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Research · January 2017

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Journal of Petroleum Engineering & Technology
ISSN: 2231-1785 (Online), ISSN: 2321-5178 (Print)
Volume 7, Issue 2
www.stmjournals.com

Biopolymer Substitution and Impact on Cuttings Transport of a Lightweight Water-Based Drilling Fluid

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Abstract

The aim is to determine the impact of substitution of a local material for another, on rheological properties and hole cleaning capability. A local biopolymer Mucuna solannie was used as a substitute for another biopolymer, Detarium microcarpum, primarily as a viscosifier in a water-based drilling fluid. Tests were carried out using standard equipment and specifications. Variations in transport efficiency and required minimum fluid flow rate at same cuttings concentration (CC) were recorded in the 12¼ in vertical hole section, while in the 8½ in directional section, the maximum ROP that can be sustained while still maintaining adequate hole cleaning was obtained by graphical method. Yield stress values of 2.7, 3 and 12.4 lb/100ft^2 were calculated based on different approaches. In the 12¼ in section, TE of 99.98% and CC of 5.002 vol.% were observed at 300 ft/h with minimum fluid flow rate of 657 gpm for the Mucuna solannie mud, from a MATLAB cuttings transport program, compared with TE of 99.98 and 98.55% at same CC of 5.002 vol.% for the Detarium microcarpum and XCD/Polymer muds respectively used as control samples. Required minimum fluid flow rates are 612.4 and 621.3 gpm respectively. In the 8½ in section, with the Herschel-Bulkley mud, an ROP of about 8.2 ft/h was obtained as the maximum drilling rate at 40° inclination. The lightweight mud exhibited good cuttings transport in the vertical well, and might not be suitable for highly deviated wells. Comparison of this kind is necessary for evaluation of respective constituents in a mud formulation where several local materials are combined, in a wholly-replaced-bentonite mud. Different models and approaches yielded various yield stress values; hence, comparison of accuracy of models in predicting yield stress is necessary.

Keywords: *Cutting carrying index, cuttings transport, lightweight mud, Mucuna solannie*

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INTRODUCTION

Since materials used to improve the quality and functions of drilling fluids contaminate the subsurface and underground systems, landfills, and surrounding environment. Future research guidelines that focus on the development of environmentally friendly drilling fluids with zero impact on the environment have been presented [1].

Similarly, potassium chloride polymer muds used for shale stabilization still lack the versatility needed for widespread usage as they appear to be suitable at low solids concentration, its limitation attributed to the control of rheological and fluid loss properties, temperature and inability to meet medium and high density requirements [2]. There exists a mud system with other potassium compounds and derivatives that enabled shale stabilization, versatility, solids tolerance, and thermal stability. Research has been ongoing for local materials as alternatives.

However, since one major function of drilling fluids is cuttings transport, a work has been presented on previous studies on drilled cuttings transport, and used a concept basis to group it in four categories [3]:

i. Sensitivity analysis: internal states changes versus input changes.
ii. Modeling: physical relations of inputs and internal state.
iii. Monitoring: using real time measured data to estimate the internal state.
iv. Control: change inputs until achieving the desired internal state.

Hence, the cuttings transport study presented in this work falls under the (i) and (ii) categories, but specifically the sensitivity analysis aspect. However, in vertical and near-vertical sections, the cuttings can be effectively carried in suspension, since the annular fluid velocity overcomes the cuttings settling force and creates a net upward movement of the cuttings. But, in a high-angle well, the gravitational force acting on the cuttings tends to cause the formation of a cuttings bed on the low side of the hole. The annular fluid velocity creates a drag force which tends to move the cuttings bed axially and a fluid lift force that tends to move the cuttings away from the wellbore (radially) and towards the higher velocity flow stream (centerline).

LITERATURE REVIEW

The need has been highlighted for selection of compromise properties for cuttings transport, since properties required of muds for lifting cuttings out of the hole, suspending them when circulation is stopped, and dropping them in the mud pit are conflicting [4]. The complexity of the interaction between particles and drilling fluid, and variations in wellbore conditions, make prediction of hole cleaning conditions a complicated subject. Several researchers have applied several techniques to determine parameters that affect cuttings transport in both vertical and directional wellbores.

Some Laboratory Works and Field Data Results for Parameters that Affect Hole Cleaning

Some researchers presented an experimental work on hole cleaning on full scale vertical annuli [5]. They reported that annular velocity and fluid rheological properties were the most significant variables, and that improving apparent viscosity improved cuttings transport. They reported that observed transport was 75 to 90% of the theoretical values.

Another work presented the effect of parameters such as particle size, flow rate, apparent viscosity and yield point to plastic viscosity ratio on mud-carrying capacity [6]. The authors observed that in vertical annuli, the fluid annular velocity has a major effect on the carrying capacity of muds, while other parameters have an effect only at low to medium fluid annular velocities.

The effects of field-measured mud rheological properties on cuttings transport in directional well drilling were also presented [7]. The authors identified three separate regions of hole inclination regarding cuttings transport: 0 to 45, 45 to 55, and 55 to 90°.

The results of an experiment for inclined boreholes, using a 21 ft borehole simulator and peripheral equipment; where cuttings are transported by rolling/sliding motion along the low-side of the annulus, and where cuttings are transported in suspension in the circulating fluid have also been published [8]. The authors concluded that the effectiveness of circulating fluid in removing drilled cuttings is not only dependent on the rheology of the fluid but also on the flow regime. Also, pipe rotation had little or no effect on fluid velocity when circulating water, but reduced the fluid velocity required to transport cuttings when circulating medium of high viscosity fluids.

A work was presented on bit hydraulics analysis for efficient hole cleaning [9]. The experiment showed that increase in drillstring rotational speed reduces apparent slip velocity but increases drag coefficient on the transported cuttings.

Drillpipe rotation, temperature and rheological parameters have also been shown to have significant effects on cuttings transport efficiency [10]. It has been highlighted that to be able to predict true volumetric flow rate, it is necessary to understand how the momentum is transferred from the fluid to the particles [11]. The author presented an experimental setup used to measure fluid velocities and bidispersed particle velocities and position distributions.

Some Mechanistic Models and Computer Programs for Parameters that Affect Hole Cleaning

A numerical model was built based on experimental data obtained in the laboratory and wells during drilling [12]. The authors concluded that the influence of hole inclination becomes apparent as soon as the well becomes slightly deviated (10°), cuttings evacuation is more difficult at 30 to 60°, high viscosity for hole cleaning is favourable in nearly vertical part, but may reduce transfer capacity in slanting parts and increase in density of the drilling fluid facilitates transport.

Similarly, a computer model was developed for hole cleaning analysis by the use of standard drilling data such as rate of penetration, pump rate, bit size, wellbore geometry and mud properties. The model was for straight holes only [13]. Similarly, a model for transport prediction, and the mechanisms that control cuttings bed was presented [14].

Other researchers developed a mechanistic model in a format for easy analysis of cuttings transport in wells of any configuration [15], presented a model for selection of proper hydraulics for problem-free drilling in high-angle holes (55 to 90° inclination) [16], and a mechanistic layer model has been developed, yielding a two-layer model that simulates a moving bed of packed cuttings below a heterogeneous layer of mud and cuttings [17]. It has been used to perform numerical simulations, predict cuttings bed heights, pressure drops, and transport velocities at varying rates of penetration and flow rates.

Similarly, a computer program for prediction of cuttings transport in multiphase gas, liquid and cuttings system [18], the use of computational fluid dynamics (CFD) software program to determine the parameters that affect cuttings transport in any wellbore [19], have been presented. For the CFD software program, they presented the effect of cutting and mud properties on vertical and horizontal wellbores.

A simulation run on three-layer cutting transport model was presented and it was observed that high angle hold segment is the most difficult for cutting transport [20]. The authors recommended the use of low viscosity drilling fluid, high flow rate and drill pipe rotation.

A model for real-time evaluation of hole cleaning conditions was also developed [21]. The authors argued that since it is not easily determined how and where cuttings are settling, getting a continuously updated prognosis of the distribution of cuttings in suspension and in beds along the annulus becomes necessary.

Some Works on the Use of Polymer Based Muds, Use of Charts, and Other Considerations for Parameters that Affect Hole Cleaning

The work on hole cleaning capability of polymer based drilling fluids, by combining the effects of rheology, flow rate, velocity profile, eccentricity, pipe rotation and inclination on hole-cleaning efficiency has been presented [22].

Researchers have also used charts to determine hole cleaning requirements in deviated wells [23]. They observed mud rheology to be a key variable for optimizing hole cleaning in deviated wells. Similarly, the work on the effect of drilling fluid rheological properties on hole cleaning was presented [24]. It was highlighted that the drilling fluid composition can be designed to minimize the gel formation in the cuttings bed, to optimize the properties to ensure a sufficient shear stress on the cuttings particles to be able to remove the cuttings.

A work on the effect of pipe rotation on velocity profile in concentric and eccentric annuli during axial flow of non-Newtonian fluid has been presented [25].

Another work combined Larsen’s model for prediction of minimum flow rate for cuttings removal from 55 to 90° and Moore’s correlation used to find the slip velocity of the cuttings in vertical wells [26].

Also, an experimental work, comparing cuttings transport in circular and non-circular borehole geometries has been presented. A flow loop of 12 m long test section, with a 2 in OD freely rotating drillstring inside a 4 in ID wellbore made of concrete was used. The test was performed at two inclinations; horizontal and 30^{o} inclination. Results showed that torque is reduced and cuttings transport improved in the non-circular wellbore relative to the circular wellbore [27].

A work was presented on hole cleaning using water and polymer-based fluids performance under turbulent conditions using empirical approach [28]. The authors observed that fluids with higher polymer concentration and hence higher viscosity required higher flow rates to start eroding the bed.

However, it has been argued that comparing different results from experiments and simulations, by different researchers, is challenging, as there is no common reference basis in a form of typical and representative set of case parameters. Hence, each case seems to be treated based on conditions peculiar to the respective drilling operation’s flow system. Also, prediction of rheological parameters such as yield stress depends on the model used for the prediction [29–31].

SUMMARY

In vertical and directional wells, cuttings transport depends on:

i. Fluid properties (yield stress, gel strength and density), rheology (flow behavior index and consistency factor), flow rate and flow regime (laminar or turbulent).
ii. Cuttings thickness, diameter, density and shape.
iii. Hole size, angle and drill string configuration (pipe sizes).
iv. Drill string rotation.
v. Rate of penetration.
vi. Multiphase flow effects.
vii. Velocity profile in the annulus.

The analysis approach using the parameters listed includes determination of terms associated with hole cleaning such as transport efficiency (TE) and cuttings concentration (CC) in the annulus, cuttings carrying index (CCI) and transport index (TI) which are interpreted to serve as indicators of efficient hole cleaning capability of muds.

However, in mechanistic approach, the assumptions that drillstring is static and eccentric, known open-hole size, that flow is isothermal and incompressible, are common. The use of mechanistic approach and charts to predict cuttings transport capability of *Mucuna solannie* water-based mud would be presented in this work.

MATERIALS AND METHOD

Materials

Local materials such as *Mucuna solannie, Brachystegia eurycoma* and *Pleurotus* were sourced, and other compositions such as caustic soda, potassium chloride, XCD polymer and barite were used to formulate a weighted mud. Properties of the mud formulated by the use of local materials as viscosifier and fluid loss control agents were determined in the laboratory by the use of API standard test procedures. Geological data on drilled cuttings were used. Software such as SOLVER was used to determine the rheological properties, and MATLAB program was used to determine transport efficiency (TE) and cuttings concentration (CC) in 12¼ in hole section to predict cuttings transport capacity of the mud and the results were compared with other known formulations with *Detarium microcarpum* and XCD/polymer. Transport index (TI) for graphical approach in the 8½ in section and cutting carrying index (CCI) in 12¼ in section were also used to determine the cutting carrying capability of the new mud formulation.

Mud Formulations

Table 1: *Additives and Functions in the Proposed Mud.*

Mud Composition	Quantity	Function(s)
Fresh Water	1 BBL	Base Fluid
Caustic soda	0.25 ppb	To add alkalinity
Mucuna solannie	6 ppb	Viscosifier and fluid loss control agent
Brachystegia eurycoma	6 ppb	Mild viscosifier and fluid loss control
Pleurotus	8 ppb	Fluid loss control agent
Potassium chloride	20 ppb	Inhibitor
XCD polymer	1 ppb	Viscosifier
Barite	75.4 ppb	Densifier

Table 2: *Additives in the Control Sample.*

Mud Composition	Quantity
Fresh Water	1 BBL
Caustic soda	0.25 ppb
Detarium microcarpum	6 ppb
Brachystegia eurycoma	6 ppb
Pleurotus	8 ppb
Potassium chloride	20 ppb
XCD polymer	1 ppb
Barite	75.4 ppb

Method

For the formulation presented in Table 1, the mud parameters such as density, gel strength, flow behavior index, and consistency factor were determined (Table 3). SOLVER was used to optimize the rheological parameters. The suitable rheological model was determined by the use of a statistical approach (the Absolute Average Error). Geological data such as cuttings density, thickness and diameter (Table 4) were used, similar to those used for analyses of mud formulation of Table 2. Tubular and geometrical data such as drill pipe size and well size (Table 5) were assumed based on standard well configurations. Other assumptions such as static and eccentric drillstring, isothermal and incompressible flow were made. The TE, CC, CCI and TI which are indicators of cuttings transport capacity of muds, determined at chosen rate of penetration and varying fluid flow rate were determined. 12¼ in hole size is used as case study for vertical well and 8½ in hole size is used for directional well. The hole cleaning effectiveness in the directional well was determined graphically.

The relevant equations include Eqs. (1)–(14).

$$\gamma_b = 186/\left(d_c\sqrt{\rho_f}\right) \quad (1)$$

Where,
y_b=the boundary shear rate, 1/sec,
d_c=cuttings diameter, in,
ρ_f=fluid density, ppg.

$$\tau_p = 7.9*\sqrt{T\left(\rho_s - \rho_f\right)} \quad (2)$$

Where,
τ_p=the particle shear stress, lb/100ft^2,
T=cuttings thickness, in,
ρ_s=solids density, ppg.

$$\gamma_p = \left(\tau_p/K_a\right)^{\frac{1}{n_a}} \quad (3)$$

Where,
γ_p=the particle shear rate, 1/sec,
τ_p=particle shear stress, lb/100ft^2,
K_a=consistency factor, eq-cp,
n_a=flow behavior index, dimensionless.

$$v_a = q/\left(2.4484\left(d_2^2 - d_1^2\right)\right) \quad (4)$$

Where,
v_a=annular velocity, ft/min,
q=the fluid flow rate, gpm,
d_2=hole size, in,
d_1=pipe size, in.

$$v_{eff} = 100*K_a*\left(\frac{144v_a}{d_2^2 - d_1^2}\right)^{n_a-1} \quad (5)$$

Where,
v_{eff}=the effective viscosity, cp.

$$v_{s1} = 16.62*\tau_p/\left(\sqrt{\rho_f}\right) \quad (6)$$

Where,
v_{s1}=particle slip velocity turbulent flow, ft/m.

$$v_{s2} = 1.22*\tau_p\left(\frac{\left(\gamma_p*d_c\right)}{\sqrt{\rho_f}}\right)^{\frac{1}{2}} \quad (7)$$

Where,
v_{s2}=particle slip velocity laminar flow, ft/m.

$$Tr = 1-\left(\frac{v_s}{v_a}\right) \quad (8)$$

Where,
Tr=transport ratio.

$$TE = Tr*100 \quad (9)$$

Where,
Te=transport efficiency, %.

$$CC = \frac{ROP*d_2^2*100}{14.7*TE*q} \quad (10)$$

Where,
CC=cuttings concentration, vol.%.

$$TI = \frac{q*\rho_f*RF}{834.5} \quad (11)$$

Where,
TI=Transport Index,
RF=Rheology Factor.

$$CCI = \frac{K_1*V_a*\rho}{400{,}000} \quad (12)$$

Where,
CCI=Cutting Carrying Index,
V_a=annular velocity, ft/min.

$$K_1 = 511^{1-n}\left(PV+YP\right) \quad (13)$$

Where,
K_1=Power Law Constant, cP,

n=flow behavior index,
PV=plastic viscosity, cP,
YP=yield point, lb/100ft^2.

$$n = 3.322 \log \frac{(2PV + YP)}{(PV + YP)} \qquad (14)$$

Tables 3–6 are used as parameters for hypothetical wells of sizes 8½ and 12¼ in.

***Table 3:** Drilling Fluid Parameters for Mucuna solannie Mud.*

Parameter	Value
Flow behavior index, n_a	0.4208
Consistency factor, eq_cps	20.04
Gel strength, lb/100ft^2	4
Fluid density, ppg	8.6

***Table 4:** Geological Data.*

Parameter	Value
Solids density, ppg (SG=2.6)	21.66
Cuttings average thickness, in	0.18

***Table 5:** Tubular and Geometrical Data.*

Parameter	Value
Hole sizes, in	12¼, 8½
Drillpipe size, in	5½

RESULTS AND DISCUSSION

Results

The suitable rheological model for the mud was determined to be Herschel-Bulkley model, based on the absolute average error (0.8856 for H-B model and 1.416 for Bingham-Plastic model) between the measured and the model shear stress data. The yield point of the H-B fluid is 2.72 lb/100ft^2 [32]. But the 3 rpm shear stress would be used as the yield point stress (Table 8) in some analyses, and 12.4 lb/100ft^2 in others since yield stress value depends on the method used.

***Table 6:** Data for CCI Determination.*

Parameter	Value	
	Herschel-Bulkley	Bingham-Plastic
Plastic viscosity, cP	11	
Mud weight, ppg	8.6	
Annular velocity, ft/min (assumed)	140	
Yield stress, lb/100ft^2	2.7 (Versan and Tolga, 2005)	37.5
	3 (3rpm Reading)	
	12.4 (Hemphill *et al*, 1993) with n=0.8	

12¼ in Hole Section (Vertical Well)

For the hypothetical well, Figures 1 and 2 show variations in CC with fluid flow rate at constant drilling rate of 300 ft/h. Table 7 and corresponding Figure 3 are comparisons of minimum fluid flow rates required to achieve a CC of 5.002 vol.% for the mud. Figure 4 is the velocity profile for the Herschel-Bulkley fluid flow in the annulus. It was generated with flow behavior index of Table 3.

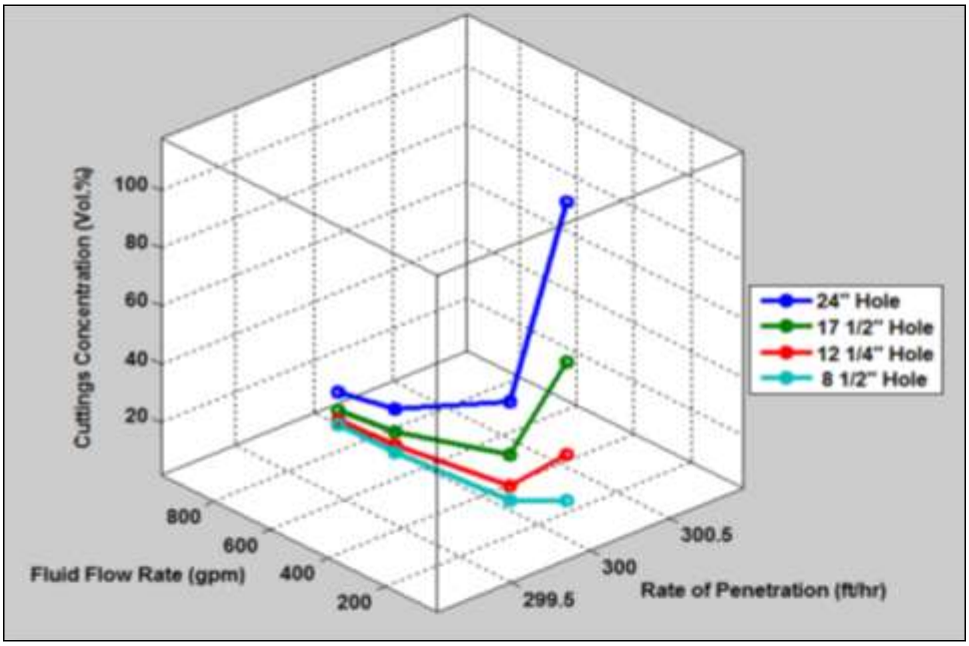

***Fig. 1:** 3D Plot of Fluid Flow Rate vs Rate of Penetration vs Cuttings Concentration from MATLAB (Generic).*

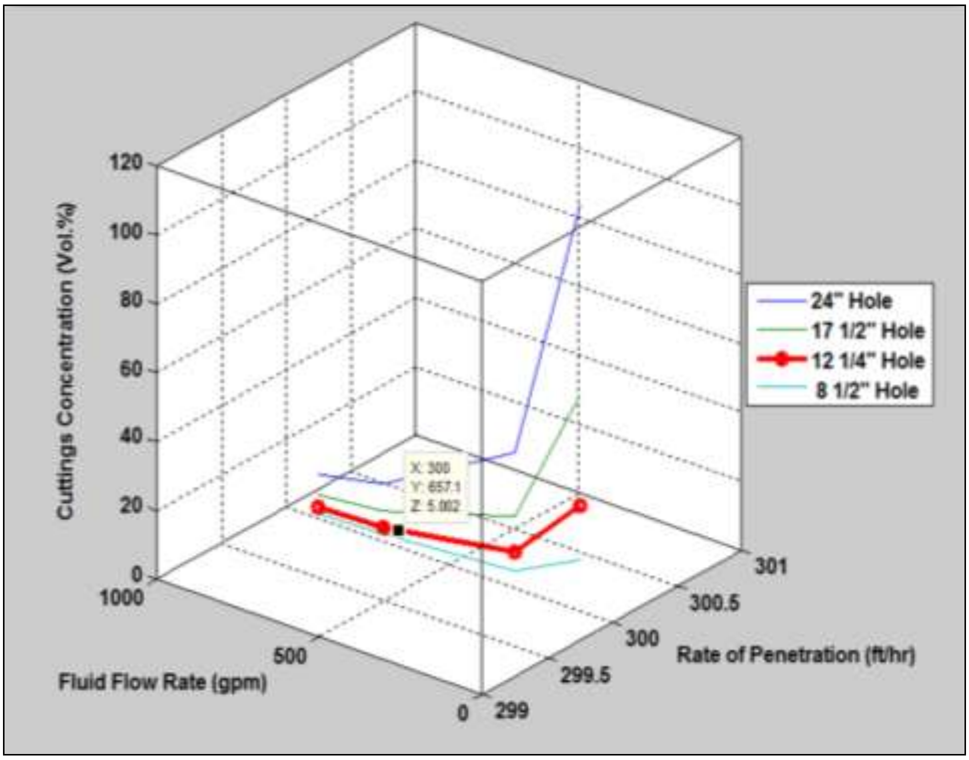

Fig. 2: *3D Plot of Fluid Flow Rate versus Rate of Penetration versus Cuttings Concentration from MATLAB (12¼ in Hole).*

Table 7: *TE and Minimum Fluid Flow Rate for Same CC Value for Three Muds.*

Parameter	***Mucuna solannie* (MATLAB)**	**Existing *Detarium microcarpum***	**Existing XCD/Polymer**
TE, %	99.98	99.98	98.55
CC, vol.%	5.002	5.002	5.002
Q, gpm	657	612.4	621.3

With Herschel-Bulkley and Bingham-Plastic yield stresses, the cutting carrying index of 0.12 and 1.12 and 11.86 respectively were calculated.

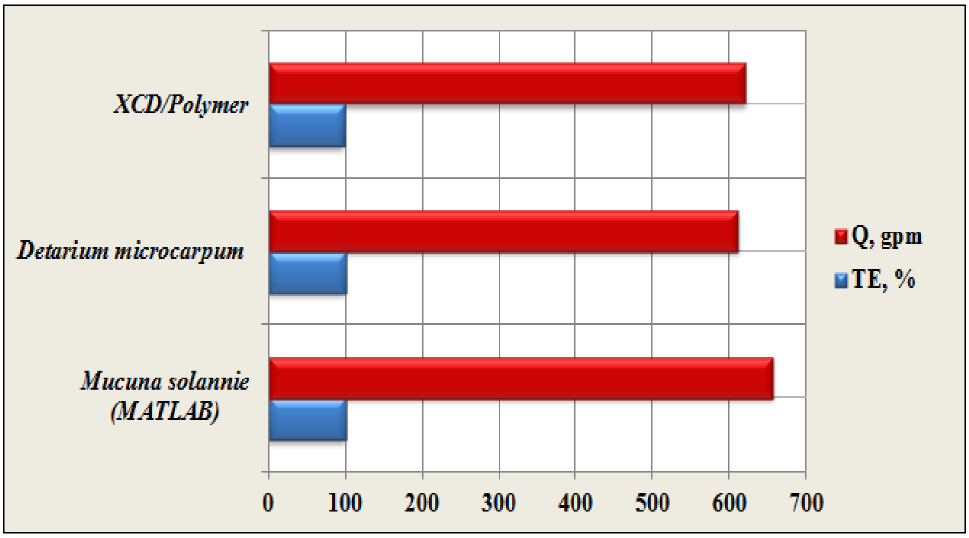

Fig. 3: *Comparison of Minimum Flow Rates Required to Achieve CC of 5.002 vol.% and Corresponding TE.*

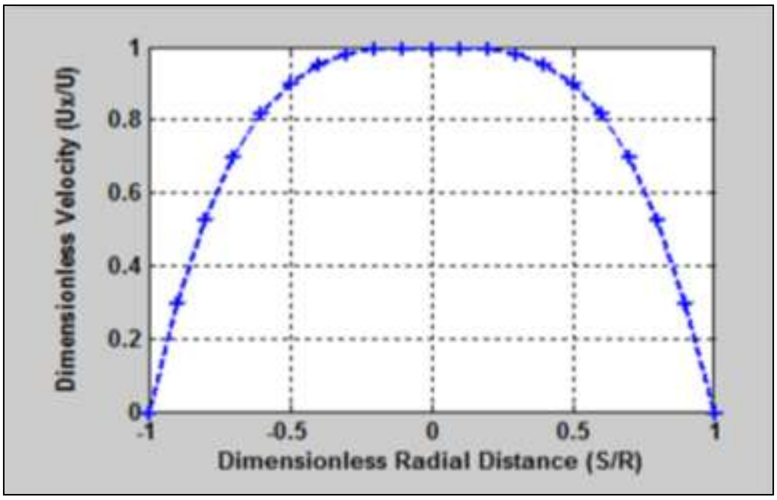

Fig. 4: *Velocity Profile in 12¼ in Hole Annulus (Generated from MATLAB).*

Table 8: *Parameters to Determine Hole Cleaning Effectiveness in Directional Well.*

Assumption: Drill pipe rotates @ 100 rev/min	Parameter	Value
	Density of mud	8.6 ppg
	ROP	50 ft/h
	Fluid Flow Rate	420 gpm
	Hole Inclination	40°
	Plastic Viscosity	11 cP
	Yield Point	3 lb/100ft^2
		12.4 lb/100ft^2

8½ in Hole Section (Directional Open Hole Section)

The RF, TI and ROP were determined to be about 1.10, 4.8 and about 8.2 ft/h with yield stress of 3 lb/100ft^2. Similarly, 1.05, 4.5 and 8.2 ft/h respectively were calculated with yield stress of 12.4 lb/100ft^2 for the H-B fluid. If Bingham-Plastic model is assumed to be the suitable model, with a true Bingham yield point of 37.5 lb/100ft^2, RF, TI and ROP would be about 1.25, 5.41 and 49 ft/h respectively.

DISCUSSION

For the 12¼ in hole, a minimum of 657 gpm fluid flow rate is required to maintain the CC of 5.002 vol.% and below. The flow rate could be below predicted value with drillstring rotation and other good oilfield practices. The velocity profile (Figure 4) indicates laminar flow regime in the annulus, and is a typical profile for non-Newtonian fluids. Hence, good hole cleaning is expected if other factors such as yield point and annular velocity etc. are appropriate.

Using cutting carrying index (CCI) as a basis for hole cleaning capability; with H-B yield stress (2.7 or 3 lb/100ft^2 from 3 rpm reading), poor hole cleaning was the result, while with the Bingham-Plastic yield stress (37.5 lb/100ft^2), a high value, good hole cleaning was observed. Observably, Bingham-Plastic overestimates yield point, while the H-B yield stress could be said to be a conservative estimate in its first approximation [32], a difference of about 92.8% from Bingham-Plastic model.

With H-B yield stress of 12.4 lb/100ft^2 using n=0.8 (Appendix A1), good hole cleaning is predicted with CCI of 1.12. With the numerical solution method, using the value of arbitrary acceptable error of 0.05, n and k values were 0.1832 and 35.04 respectively, which yielded a negative yield stress value of –46.43 lb/100ft^2. In this case, power law model behavior should be assumed, as the numerical procedure had problem fitting the data at the acceptable error value.

For the 8½ in section, the yield point is also assumed to be the 3 rpm viscometric reading. The yield point approximation is estimated to be 2.7 lb/100ft^2 [32]. The drilling rate predicted from the graph would be below the required drilling rate [23]. Also, about 8.2 ft/h drilling rate predicted from the graph would be below the required drilling rate of 50 ft/h if 12.4 lb/100ft^2 yield stress value is applied. Similarly, if Bingham-Plastic model is assumed to be the suitable model, the maximum ROP that can be sustained while still maintaining adequate hole cleaning would be about 49 ft/h at 40^o hole inclination. The drilling rate is also below the assumed required rate of 50 ft/h [33].

Hence, this lightweight mud might not be suitable for highly deviated wells. Increase in the mud weight, flow rate, use of viscous pills and other factors are necessary to influence cuttings transport. High fluid flow rate at the given mud weight might be required for adequate hole cleaning at the intended rate of drilling, which might result in washout and other problems [34]. Quantitatively measuring the cuttings return rate at the shakers, and comparing with the volume predicted from the ROP is a good operational practice. Observed transport should be 75 to 90% of theoretical values [35].

CONCLUSION

Determination of hole-cleaning capability of muds is dependent on yield-stress and other rheological parameters, and relies upon the model under consideration. Determination of accurate yield stress value is important in estimating the hole cleaning capability of muds in models where yield stress is a parameter. As there seems to be a zoo of yield stresses, comparison of laboratory data with actual field observations is paramount. The mud exhibited excellent cuttings carrying capability in the 12¼ in vertical well. The lightweight mud might not be suitable for highly deviated wells, unless other operational practices such as varying the flow rate, ROP, cuttings monitoring, use of viscous pills, and wiper trips are monitored.

CONFLICT OF INTEREST

No conflict of interest has been declared by the authors.

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Cite this Article
Uwaezuoke N, Onwukwe SI, Igwilo KC *et al*. Biopolymer Substitution and Impact on Cuttings Transport of a Lightweight Water-Based Drilling Fluid. *Journal of Petroleum Engineering and Technology*. 2017; 7(2): 54–64p.

APPENDIX

A.1 Numerical solution method for mud Herschel-Bulkley Yield Stress [29, 31]:

$$\tau_y = \left(\frac{\Sigma\tau_i \Sigma \dot{\gamma}_i^{2n} - \Sigma\tau_i \dot{\gamma}_i^{n} \Sigma \dot{\gamma}_i^{n}}{N\Sigma \dot{\gamma}_i^{2n} - \left(\Sigma \dot{\gamma}_i^{n} \right)^2} \right) \qquad \text{A.1.1}$$

$$k = \left(\frac{N\Sigma\tau_i \dot{\gamma}_i^{n} - \Sigma \dot{\gamma}_i^{n} \Sigma \tau_i}{N\Sigma \dot{\gamma}_i^{2n} - \left(\Sigma \dot{\gamma}_i^{n} \right)^2} \right) \qquad \text{A.1.2}$$

$$Err = \tau_y \left[\Sigma \dot{\gamma}_i^{n} \ln\left(\dot{\gamma}_i \right) \right] + k \left[\Sigma \dot{\gamma}_i^{2n} \ln\left(\dot{\gamma}_i \right) \right] - \left[\Sigma\tau_i \dot{\gamma}_i^{n} \ln\left(\dot{\gamma}_i \right) \right] \qquad \text{A.1.3}$$