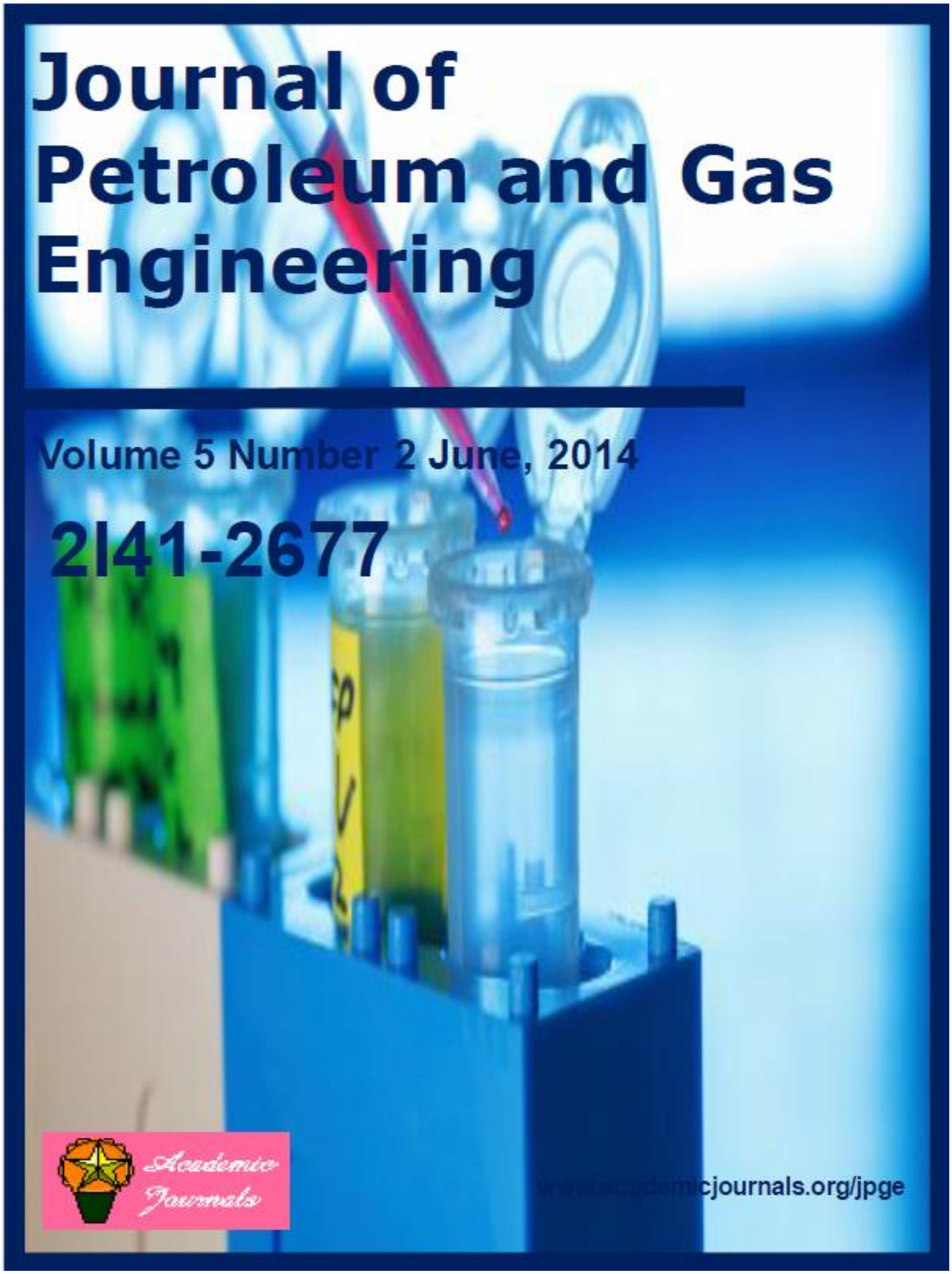

Journal of Petroleum and Gas Engineering

Volume 5 Number 2 June, 2014

2141-2677

Academic Journals

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Vol. 5(2), pp. 15-23, June, 2014
DOI: 10.5897/JPGE2014.0181
Article Number: 1A8280D45459
ISSN 2141-2677

http://www.academicjournals.org/JPGE

Journal of Petroleum and Gas Engineering

Full Length Research Paper

Effect of water influx on the inventory of underground gas storage developed in a depleted oil reservoir

Anyadiegwu C.I.C. and Anyanwu E.E.

[1]Department of Petroleum Engineering, Federal University of Technology, Owerri, Nigeria.
[2]Department of Mechanical Engineering, Federal University of Technology, Owerri, Nigeria.

Received 10 February, 2013; Accepted 26 May, 2014

Effect of water encroachment into an underground gas storage reservoir on its storage capacity (verification of inventory) is presented. Inventory verification is to determine the amount of natural gas to be injected into a particular underground reservoir. Reservoir and production history of a depleted oil reservoir, Z-16T, located in the Niger Delta region were obtained for the analyses. A volumetric equation was used to estimate the storage capacity of the reservoir in two cases ($W_e = 0$ and $W_e \neq 0$, for fifteen different pressures). Microsoft Visual Basic computer model developed based on the same volumetric equation was applied for the same purpose. It was confirmed that the amount of gas to be injected at any given pressure is higher when there is no water influx into the storage reservoir. This has shown that water influx reduces the storage space of an underground storage reservoir.

Key words: storage, capacity, water influx, inventory, encroachment, gas, underground.

INTRODUCTION

Underground natural gas storage acts as the swing capacity due to the seasonal variations in demand. Natural gas is injected into the underground gas reservoirs for the purpose of storage for future use during the second and third quarters when supply exceeds demand (Dietert and Pursell, 2008). This injected gas is withdrawn from these reservoirs during the first and fourth quarters when demand is at the peak and exceeds supply. There are 3 types of reservoirs commonly used for underground gas storage: depleted oil/ gas reservoir; aquifer and salt cavern; each of the storage reservoirs has very specific producing parameters (Anyadiegwu, 2012).

Statement of the Problem

It is a challenge for the natural gas producers in Nigeria to remove the bottleneck of meeting up with the gas demand by relying on the pipeline supply alone especially now that natural gas price is put at $4.45 per 1000scf, the obvious and urgent need by the oil and gas producing companies to be compliant with the new gas flares out/down target which is put at 2012. Also, the recent increase in gas flare penalty is currently put at $3.5 per 1000scf and the environmental degradation and green house emission caused by gas flaring. Furthermore, supply of natural gas stopped even though there is high

*Corresponding author. Email: drcicanyadiegwu@yahoo.com; dranya@yahoo.com

demand in the event of national or local producing community unrests when gas production is disrupted and/or when there is breakdown in heavy equipment for gas production, which takes a long time to restart. Natural gas price/supply instability leads to poor monitoring of gas sales transactions.

To date, there is no record of underground gas storage in the country in spite of the strategic importance of petroleum resources in Nigeria. Therefore, it is very vital to turn to underground storage as a viable solution due to the above-listed problems.

Storage in depleted reservoirs is an underground gas storage that occurs in porous and high deliverability depleted reservoirs, which are close to the consumption centre. The conversion of the oil fields from the production to storage duty takes advantage of the existing wells, gathering systems and pipeline connections. Depleted oil reservoirs are used for underground gas storage due to their wide availability and well known geology. The requirements for each of the reservoirs vary since no two reservoirs are the same, typically these types of reservoirs require 50% base gas (that is, equal amount of working gas) and one cycle per season (EIA, 2002).

Below are the 3 basic requirements in underground storage of natural gas:

(1) Verification of inventory
(2) Retention against migration
(3) Assurance of deliverability

The particular characteristic of an underground storage reservoir taken into consideration in this research is the Storage Capacity (Verification of Inventory). Storage Capacity of a depleted reservoir refers to the volume of gas that can be stored in the reservoir in accordance with its design. There had been methods and models for the estimation of the storage capacity of an underground gas storage reservoir, but most of the models estimate the storage capacity of the reservoir without taking into consideration the effect of underlying aquifer on the storage capacity.

In this work, the effect of an underlying aquifer in the storage capacity of a storage reservoir is studied. Models are developed for this study and the results are presented.

Research Objective

There is no underground storage of natural gas in the numerous depleted oil and gas wells available in Nigeria. This is in spite of the fact that underground storage of natural gas is a developed industry elsewhere in the world necessary for effective gas delivery.

Nigeria needs to urgently expand its gas storage capability to include underground storage in depleted crude oil wells. It is therefore vital to evolve the development and performance analysis of depleted crude oil reservoirs for underground natural gas storage.

In order to address these problems, the specific objectives of this research are:

(1) To evaluate the storage capacity of an available depleted crude oil reservoir for underground natural gas storage. The intention is to provide basic knowledge of the verification of inventory (storage capacity) for the depleted reservoir.
(2) To obtain suitable equations from the existing material balance equations that will estimate the reservoir capacity with and without water encroachment respectively.
(3) To apply visual basic computer model for characterizing the depleted reservoir in (2) above.

Natural water encroachment is commonly seen in many oil and gas reservoirs. In fact, some times, there is more water than oil produced from oil reservoirs, much of this is natural water influx. Thus, it is clear that an understanding of reservoir/aquifer interaction can be an important aspect of reservoir management to optimize recovery of hydrocarbons (William, 1997).

There are more uncertainties attached to the subject of water influx than to any other in reservoir engineering. This is simply because one seldom drills wells into aquifer to gain the necessary information about the porosity, permeability, thickness and fluid properties. Instead, these properties have frequently been inferred from what has been observed in the reservoir. Even more uncertain, however, is the geometry and real continuity of the aquifer itself. Due to these inherent uncertainties, the aquifer fit obtained from history matching is seldom unique and the aquifer model may require frequent updating as more production and pressure data becomes available. This is unsteady state water influx theory (Van Everdingen and Hurst, 1949).

The recovery from many oil reservoirs is affected by water influx, either from the perimeters of the oil reservoirs, from below, or from both. An understanding of the interplay between aquifers and the oil reservoirs is important to properly perform oil recovery calculations (William, 1997). A large water influx decreases recovery because a large amount of gas is trapped by the rise of the gas-water interface, and the water reaching the wells means a higher abandonment pressure (high water-cut), and hence a shorter production period while a moderate water influx increases recovery (Cosse, 1993). The water inflows resulting from gradual expansion of the aquifer continue in transient conditions over a relatively long period. Since the pressure at oil/water interface drops as a function of time, the superimposition theorem is used to obtain an equation given below for the estimation of water influx (Van Everdingen and Hurst, 1949):

$$W_e\,(P, t) = B \sum_{i=0}^{n} \overline{C}\,(t_D - t_{D\,i})\, DP_i \qquad (1)$$

$\underline{B}$ = Constant = $2\pi R^2_i h\Phi (C_w + C_p)$
C = tabulated aquifer function (from time t to time t_i)
DP_i = half pressure drop at interface from time (i-1) to (i+1).
Also, the maximum theoretical water influx is obtained with the following equation (Van Everdingen and Hurst, 1949):

$$W_{em} = V_w (C_w + C_p) (P_i – P) \quad (2)$$

V_w = estimated volume of aquifer water
Water influx into storage reservoir reduces the storage volume of the reservoir and in turn affects the total investment cost and the expected revenue.

EXPERIMENTAL PROCEDURE

Estimation of storage capacity (Inventory Verification)

To determine the volume of gas to be injected at different pressures of the storage reservoir, pressure is varied for fifteen different cases. At each pressure variation, new reservoir parameters, B_o, B_g, and R_s were obtained. Table of values was generated for the plot of gas versus reservoir pressure which represents the volume to be injected at different pressures.

The steps for the reservoir engineering calculation of the gas storage capacity of the reservoirs are as shown below:

From gas material balance equations

$$\text{Production (scf)} = \text{GIIP (scf)} - \text{Unproduced Gas (scf)} \quad (3)$$

$$G_p=G - (HCPV) \times E \quad (4)$$

$$G_p = G - G/E_i \times E \quad (5)$$

Where G_p = Gas Production (scf)
G = Gas initially in place, GIIP (scf)
E = Gas Expansion Factor = standard volume of n moles of gas / reservoir volume of n moles of gas

$$E = V_{sc}/V \quad (6)$$

$$\text{For real gas, } PV = znRT \quad (7)$$

$$\text{So, } V_{sc}/V = P/P_{sc} \times T_{sc}/T \times z_{sc}/z \quad (8)$$

$$\text{In field units, } V_{sc}/V = P/14.7 \times 520/T \times 1/z = 35.37 \times P/(zT) \quad (9)$$

Where V_{sc} = Volume at standard condition
V = Reservoir volume
P = Storage pressure
P_{sc} = Pressure at standard condition
T_{sc} = Temperature at standard condition
T = Temperature
z_{sc} = Compressibility factor at standard condition
z = Compressibility factor

$$\text{Therefore, } E = 35.37 \times P/(zT) \quad (10)$$

$$E_i = 35.37 \times P_i/(z_iT_i) \quad (11)$$

Where E_i, P_i, z_i and T_i are expansion factor, pressure, compressibility factor and temperature at the initial state before gas storage.
Substituting Equations (10) and (11) in Equation (5), putting $T = T_i$, and making G the subject:

$$G = G_p/[1 – Pz_i/(P_iz)] \quad (12)$$

$$V_t = G_p/[1 – Pz_i/(P_iz)] \quad (13)$$

Where V_t = Total Storage capacity, scf.
This is the volume of gas required to replace the produced oil. It is also called the total storage capacity.
Since working gas is 50% of the total storage for a depleted reservoir, the working gas capacity is estimated using:

$$V_{sc} = 0.5*V_t \quad (14)$$

$$V_{sc} = 0.5* G_p/[1 – Pz_i/(P_iz)] \quad (15)$$

Where V_{sc} = Working gas capacity, scf
N_p is expressed in gas terms as G_p from $G_pB_g = N_pB_o$ as:

$$G_p = N_pB_o/B_g \quad (16)$$

N_p = Cumulative oil production, scf
B_o = Oil formation volume factor, rb/stb
B_g = Gas formation volume factor, rcf/scf
P_i = Initial pressure, psia
T_i = Initial temperature, °R
Z_i = Initial compressibility factor
P = Pressure, psia
T = Temperature, °R
Z = Compressibility factor

As stated in this section, the storage capacities at various pressures represent the volume of gas to be injected into the storage reservoir at the various pressures. It guides the operator of the gas storage facility in choosing the initial injection pressure.

A Microsoft Visual Basic Program (MVBP) was developed using Equations (13) and (15), and was used to obtain the volume of gas injected into the reservoirs at various pressures and presented in a table which was used to make a plot of volume of gas injected against Reservoir pressure.

Estimation of storage capacity of reservoir with water influx

Recalling Equation (5) and considering water encroachment (net water influx) into the reservoir becomes:

$$G_p = G – (G/E_i – W_e) \times E \quad (17)$$

Where W_e = Net water influx, scf
W_e is expressed in gas terms from $W_{eg}B_g = W_eB_w$ as:

$$W_{eg} = W_eB_w/B_g \quad (18)$$

Where W_{eg} = W_e in gas terms, scf
Making G the subject and putting Equations (10) and (11) into the equation:

$$G = [G_p – (W_{eg} * 35.37P/zT)]/[1 – Pz_i/(P_iz)] \quad (19)$$

Then total storage capacity is given as:

$$V_t = [G_p – (W_{eg} * 35.37P/zT)]/[1 – Pz_i/(P_iz)] \quad (20)$$

And working gas capacity is given as:

$$V_{sc} = 0.5*[G_p – (W_{eg} * 35.37P/zT)]/[1 – Pz_i/(P_iz)] \quad (21)$$

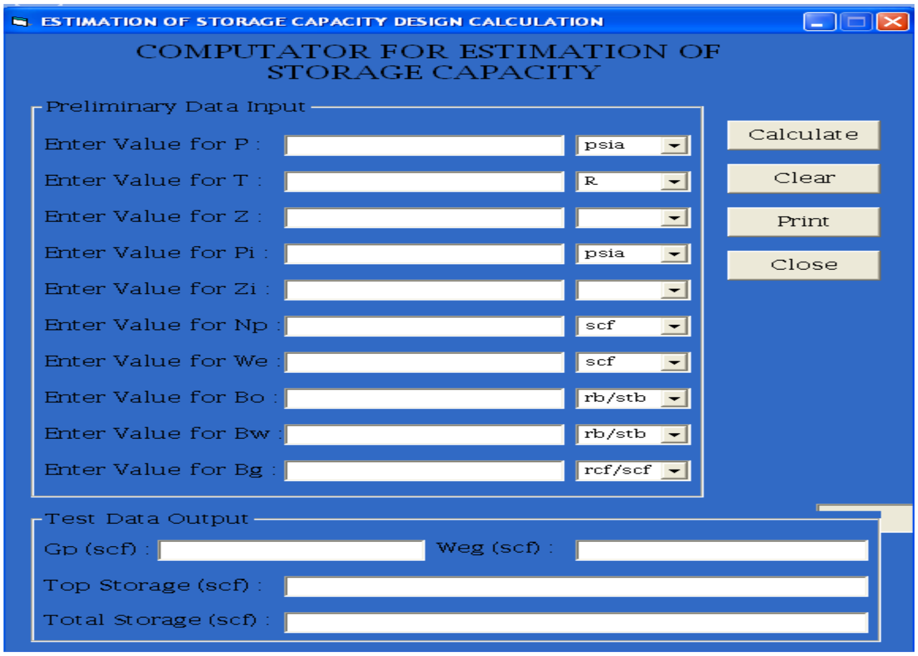

Figure 1. Microsoft Visual Basic Program for Estimating Storage Capacity.

Equations (20) and (21) were used to develop a Microsoft Visual Basic computer program and were applied in generating the volume of gas to be injected into the storage reservoir at different pressures considered. The sample of the MVBP sheet is shown in Figure 1.

Description of the Study Area

The test field is located onshore in the eastern part of the Niger Delta oil producing fields. Niger Delta covers the nine states where the oil producing fields are located in Nigeria, they include: Abia, Akwa Ibom, Bayelsa, Cross Rivers, Delta, Edo, Imo, Ondo and Rivers state. It stretches from east to west, as shown in Figure 2 below. Oil and gas production from the Niger Delta fields started in the late fifties till date. The reservoir selected for the study is a depleted crude oil reservoir. It was selected due to:

(1) Geologic features: Having retained oil/gas for millions of years and produced same before depletion, hence good porosity and permeability.
(2) Geographical location: The field is located near the region where population and industries are located, this will make supply easier.

RESULTS

CASE 1: No Water Influx (We = 0), Table 1.

Estimation of the storage capacity (Inventory Verification)

The storage capacity is computed using Equation (14) as:

V_{sc} = 0.5 * 0.82554Bscf / [1 – (3634 * 0.86)/(3955 * 0.84)] = 6.96 Bscf

The total storage capacity is computed using eq 2.10a as:

V_t = 0.82254Bscf / [1 – (3634 * 0.86)/(3955 * 0.84)] = 13.92 Bscf

The storage capacities of reservoir Z-16T at various pressures were estimated and the results are shown in Table 1.

Estimation of storage capacity using MVBP

The volume of gas to be injected into the reservoir was estimated using the MVBP as shown in Figure 3. The results are presented in Table 2, which is used to obtain the plot of the volume of gas injected at various injection pressures as shown in Figure 4.

CASE 2: With Water Influx (We ≠ 0)

Estimation of the storage capacity of the reservoir with water influx

Recall Equation (19):
$V_{sc} = 0.5*[G_p – (W_{eg} * 35.37P/zT)]/[1 – Pz_i/(P_i z)]$

In computing B_w, Figure 5 was employed, considering the discovery pressure and temperature of the reservoir:

At a pressure of 3634 psig and temperature of 210°F, B_w = 1.0359

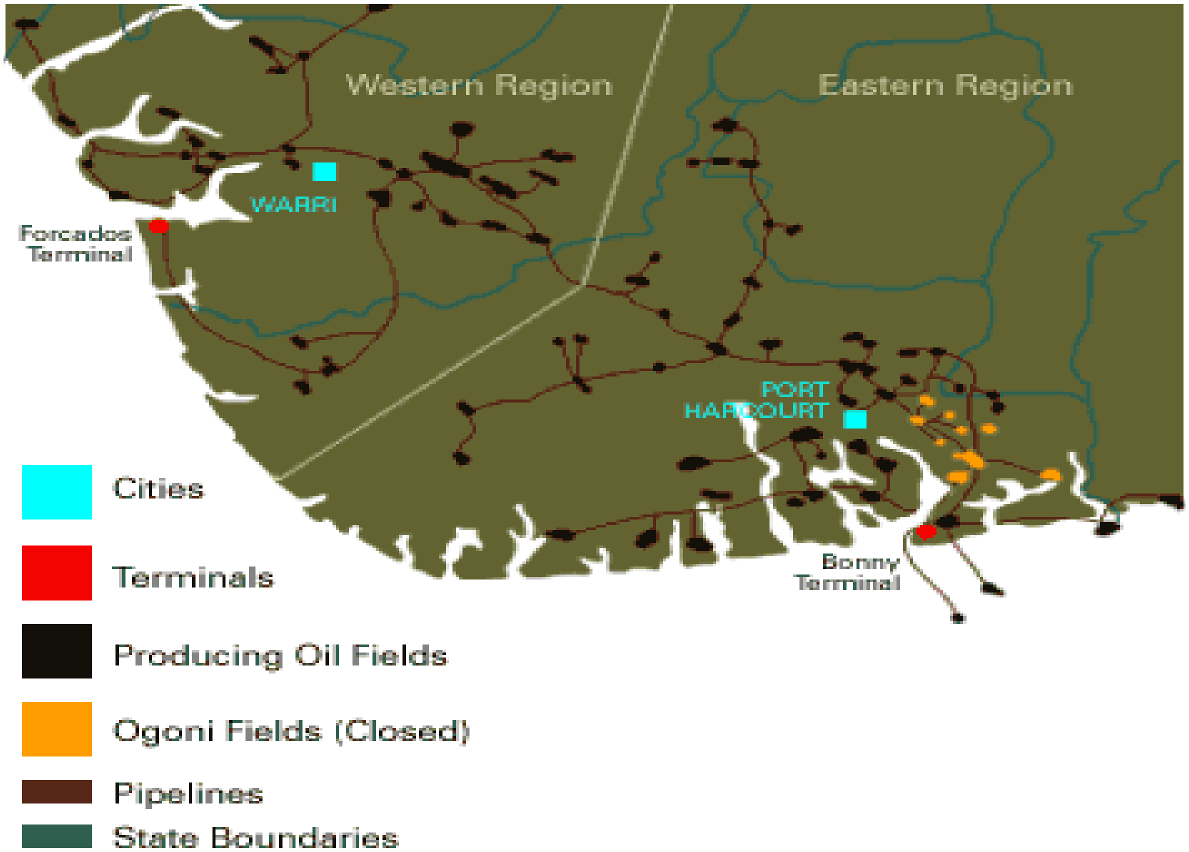

Figure 2. A map of Niger Delta showing oil fields and pipelines
*Source: Ministry of Lands and Urban Planning, Owerri.

Table 1. Reservoir and Fluid Data for Reservoir Z-16T.

Initial pressure, P_i	3955 psig
Initial storage pressure, P	3634 psig
Saturation pressure, P_{sat}	3290 psig
Reservoir temperature, T	210°F
Initial Gas compressibility factor, Z	0.86
Initial oil formation volume factor, B_{oi}	1.405
Specific gravity, SG	25.7°API
Height, h	80 ft
Porosity, Ø	0.25
Initial water saturation, S_{wi}	20 %
Permeability, k	30 MD
Well depth, d	11 000 ft
Net Water Influx, W_e	0.004582 MMscf
Initial Water formation volume factor, B_{wi}	1.0359

The Storage capacity of the reservoir is given as:

V_{sc} = 0.5*[0.82254Bscf – (0.001084Bscf * 35.37*3634/(0.84*210)]/[1 – (3634*0.86)/(3955*0.84)] = 4.87 Bscf

The total storage capacity is given as:

V_t = [0.82254Bscf – (0.001084Bscf * 35.37*3634/(0.84*210)]/[1 – (3634*0.86)/(3955*0.84)] = 9.74 Bscf

Estimation of storage capacity of Z-16T using MVBP

Figure 6 is a Microsoft Visual Basic Program used in estimating the storage capacity of reservoir Z-16T at any given pressure. It was used in generating new volume of gas to be injected into the reservoir at different pressures considered. The volume of gas that can be injected at various reservoir pressures are presented in Table 3 and used to obtain the plot of the volume of gas injected at various injection pressures as shown in Figure 7.

RESULTS AND DISCUSSION

One basic requirement in underground storage of natural gas which is the verification of inventory was evaluated for the reservoir. The storage capacity of the reservoir was estimated using the models and the MVBP. The total

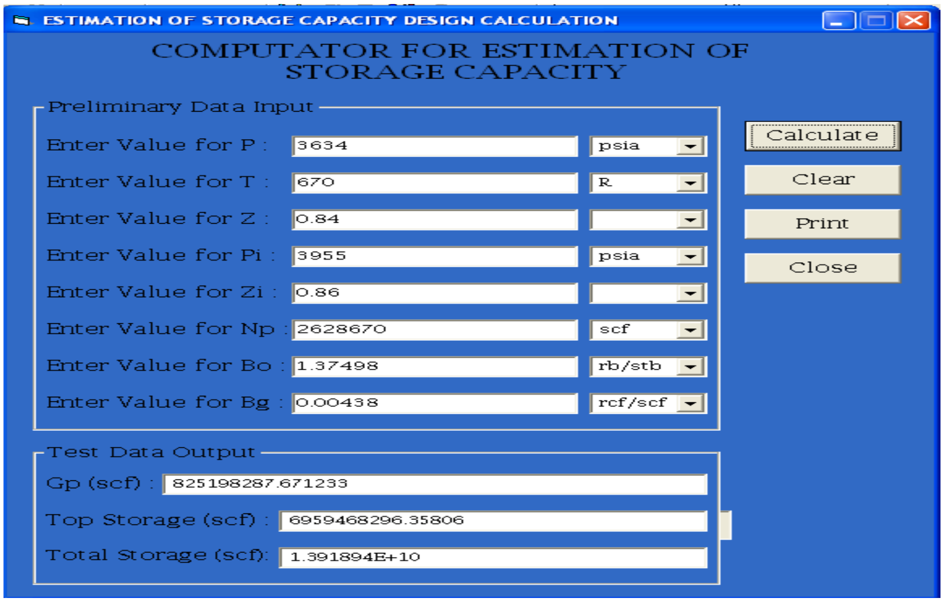

Figure 3. Storage Capacity of reservoir Z-16T at a pressure of 3634psia.

Table 2. Volume of gas injected at various pressures of Res Z-16T.

P (psia)	N_p (MMstb)	B_g (scf/scf)	B_o (rb/stb)	R_s (scf/rb)	G_p (Bscf)	V_{sc} (Bscf)
3634	468.1514	0.00438	1.37498	769.3446	0.82554	6.962322
3561	487.1965	0.00444	1.36776	750.8924	0.84246	5.797014
3534	489.6978	0.00442	1.3651	744.087	0.8489	6.192776
3350	545.5654	0.00461	1.34708	697.9943	0.89552	4.21611
3288	558.4096	0.00461	1.34105	682.5773	0.91241	4.291837
3212	584.6983	0.00469	1.33369	663.7595	0.934	3.844802
3043	655.326	0.00492	1.31746	622.2407	0.98587	3.034957
2922	712.4505	0.00509	1.30595	592.7992	1.02669	2.693303
2911	717.5029	0.0051	1.30491	590.1348	1.03057	2.67515
2857	746.8523	0.00519	1.29981	577.0848	1.05005	2.541455
2767	798.3728	0.00534	1.29135	555.4463	1.08421	2.371164
2427	1049.995	0.00601	1.2599	475.0178	1.23609	1.96442
2237	1253.034	0.00652	1.24271	431.0394	1.34108	1.820755
2145	1373.683	0.00681	1.23448	410.0111	1.3986	1.770191
2057	1505.177	0.00711	1.22669	390.0672	1.45843	1.733702

storage capacity of the reservoir without water influx was computed as 13.92Bscf while the working gas capacity was generated as 6.96Bscf which is exactly 50% of the total storage capacity as required for storage in depleted reservoirs. Considering water influx into the reservoir, the total storage capacity of the reservoir was estimated as 9.74Bscf, while the working gas capacity was gotten as 4.87Bscf, which is also 50% of the total storage capacity as required for storage in depleted reservoirs. The results show that water influx reduced the total storage capacity of the reservoir by 4.18Bscf and the working gas capacity by 2.09Bscf.

Conclusion

The following conclusions were drawn at the end of this study:

(1) That it is possible to rework a depleted oil reservoir for use as an underground gas storage vessel provided the water is controllable.
(2) Water influx into an underground storage reservoir reduces its storage capacity, hence the storage capacity of Z-16T in both cases were estimated to be 6.96 Bscf and 4.87 Bscf respectively.

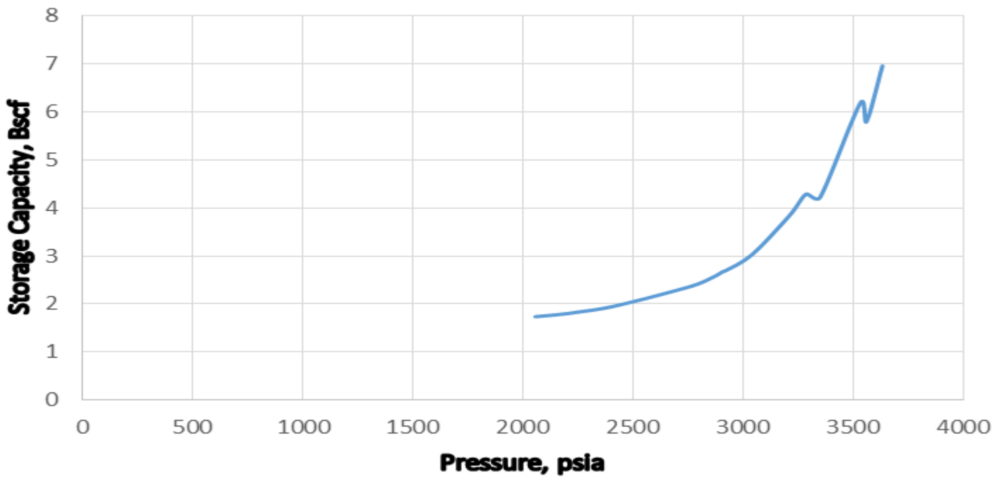

Figure 4. A plot of volume of gas to be injected at various pressures for reservoir Z-16T.

Table 3. Volume of gas injected at various pressures of Z-16T with water influx.

P (psia)	N_p (MMstb)	B_w (bbl/stb)	W_e (MMscf)	W_{eg} (MMscf)	V_{sc} (Bscf)
3634	468.1514	1.0359	0.004582	1.084122	4.874171
3561	487.1965	1.0360	0.00478	1.115	4.069682
3534	489.6978	1.0361	0.005057	1.185	4.237888
3350	545.5654	1.0365	0.005357	1.205	2.985076
3288	558.4096	1.0367	0.005446	1.225	3.041601
3212	584.6983	1.0369	0.005674	1.255	2.742906
3043	655.326	1.0373	0.005997	1.265	2.243078
2922	712.4505	1.0376	0.006302	1.285	2.030907
2911	717.5029	1.0377	0.006342	1.29	2.018785
2857	746.8523	1.0378	0.006478	1.295	1.937715
2767	798.3728	1.0380	0.006713	1.305	1.83668
2427	1049.995	1.0387	0.007553	1.3055	1.619197
2237	1253.034	1.0391	0.00847	1.35	1.539652
2145	1373.683	1.0393	0.008974	1.37	1.51552
2057	1505.177	1.0394	0.009541	1.395	1.500443

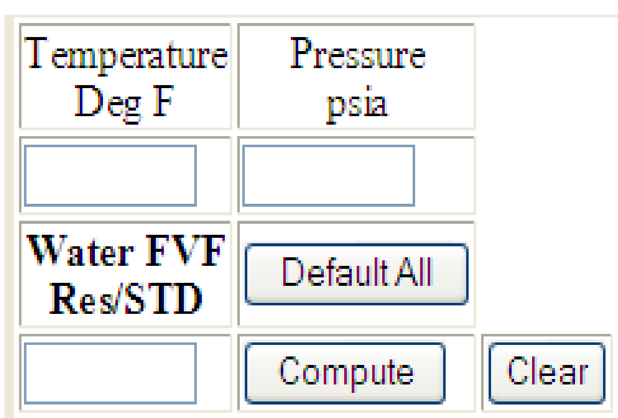

Figure 5. Spreadsheet for the Computation of water formation volume factor, Bw
*Source: Liu, (2009).

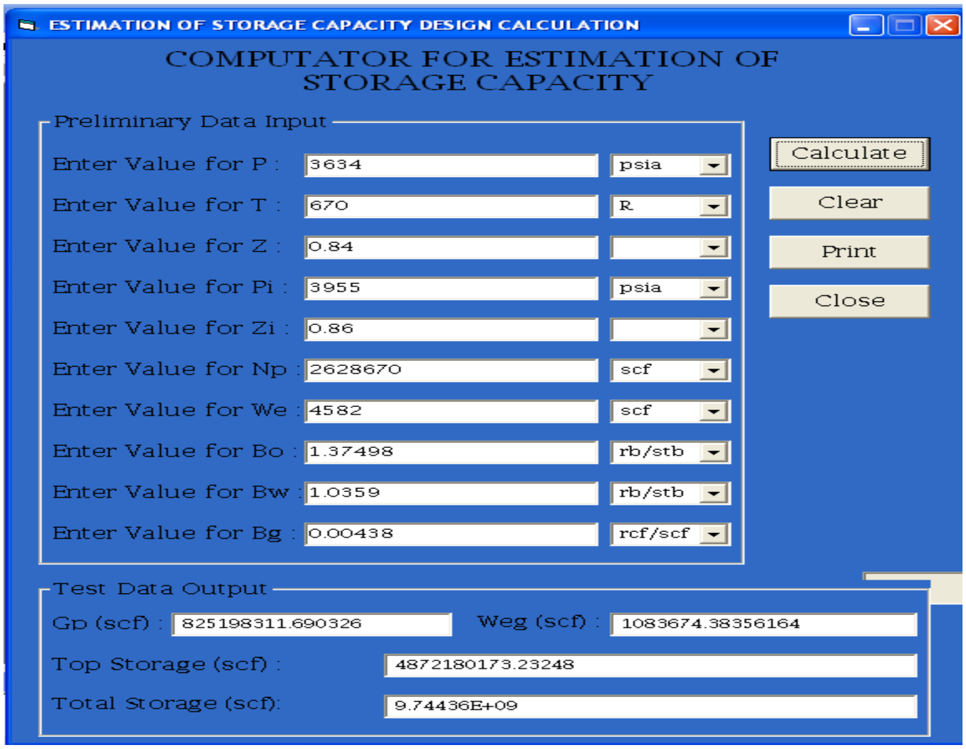

Figure 6. Storage Capacity of Z-16T with water influx at 3634psia.

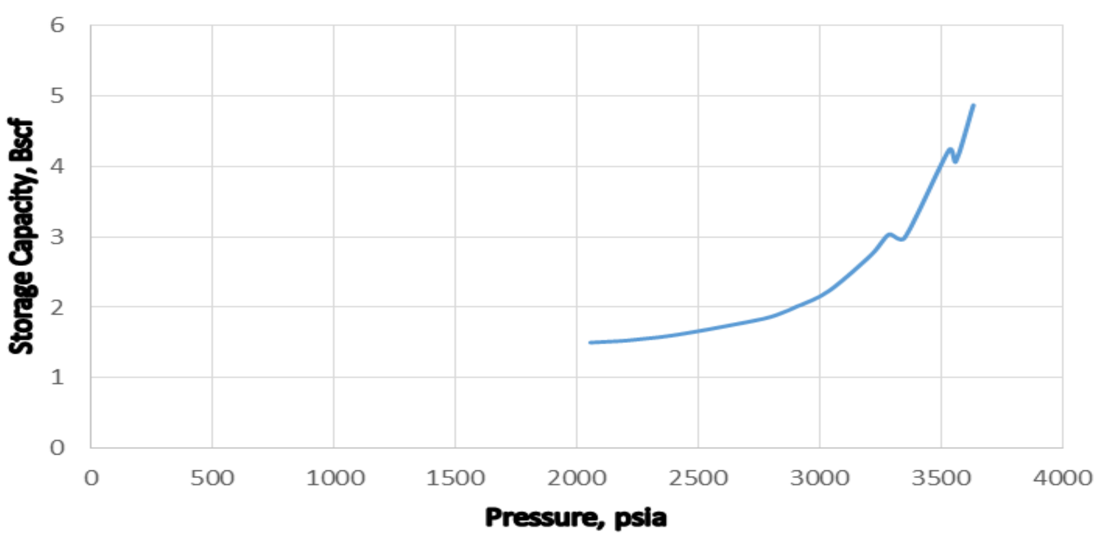

Figure 7. A plot of Volume of gas injected at various pressures for reservoir Z-16T with water influx.

(3) In choosing reservoirs for the purpose of gas storage, considerations should be made on the amount of water influx into the system and preference is given to the reservoir with less W_e, reason given in 1 above.

Conflict of Interest

The author(s) have not declared any conflict of interests.

NOMENCLATURE

B = Constant = $2\pi R^2_i h\Phi (C_w + C_p)$
B_o = Oil formation volume factor
B_g = Gas formation volume factor
B_{gi} = Initial gas formation volume factor
B_w = Water formation volume factor
Bscf = Billion standard cubic foot

Bcf = Billion cubic foot
$\overline{C}$ = Tabulated aquifer function (from time t to time t_i)
DP_i = Half pressure drop at interface from time (i-1) to (i+1).
E = Gas Expansion Factor
E_i = Gas Expansion Factor at initial state
EIA = Energy Information Administration
Eq = Equation
Ft^3 = Cubic foot
G = Gas initially in place, GIIP (scf)
G_p = Gas Production (scf)
MMscf = Million standard cubic foot
MVBP = Microsoft Visual Basic Program
N = Initial oil in place
N_p = Cumulative oil production
P = Storage pressure
P_i = Pressure at the initial state
P_{sc} = Pressure at standard condition
Res = Reservoir
R_p = Gas oil ratio
R_s = Gas solubility
T = Temperature
T_i = Temperature at initial state
T_{sc} = Temperature at standard condition
V = Reservoir volume
V_{sc} = Volume at standard condition
V_{sc} = Working gas capacity, scf
V_t = Total storage capacity, scf
V_w = Estimated volume of aquifer water
W_e = Net water influx
W_{eg} = W_e in gas terms, scf
z = Compressibility factor
z_i = Compressibility factor at the initial state
z_{sc} = Compressibility factor at standard condition

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Vol. 5(2), pp. 24-31, June, 2014
DOI: 10.5897/JPGE2014.0191
Article Number: A8273E745461
ISSN 2141-2677

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Journal of Petroleum and Gas Engineering

Full Length Research Paper

Evaluation of rheological properties of Detarium micocarpum, Brachystegea eurycoma using Herschel-Buckley model and their commercial availability

Igwilo Kevin[1*] and Zakka Bala[2]

[1]Department of Petroleum Engineering, Federal University of Technology, Owerri, Imo State, Nigeria.
[2]Society of Petroleum Engineers UK.

Received 31 March, 2014; Accepted 26 May, 2014

Drilling fluids were formulated from biomaterials such as *Brachystegea eurycoma* and *Detarium micocarpum*. The laboratory measurements were carried out, and their rheological properties then evaluated. The drilling properties such as yield point, apparent viscosity, and low shear rate yield point were determined from the experimental data. The field polypac additive that is currently in use was formulated and used as control sample to biomaterial products. Both were supplemented with equal concentrations of XC polymer additive and potassium chloride, weighted up with calcium carbonate and barite. Herschel-Buckley model was used to obtain the yield stress. Regression line was established. Plots of cutting transport ratio versus fluid flow rate, and cuttings concentration versus average annular velocity of the biomaterial mud and the existing polypac mud were made at both low and high flow rates for 8½ inch hole diameter. The biomaterial mud was compared with the existing polypac mud and results show that yield stress for low solids, and barite weighted muds are 36 and 30 lbs/100 ft^2 for biomaterial muds, respectively. The results for low solids and weighted muds of the existing polypac muds also show the yield stress of 35, 26 and 6 lbs/100 ft^2 for both regression lines. The plots of transport ratio versus fluid flow rate and cuttings concentration versus annular velocity for both biomaterial mud and the existing Polypac mud gave the same trend. Both mud types show good hole cleaning at high flow rates and small diameter holes. The investigations also show that biomaterial products are not commercially available to be used in preparing drilling fluids.

Key words: Biomaterial mud, Polypac mud, *Brachystegea eurycoma*, *Detarium micocarpum*.

INTRODUCTION

Drilling fluid's effectiveness is measured based on its rheological properties among other yardsticks, which include mud weight, yield point, low shear rate yield point, plastic viscosity, fluid loss, gel strength and lubricity. The functions of drilling fluids that are dependent on these properties include:

1) Cuttings transportation along the wellbore annulus.
2) Cooling and lubricating the bit and drill string.
3) Maintaining sufficient hydrostatic pressure to withstand

*Corresponding author. Email: meetkevin2006@yahoo.com.

the borehole pressure.
4) Being capable of suspending drilled cuttings and high gravity solids when the circulation is stopped.
5) Depositing of impermeable filter cake on the wall of the wellbore.
6) Transmitting hydraulic horsepower to the bit.
7) Ability to remove cuttings under the bit to avoid smaller particles from adversely affecting the penetration rate, bit life and mud properties.

One of the fundamental aspects of Fluid Engineering is the evaluation of rheology in order to predict behavior of fluids. To do so, it is necessary to select the parameters and utilize instruments that effectively measure them. There are many situations where some of the mud properties can be found to approximate the behavior of the actual fluid with accuracy which reflects the image of the measured fluid data. The study of the deformation of drilling fluids is not an exact standardized knowledge. They are based on mathematical models that closely describe the behavior of the fluids. Various physical properties of mud like plastic viscosity, yield point, low shear rate yield point, and gel strength are used in determining partially the rheological behavior of drilling mud. These physical properties influence the behavior of a drilling mud as it is circulated in the borehole. The relationship of these physical properties of a drilling fluid in conjunction with shear stress and shear rate are used to characterize the rheological behavior of fluid.

HERSCHEL BUCKLEY MODEL (MODIFIED POWER LAW MODEL)

Herschel-Buckley is a three parameter model that describes the behavior of yield-pseudo plastic fluids (Duru et al., 2005). This model combines the behavior of the Newtonian, Bingham plastic, and Power law models. The mathematical equation that is used to describe the model is:-

$$\tau = \tau_y + k\gamma^n \quad (1)$$

The model perfectly describes the behavior of drilling mud. It has a yield stress at low shear rates responsible for hole cleaning in the annulus.

To obtain the Power law constant corresponding to fluid flow in annulus, the 300 and 3 rpm readings are used as shown in Equations 2 and 3 (Baker Hughes Inteq, 1991).

$$n_a = 0.5 \log\left(\frac{\theta 300}{\theta 3}\right) \quad (2)$$

$$k_a = \frac{5.11 \times \theta 300}{511^{na}} \quad (3)$$

Where n_a = flow behavior index, dimensionless; k_a = consistency factor, eq-centipoise.

Characterization/commercial availability of the biomaterials

Detarium micocarpum

The roots, stem, bark, leaves and fruits are all used to treat ailment e.g. tuberculosis, meningitis and diarrhea (Abdalbasit et al., 2009). The fruit is edible and rich in Vitamin C and the leaves and the seeds are also used in cooking. The pulverized seeds cotyledons are used as a thickener and emulsifier in traditional food preparations in some African countries. A compositional study of this legume revealed that it is a rich source of polysaccharide gum (Onweluzo et al., 1994). The dehulled seed flour contains 3.5% moisture, 3.5% ash, 2.9% crude fiber, 15% crude fat, 37.1% crude protein and 39% carbohydrate (Akpata and Miachi, 2001). Benzoylated carbohydrate fractions were isolated from the bark extract of *D. micocarpum* and they analyzed its carbohydrate content using chromatographic fractionation method (Abreu and Relva, 2002). The seed polysaccharide was evaluated as a stabilizer and gelling agent in some processed fruit products and were highly acceptable and had good storage stability for 2 months at ambient storage (Onweluzo et al., 1999). The fruit of *D. micocarpum* had the highest total phenolic, flavonoid and antioxidants values among fourteen wild edible fruits from Burkina Faso (Meda et al., 2008). A research work was carried out on the oil contents extracted from *D. micocarpum* seeds which contain about 7% of oil (Kyari, 2008). He concluded that the extracted oil from *D. micocarpum* seeds contain high levels of saturated fatty acids.

It is confined to West and Central Africa. It is typically a species of dry savanna (Leung et al., 1988). Among the Ibo tribe of South-eastern Nigeria, the plant is known as “Ofo”. It is believed to be a “religious” tree which grows in God’s own compound, symbolizing truth and honesty (Ejizu, 1986). It is the most investigated specie of the genus because of its popular use in Africa traditional medicine. In the eastern part of Nigeria, they are revered plants, mythically believed to be chip of the primal trees that germinate and grow in God’s own garden by water or animal dispersal. The organization known as the Integration Action for Human Rights in Mali revealed that, 200 ha of degraded populations of *D. micocarpum* were restored/protected in 10 villages. 400 people in 10 villages trained and can apply biodiversity protection practices. 90% of people and involved in protecting *D. micocarpum* and it is their main source of income. Gender and social inclusion 500 to 800 men are involved in protection work. 600 children and 500 women are involved in making products and commercialization. 100 elders (village leaders) are involved in monitoring of environmental protection activities. Total revenue for 10

Table 1. Composition of weighted mud with calcium carbonate (low solids mud).

Composition	Concentrations
Biomaterial	
Fresh water	350 ml
Potassium chloride	10 g
Caustic soda	0.25 g
Detarium microcarpum	5 g
Brachystegia eurycoma	5 g
XCD polymer	1 g
Calcium carbonate	103.7 g
Existing	
Fresh water	350 ml
Potassium chloride	10 g
Caustic soda	0.25 g
Polypac	5 g
Calcium carbonate	103.7 g

villages in 2006 was $37,028US.

Brachystegea eurycoma

Their seeds are used in making soup as thickener. *B. eurycoma* was subjected to standard analytical techniques in order to evaluate the composition, physicochemical properties and contents of nutritional valuable elements and fatty acids of the seeds and oils (Ibironke et al., 2005). The analysis indicated that the oil content was 5.87 ± 0.30 mg/100 g. The seeds are rich in protein and carbohydrate. The protein content ranges from 11.82 ± 0.25 mg/100 g dry matter. These compare favorably with high protein animal sources like oyster, beef, pork and marine fishes. It contains 8% of oil. Eight nutritional valuable minerals were determined in the seed flours (Ibironke et al., 2005). The seeds are rich in potassium (52.1 mg/100 g - 131 mg/100 g). They also contain significant concentration of Iron (4.55 mg/100 g - 8.20 mg/100 g). *B. eurycoma* is one of the lesser known legumes, which have not been fully utilized to alleviate the problem of protein - energy malnutrition common in developing countries of the world such as Nigeria. It is a large crowded forest tree. It is 60 m high and common on stream banks. *B. eurycoma* is a woody plant mostly found in the rain forest zone, eastern part of the country. In order to boost the small *eurycoma* production and develop the new market opportunities to stimulate economic growth in the South-east of Nigeria, one would have to expand alternative utilization/processing techniques in Agro - food systems. The rate of *B. eurycoma* harvested as timber in tropical rain forest ecosystem of Nigeria, Ondo between 2003 and 2005 is 2693 trees (Adekunle et al., 2009).

Table 2. Composition of weighted mud with barite.

Composition	Concentrations
Biomaterial	
Fresh water	350 ml
Potassium chloride	10 g
Caustic soda	0.25 g
Detarium microcarpum	6 g
Brachystegia eurycoma	6 g
XCD polymer	1 g
Barite	75.4 g
Existing	
Fresh water	350 ml
Potassium chloride	10 g
Caustic soda	0.25 g
Polypac	6 g
XCD polymer	1 g
Calcium carbonate	75.4 g

METHODOLOGY

The rheology experiment was conducted from the D. micocarpum, B. eurycoma and the existing polypac. The experimental data shown in Tables 3 and 4 were used to evaluate the yield stress using Herschel-Buckley model. Different annular flow behavior index, na and the annular consistency factor, ka, were calculated at different temperatures using Equations 2 and 3. The fann readings were evaluated using shear stress versus shear rate as shown in Figures 1 and 2 were obtained for the regressed line, biomaterial and polypac muds.

Mud formulations/experimental procedure

Two sets of measurements were carried out, the proposed mud obtained from biomaterials: *D. micocarpum*, *B. eurycoma* and the existing polypac muds. Tests were conducted as per API standard. Formulations of the muds are shown in Tables 1 and 2. All tests were carried out at room temperature and temperatures of 120, 150, and 200°F. The tables show the laboratory measurements of the *D. micocarpum, B. eurycoma* muds, and the existing polypac muds. Equal concentrations were applied for *D. micocarpum*, *B. eurycoma*, muds and the existing polypac muds for easy comparison.

The seeds of *D. micocarpum* and *B. eurycoma* were grinded separately using Hamilton grinder to powder form, dried in the sun for 24 h and finally re-grinded. The coarse powdered materials were sieved until the fine powder of each specimen was obtained. Data for the calculation of the samples rheological properties were obtained using the Fann VG viscometer.

The rheological parameters calculated from the laboratory measured data were used to determine the rheological parameters for both the biomaterial and the existing polypac samples. The annular hole cleaning abilities of the mud samples were investigated using shear stress versus shear rate relationship and applying the Modified Power law model for the determination of yield stress, which is the major factor of consideration in annular hole cleaning studies.

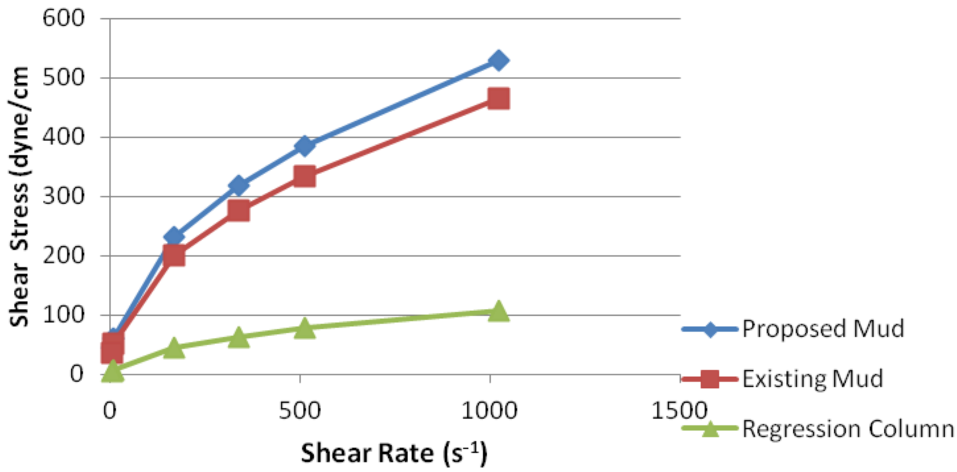

Figure 1. Estimation of yield stress for low solids muds using Herschel-Buckeley model.

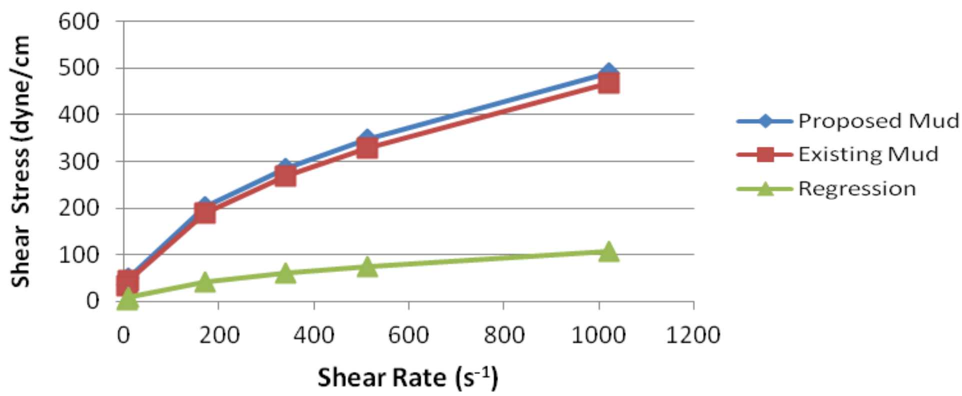

Figure 2. Estimation of yield stress for barite mud using Herschel-Buckeley model.

Hole cleaning efficiency validation

The evaluation of hole cleaning ability of 8½" hole for *D. micocarpum*, *Brachystegea eurycoma* muds and polypac muds were carried out. Cutting transport ratio, transport efficiency and cuttings concentration were determined to know the degree of effectiveness of the proposed muds in terms of annular hole cleaning (Baker Hughes Inteq, 1991).

The hole cleaning equations are stated from Equations 4 to 12. The step by step procedure followed in this study is shown as follows:

$$D_p = \frac{\tau_g}{10.4\left(\rho_s - \rho_f\right)} \quad (4)$$

Where τ_g *is* the gel strength, lbs/100 ft^2

The average fluid velocity can be obtained from Equation 5 (Baker Hughes Inteq, 1991).

$$V_a = \frac{q}{2.4484\left(d_2^2 - d_1^2\right)} \quad (5)$$

Where q is the fluid flow rate, (gpm)

The effective viscosity,(μ_{eff}) can be determined from Equation 6 (Baker Hughes Inteq, 1991).

$$\mu_{eff} = 100k_a\left(\frac{144v_a}{d_2 - d_1}\right)^{na-1} \quad (6)$$

T is the thickness of the particle, inches.

The particle shear rate γ_p can be obtained using Equation 7 (Baker Hughes Inteq, 1991).

$$\gamma_p = \left(\frac{\tau_p}{k_a}\right)^{1/n_a} \quad (7)$$

The particle shear stress, τ_p can be determined using Equation 8 (Baker Hughes Inteq, 1991).

$$T_p = 7.9\sqrt{T\left(\rho_s - \rho_f\right)} \quad (8)$$

Where γ_p is in s^{-1}.

For particle shear rate less than the boundary shear rate, slip velocity is determined from Equation 9 (Baker Hughes Inteq, 1991).

$$V_s = 1.22\tau\rho\left(\frac{\gamma_p d_p}{\sqrt{\rho_f}}\right)^{\frac{1}{2}} \quad (9)$$

Table 3. Viscometric readings with calcium carbonate (Low solids mud) at different temperatures.

Constituents	Room Temperature	120°F	150°F	180°F
	Fann readings			
Proposed mud				
Fresh water (350 ml)	116, 87, 72, 52, 11, 9	79, 59, 47, 34, 9, 8	77, 57, 47, 33, 9, 8	72, 52, 40, 30, 7, 6
Potassium chloride (10 g)				
Caustic soda (0.25 g)	10 s/10 min Gel = 9/11	10 s/10 min Gel = 8/10	10 s/10 min Gel = 8/9	10 s/10 min Gel = 7/9
Detarium microcarpum (5 g)				
Brachystegia eurycoma (5 g)				
Calcium carbonate (124 g)				
XCD ploymer (1 g)				
Existing polymer mud				
Fresh water (350 ml)	106, 75, 62, 50, 10, 8	73, 52, 44, 32, 8, 6	70, 50, 42, 30, 7, 6	67, 47, 38, 28, 6, 5
Caustic soda (0.25 g)				
Polypac (5 g)	10 s/10mins Gel = 9/11	10 s/10mins Gel = 7/9	10 s/10 min Gel = 7/9	10 s/10 min Gel = 6/8
XCD Polymer (1 g)				
Potassium Chloride (10 g)				

Where V_s is in ft/s.

Hence, the transport ratio (T_r) can be obtained using Equation 10 (Baker Hughes Inteq, 1991).

$$T_r = 1 - \frac{V_s}{V_a} \quad (10)$$

The cutting transport efficiency (T_c) can be determined from Equation 11 (Baker Hughes Inteq, 1991).

$$T_c = 1 - \left(\frac{v_s}{v_a}\right) x\ 100 \quad (11)$$

Hence, the cuttings concentration (C_a) is calculated using Equation 12 (Baker Hughes Inteq, 1991).

$$C_a = \frac{(\text{rop}) d_2^2\ x\ 100}{14.7\ T_c q} \quad (12)$$

Where C_a is in vol. %; ROP is the rate of penetration, ft/hr.

Application of Modified Power law model

This involves the application of the Herschel-Buckley (Modified Power law) model which describes the behavior of the drilling fluids perfectly well. It indicates the yield stress especially at a very low shear rate of 3 and 6 rpm which demonstrates the hole cleaning in the annulus using Equations 1 and 2.

RESULTS AND DISCUSSION

The measured data were related to the Modified Power law model, for yield stress estimation which is one of the criteria for cuttings removal from the hole. Tables 3 and 4 show the experimental results got from Formulations 1 and 2 to be applied to obtain yield stress using Herschel-Buckley model.

Equations 2 and 3 were used to obtain different values of annular flow behavior index, n_a and consistency index k_a, at different temperatures. The calculations of the biomaterial mud and the polypac mud shear stress of weighted mud with calcium carbonate and barite were performed at different shear rates.

From Figure 1, the biomaterial mud gave the yield stress of 36 lbs/100 ft^2 as against 35 and 6 lbs/100 ft^2 for polypac mud and the regression line, respectively. In Figure 2, the weighted mud with barite gave 30 lbs/100 ft^2 for biomaterial mud, 26 lbs/100 ft^2 for polypac mud and 6 lbs/100 ft^2 for regression line. Yield stress is responsible for the annular hole cleaning during drilling. The hole cleaning at low shear rates prevents pipe stuck known as differential sticking which may occur as a result of poor hole cleaning. This will also lead to increase in equivalent circulating density due to increase in mud weight resulting from high cuttings concentration. Also, inadequate hole cleaning may result to reduction in penetration rate.

Furthermore, the flow behavior index of both proposed muds and the existing polymer muds for annular flow ranges from 0.4 to 0.5. For non-dispersed mud, n is usually between 0.4 and 0.7; for highly dispersed mud, n is usually between 0.7 and 0.9 (Mian, 1992). The lower the n value, the more non-Newtonian the mud, showing the property of shears thinning for drilling bits and nozzles cleaning. All the values of the annular flow behavior index for both biomaterial mud and the polypac mud ranges between 0.4 to 0.5, showing enough shear thinning at the bit for nozzles cleaning. The Biomaterial mud has a higher yield stress than the existing polypac mud and it is a function of good hole cleaning. Anything less than the reference line, called a critical line. This is the region of high cuttings concentration that will lead to poor hole

Table 4. Viscometric readings with barite as the weighting material at different temperatures.

Constituents	Room temperature	120°F	150°F	180°F
	Fann readings			
Proposed mud				
Fresh water (350 ml)				
Caustic soda (0.25 g)	95, 67, 56, 40, 9,7	86, 60, 50, 36, 7, 6	75, 54, 44, 31, 6, 5	64, 46, 37, 25, 6, 5
Detarium microcarpum (6 g)				
Brachystegia eurycoma (6 g)	10 s/10 min Gel = 9/11	10 s/10 min Gel = 7/9	10 s/10 min Gel = 7/9	10 s/10 min Gel = 6/8
Potassium chloride (20 g)				
XCD Polymer (1 g)				
Barite (75.4 g)				
Existing polymer mud				
Fresh water (350 ml)				
Caustic soda (0.25 g)	90,62, 51, 37, 8, 7	81,57, 46, 32, 6, 5	72, 51, 42, 30, 6, 5	60, 42, 36, 25, 5, 4
Polypac (6 g)				
Potassium Chloride (20 g)				
XCD ploymer (1g 74.5g)	10 s/10 min Gel = 8/10	10s/10 min Gel = 6/9	10 s/10 min Gel = 6/8	10 s/10 min Gel = 5/7

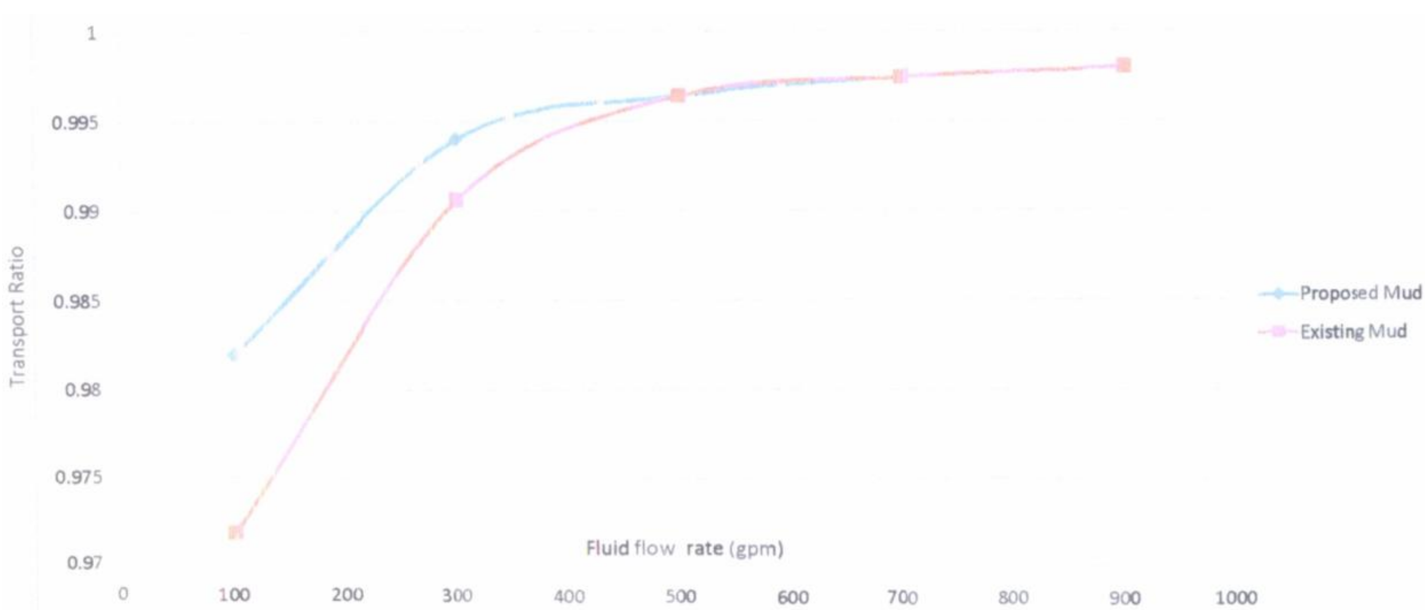

Figure 3. The relationship between transport ratio and fluid flow rate for 8.5 inch Hole Low-solids biomaterial mud and existing mud.

cleaning. In the other way round, the value of yield stress should not be excessively high to avoid surge and swab problems during tripping operations.

As shown in Figures 3 to 6, both show the same pattern, the flow rate increased with increase in cutting transport ratio, and slows down at 500 gpm. The cuttings concentration of the biomaterial mud and polypac mud were highly reduced for small diameter holes and high flow rates. The effect of annular velocity on cuttings concentration on biomaterial mud and the polypac mud show the same trend.

Conclusions

1) The rheological properties of the biomaterial muds and

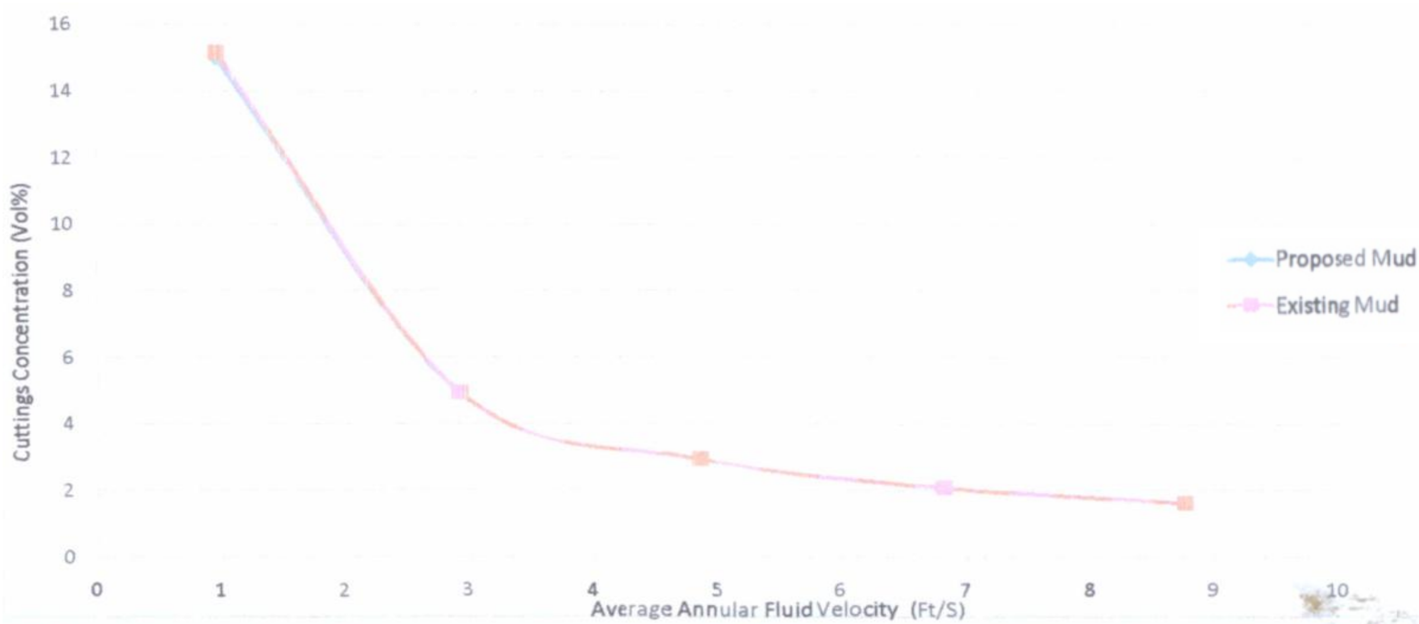

Figure 4. The relationship between cuttings concentration and average annular fluid velocity for 8.5 inch hole low-solids biomaterial mud and existing muds.

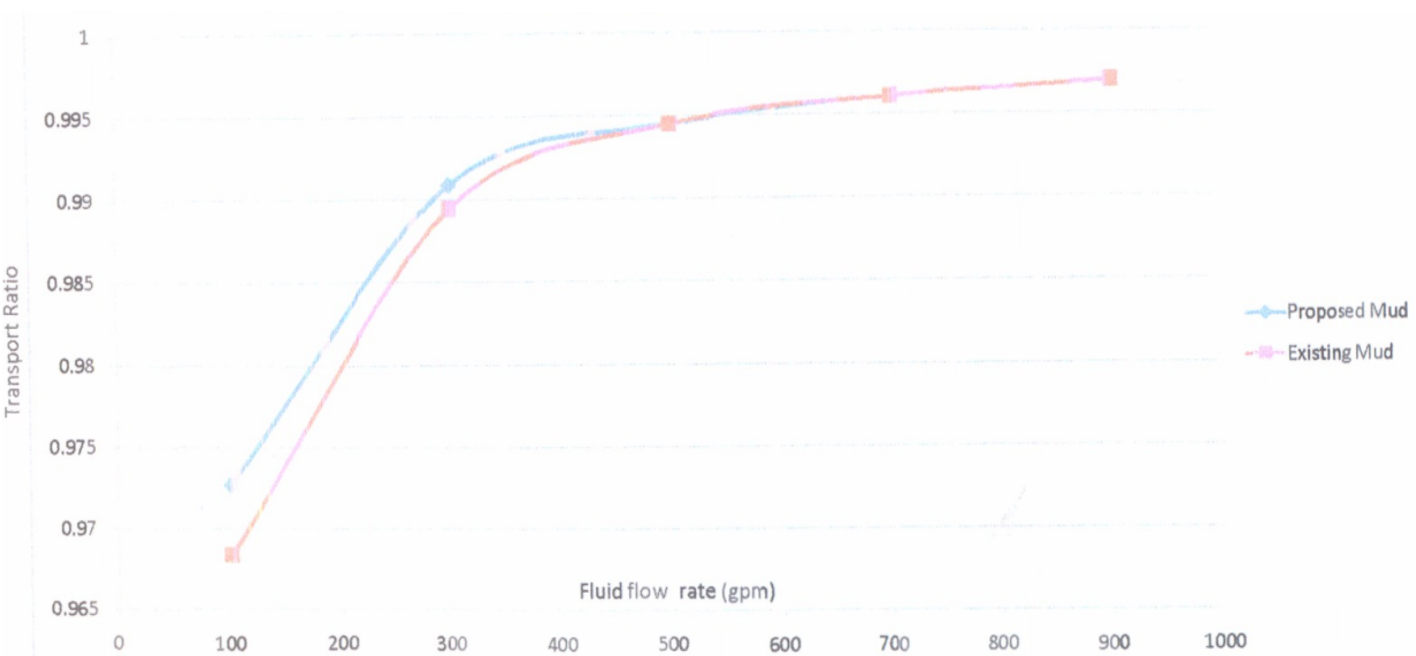

Figure 5. The relationship between transport ratio and fluid flow rate for 8.5 inch hole weighted biomaterial mud and existing mud.

the yield stress when evaluated using Herschel-Buckley model are slightly better than the existing polypac muds of equal concentrations.

2) The *D. microcarpum* and *B. eurycoma* muds and the existing polypac muds show good hole cleaning at high flow rates and small diameter holes. The cuttings concentration of 1.64 volume % and cutting transport ratio of 0.997 were recorded at 900 gpm flow rate and 8.5 inches hole size.

3) In all considerations, the rheological properties of the biomaterial muds are slightly better than the existing polypac muds, but the former are not commercially

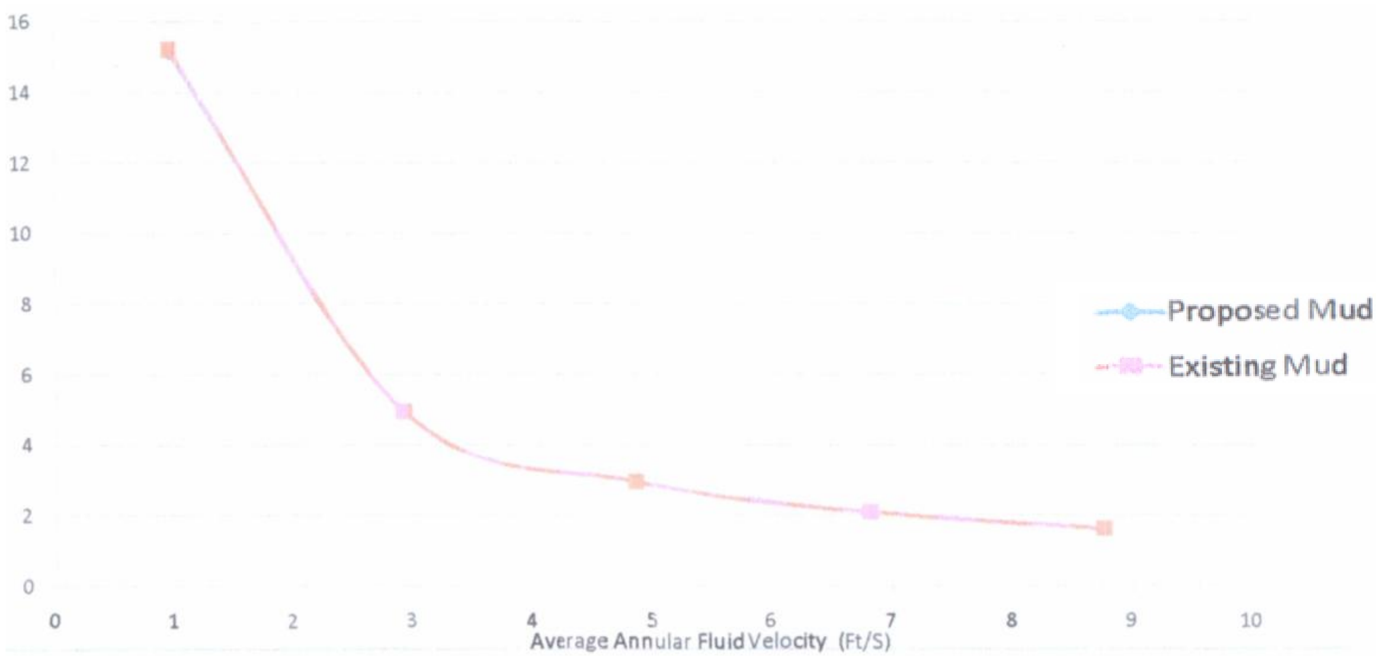

Figure 6. The relationship between cuttings concentration and average annular fluid velocity for 8.5 inch hole weighted biomaterial mud and existing muds.

available for preparing drilling fluids.

Contribution to knowledge

The major contribution of this study was to formulate drilling fluids from locally sourced biomaterials for effective drilling. Based on the result of the work, it is confirmed that the local products are not economically and commercially comparable to currently used polypac additive. Hence, the major contribution is to dissuade investors from using these products as they are, without further evaluation using the results of this work as a base.

ACKNOWLEDGEMENTS

We thank the management of Federal University of Technology, Owerri, Nigeria for allowing us to use their laboratory We are also grateful for the contributions and insights of Prof. Godwin Chukwu, Prof. Boniface Obah and Prof. Ogbobe O. and Dr Nwakudu M.S.

Conflict of Interests

The author(s) have not declared any conflict of interests.

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