Future research directions

The leaning of most researchers on Nigerian clay deposits as it relates to its use for drilling mud formulation has largely been focused on the rheological analysis and mineral characterization of the clay samples. According to the findings of Agwu et al. (2015), about 44% of researchers focussed on rheological analysis, which comprises of estimating the plastic viscosity, apparent viscosity, yield point and fluid loss while a little above 40% of the researchers carried out a mineralogical study of the clay deposits (Fig. 1). Not much is known about the cost and economic implications of beneficiation beyond what was reported by Joel and Nwokoye (2010) and this constitutes a little over 1% of the work carried out by researchers on Nigerian clay deposits. Despite the areas covered by most researchers, there are still areas, which still requires further research endeavors (Fig. 1).

7.1. Modeling the flow, rheological and thixotropic behavior of locally formulated drilling mud

The efforts of researchers on the use of Nigerian bentonite has majorly been targeted at ensuring that its properties compare favorably with the API requirements and this has been aided by the technique of beneficiation. The One Factor at a Time (OFAT) approach has been used to study the effect of the beneficiating agents and other types of additives employed on the rheological properties of the locally formulated drilling mud. The OFAT approach does not account for interaction effects but only accounts for the main effects of the factors being considered. Makinde et al. (2011) modeled the effect of temperature and aging time on the rheological properties of locally formulated drilling mud. The authors came up with a predictive model equation for analyzing effective and plastic viscosities respectively. Oyegoke (2013) employed a factorial design approach in optimizing the rheological and filtration properties of locally formulated drilling mud involving Nigerian bentonite clays. Statistical models have been the only tool used to characterized properties of the formulated drilling mud and this was developed based on the use of a Design of Experiment (DOE) approach to relate the main effects of the various beneficiating agents employed, amount of bentonite clay, aging time etc. and the interaction effects of these factors on the rheological properties of the prepared drilling mud (Abdulkadir et al., 2013a,b; Makinde et al., 2011; Oyegoke, 2013). Despite the large work done in the area of improving the rheological properties of the locally sourced Nigerian bentonite clays, little attention has been given to studying the flow characteristics of drilling mud prepared from Nigerian bentonite clays and applying the appropriate rheological models to it. Appropriate description of the rheological or flow behavior of the mud is necessary for proper estimation of flow hydraulic parameters such as pressure loss during drilling operation and the hole cleaning efficiency (Kelessidis et al., 2006; Dolz et al., 2007). For Non-Newtonian fluids, effective viscosity is not constant but shear rate dependent. Non-Newtonian fluids are generally characterized as Pseudoplastic, Dilatants, Bingham Plastics, Thixotropic and so on. Most bentonite dispersions and drilling fluid made from bentonite clays are non-Newtonian, and hence their viscosity is dependent on shear rate. Many rheological models have been used to describe Non-Newtonian fluids especially the rheological behavior of bentonite dispersions for drilling mud formulation. These models can be classified into two, three, four or even five parameter models.

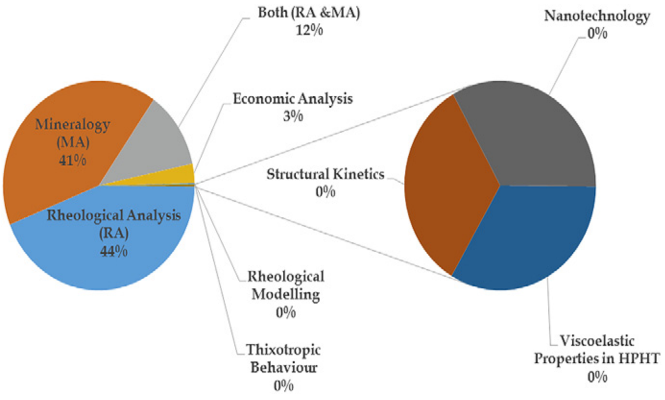

Fig. 1. Properties of local clay deposits studied and percentage of researchers.

The two-parameter models are often used because of their simplicity and fair agreement of their predictions with rheological flow curves. The Bingham Model (Eq. (1)) consists of the parameters τ_o and μ_p which represents the yield stress and plastic viscosity respectively.

$$\tau = \tau_o + \mu_p \gamma \tag{1}$$

$$\tau = K\gamma^n \tag{2}$$

Bingham fluids are characterized by these two parameters. The yield stress is a measure of the shear stress needed to make the fluid flow. It is also a measure of the attractive forces between molecules of the fluid under flowing conditions. The plastic viscosity should be low to enhance fast drilling (increase in ROP). The plastic viscosity can be reduced by decreasing the amount of colloidal particles in the drilling fluid. The yield point of the fluid should be high to ensure high carrying capacity but not too high to a point where pressure required to pump the fluid will be high. The Power Law Model (Eq. (2)) is made up of the parameters *K* and *n*. The consistency index, *K*, defines the thickness of the fluid while the flow index, *n*, also called power law index indicates the level of non-Newtonian behavior. If $n = 1$, the model becomes similar to Newtonian model. Moreover, $n > 1$ indicates a dilatant type of fluid while pseudoplastic (shear thinning) fluid would exist if n becomes <1. The Power Law Model is often considered for correcting to Newtonian fluid behavior but this may not be accurate if the fluid in question exhibit yield stress (Kelessidis et al., 2006). Casson Model (Eq. (3)) and Prandtl-Eyring Model (Eq. (4)) are another set of two parameter models that are yet to find much acceptance in describing the flow characteristics of fluids.

$$\tau^{1/2} = \tau_o{}^{1/2} + \mu_p{}^{1/2}\gamma^{1/2} \tag{3}$$

$$\tau = A\sinh^{-1}\left(\frac{\gamma}{B}\right) \tag{4}$$

The Casson model is known to describe the shear thinning attributes of fluid at high shear rates with some degree of accuracy when compared with other two-parameter models. This may become significant when extrapolation is needed. The parameters τ_o and μ_p are similar to those in the Bingham Plastic Model. The Prandtl-Eyring Model represent an alternative to the Power Law Model and tends to a constant viscosity, *A*, in the limit of γ going to zero. However, the viscosity function tends to zero as γ tends to infinity. *A* and *B* are material (fluid) constants.

Rheological models such as the Herschel Bulkley, Robertson-Stiff and Sisko Models constitutes three parameter models. The Robertson-Stiff Model (Eq. (5)) combines the Power law and Bingham Plastic Model with *K* representing the consistency index. The model tends to Bingham plastic model if n (flow index) is zero; and behaves like power law model when γ_o (shear rate correction factor) approaches zero. It has the advantages of Bingham and Power Law Models, and as such can describe the rheology of drilling fluids under high or low shear rate.

$$\tau = K(\gamma_o + \gamma)^n \tag{5}$$

$$\tau = \tau_o + K\gamma^n \tag{6}$$

$$\tau = a\gamma + b\gamma^c \tag{7}$$

$$\tau = \tau_o + \frac{\gamma}{D + G\gamma} \tag{8}$$

The Herschel Bulkley Model (Eq. (6)) is a power-law model with yield stress. It is a complex model, which is notable for accurate results than the simple Bingham and Power Law models when enough experimental data is available. The main challenge in the use of this model and other higher parameter non-linear models is curve fitting to evaluate model parameters. However, the advent of computer and non-linear curve fitting has helped in solving this problem. Usually, the value of the yield stress used is the 3-RPM reading from the viscometer. 300-RPM or 600-RPM viscometer readings are used to compute n and K or they can be estimated graphically. Although a certain level of stress is required to begin flow, this stress value becomes less with increasing shear. The Sisko Model (Eq. (7)) is one of the rarely used rheological models to describe the behavior of drilling fluids when performing hydraulic calculations in the oil and gas industry. This is because the form of this model makes the derivation of tractable expressions for pressure drop as a function of flow rate nontrivial or impossible. The solution of their expression requires rigorous computation. The constants "a", "b" and "c" represents the coefficient of viscosity, consistency coefficient and flow index respectively. Another notable 3-parameter model is the Hyperbolic Model (Eq. (8)). Vipulanandan and Mohammed (2014) used a Hyperbolic Model to predict the maximum shear stress tolerance of a drilling mud. The maximum shear stress tolerance is an indication of the eroding potential of the drilling mud. The current rheological models (Bingham Plastic Model, Power Model etc.) enable viscosity and rheology data from rheological analysis to be fitted. The rheological properties obtained from these models tend to differ depending on the choice of model. The maximum value for shear stress of a drilling mud is influenced by the components of the mud. These models accepted in the oil industry cannot predict values for the maximum shear stress produced by a drilling mud. The maximum shear stress tolerance is obtained at $\gamma = \infty$. Therefore, Eq. (8) becomes Eq. (9)

$$\tau = \tau_o + \frac{1}{G} \tag{9}$$

7.2. Nanotechnology

An important material that is gaining significant attention as a drilling mud additive is the use of nanoparticles. The world is scaling down with respect to technological innovations and inventions, this has developed research interest in nanoscience and nanotechnology as it is the current domain for miniaturization with respect to scientific and technological advancement. The oil and gas industry is not left out from this advancement as different areas from exploration, drilling to development and production have witnessed gradual research into the application of nanotechnology. One of the important use of nanoparticles in drilling fluid preparation is to control fluid loss. The use of nanoparticles for Water Based Muds (WBMs) in shale formations have shown how effective nanoparticles are in improving the rheology and preventing fluid loss due to their small size (Hoelscher et al., 2012; Zakaria et al., 2012; Jung et al., 2013; Sadeghalvaad and Sabbaghi, 2015). The properties of nanoparticles can be further improved upon through functionalization with other chemical compounds (Hoelscher et al., 2012; Zakaria et al., 2012; Ismail et al., 2016). It is often believed that adding a functional group to a nanoparticle or coating it with another group would improve the overall property of the resulting compound compared to the individual properties of the components that make up the compound. This may also lead to a reduction in the amount of nanoparticles needed for a given application when compared with unfunctionalized nanoparticles (Hoelscher et al., 2012; Fazelabdolabadi et al., 2015). Functionalization may come in the form of surface modification of nanoparticles with functional groups or in the form of nanocomposites where nanoparticles act as fillers in a continuous medium. The use of nanocomposites as drilling fluid additive has been reported in literature. Polymer nanocomposites play a major role in drilling mud application where the nanoparticle and the polymer acts synergistically to improve the rheology of the drilling mud (Sadeghalvaad and Sabbaghi, 2015; Jain et al., 2015; Mao et al., 2015). Polymetallic nanoparticles are another class of composite material, which shows improved synergistic properties than the individual metallic nanoparticles that make it up.

The use of nanotechnology in the western world is gaining and gathering momentum every day. The application of these nanomaterials cuts across almost every sphere of life (Subbiah et al., 2010; ShamsiJazeyi et al., 2014). The same cannot be said within the context of most third world countries where nanotechnology is yet to be fully embraced in solving challenges encountered in key sectors of the economy. The use of nanotechnology in the Nigerian oil and gas industry has not been recorded. Although, there has been researchers and companies advocating for its use but what has been obtained include a few research works done on the use of nanotechnology for Enhanced Oil Recovery (EOR) (Agwu et al., 2015). Nanotechnology can be viewed as an aspect of the engineering discipline that involves the manipulation of matter on a nanoscale. It is understood that nanotechnology may help solve some of the modern day societal challenges confronting Africa and Nigeria in particular. This could be attributed to the fact that nanomaterials often require less amount to achieve a particular task due to their small size thereby cutting down on cost. The full application of nanomaterials in the oil and gas industry must consider the synthesis procedure. This is because the use of nanomaterials requires it to be inexpensive which could be explained in terms of the production route being easily sustainable. The local content act has encouraged the use of local materials in formulating solutions to problems encountered in the oil and gas industry and locally synthesizing these nanomaterials should not be an exception. Although there are well established methods involved in the synthesis of nanomaterials, however these methods may not be economically and environmentally desirable (Kavitha et al., 2013; Logeswari et al., 2013).

Green technology can be described as an exponent of systems, processes and procedures involving a biological approach. This is borne out of the need to preserve and maintain the green environment and reduce the hazards of most conventional physical and chemical approach to systems, processes and procedures. The biological synthesis of nanoparticles has been mostly reported in the field of medicine and pharmacological sciences for antibacterial applications (Logeswari et al., 2013; ShamsiJazeyi et al., 2014). A closer look at this synthesis route for nanoparticles brings to fore a couple of the advantages it has over the well-known conventional methods. Herlekar et al. (2014) pointed that most of these biological molecules either from microorganism or extracts from plants tend to act as both a reducing agent in reducing metal ions to metal particles and a capping agent in preventing the nanoparticles from aggregating. Furthermore, it was also identified that most experimental conditions required in conventional approaches such as high temperature or pressure is not needed and this contributes to energy saving. The biosynthesis of nanoparticles is a one-step, one stage bio-reduction process that involves the use of microorganism, plant extracts or any other biological molecule. The use of plants might possibly be seen as negatively influencing in the form of plant destruction but research trends in biosynthesis have shifted towards the use of agricultural waste, which is a form of biodegradable waste (Kavitha et al., 2013). An important agro-waste is bagasse. Bagasse can be described as the fibrous material left after sugarcane liquid must have been extracted from it. Bagasse waste in Nigeria amounts to about 22,000 tons annually and this is mostly incinerated rather than put into profitable use in others areas (Ibrahim et al., 2011). Sugarcane processing also leaves other forms of waste product, which is collectively known as sugarcane trash (tops and leaves left after sugarcane processing), and this can be harnessed for nanoparticle synthesis. Besides the use of sugarcane bagasse for nanoparticle synthesis, other plant waste such as orange peels have been reportedly used in synthesizing nanoparticles (Herlekar et al., 2014; Kumari et al., 2015; Kuppusamy et al., 2015).

7.3. Challenging downhole environments: High pressure high temperature (HPHT)

As conventional sources of oil and gas decline, operators are increasingly turning their attention to unexplored or underdeveloped areas. High temperatures and/or high pressures are often found in these uncharted territories, presenting complex challenges including casing buckling, accelerated drilling fluid chemical reactions and rock collapse. Historically, Water Based Muds (WBMs) use bentonite clay to modify the filtration and rheological behavior of the muds. When temperatures above 300 °F are applied to bentonite dispersions, they begin to flocculate under such thermal conditions. Under significantly higher temperatures, a water-based mud made up of a lignosulfonate component might gel so to an extent that it is rendered ineffectual or entails severe and expensive dilution and conditioning. Maintaining drilling mud under a deflocculated state helps to keep the fluid loss and rheological properties within acceptable range under high temperature conditions. Accurate knowledge of drilling fluid behavior under actual conditions is required to maximize operational efficiency and to minimize cost and drilling fluid related risks on extreme (HPHT) wells. The viscoelastic properties and thermal stability of bentonite dispersions/drilling mud formulated from these Nigerian clay deposits must be explored under HPHT conditions.

7.4. Beneficiation: Cost implications and process optimization

Beneficiation of the local bentonite clay deposits have seen it upgraded from a low grade calcium based montmorillonite clay to a sodium activated clay with comparable properties to the industry standard Wyoming bentonite clay. More research is still needed on the cost implications of beneficiating the local bentonite clay deposits as against the importation of foreign bentonite clay. An optimization of the beneficiation process is required to determine the optimal quantity of additives needed to standardize the local clay to API requirements for drilling grade bentonite.

8. Conclusion

The review work has been prepared to capture virtually all known research work on Nigerian bentonite clays as it relates to drilling operation in the Nigerian oil and gas industry. Overall, the following areas were summarized from literature:

- ➢ The known estimates of bentonite clay reserve in various regions of Nigeria and those requiring quantification.
- ➢ The mineralogy of these clay deposits obtained from the different areas studied and the techniques so far employed to upgrade the bentonite clay to drilling grade standard.
- ➢ The suitability of these local bentonite clays for drilling mud formulation and how it compares to mud formulated from foreign bentonite clay.

All recorded research work points to a common path that Nigeria has a huge potentially exploitable reserve of bentonite clay, which are predominantly calcium montmorillonite. Beneficiation of these clays has brought about tremendous improvement in its quality, which is comparable to the standard drilling grade bentonite as recommended by API. In addition, Beneficiation of the local clays remains the major research work carried out over the past couple of years but in the present dispensation more must be done in order for these beneficiated clays to fully act as a substitute to the imported bentonite clays which represents a large percentage of clay consumption in the Nigerian oil and gas industry.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgement

The authors would like to appreciate the management of Covenant University for providing an enabling environment to carry out this research.

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