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RHEOLOGICAL MODEL PARAMETERS FOR BENTONITE DRILLING MUD TREATED WITH LOCAL CASSAVA STARCH

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ABSTRACT

Rheological model parameters were determined for bentonite muds treated with two local cassava starches (TMS 98/0581 and M98/0068) and an imported starch. The parameters were that of Power Law, Casson and Herschel-Bulkley models which predict the shear stress - shear strain rate relationships. Physicochemical properties were determined for the starches. Herschel-Bulkley model provided the best correlation with experimental data, while Casson model was next. Correlation between Casson and Herschel models yield stresses was good. The yield stress was found to increase with increase in temperature and behaved differently with the starches. It was found to be highest at 1.0 percent of M98/0068 starch concentration in the bentonite mud system. However, the yield stress did not differ significantly for the mud system with TMS 98/0581 starch concentrations. For the imported starch, the yield stress was highest at 2.0 percent concentration at 80 ^{o}F and 120 ^{o}F, while it was highest at 0.5 percent at 150 ^{o}F and 190 ^{o}F. The yield stresses ranged between 3 and 30 Pa for the bentonite starch mud systems investigated. The model parameters predicted the shear stress - shear rate relationships for bentonite-local polymer drilling mud system and supported the utilization of the local cassava starches as drilling fluid additives.

Keywords: local cassava, rheological parameter, yield stress, starch, drilling mud.

1. INTRODUCTION

The science of deformation and flow of matter is described as rheology. It could be seen as the analysis of fluid viscosity behaviour under variable shear rate conditions. For a drilling mud, the properties that describe the flow characteristics under various conditions are called flow (or rheological) properties. Various viscosity regimes of fluids are used when drilling. Water or less viscous fluid may be used at the shallow part of the hole, but more viscous mud would be required for deeper depths (Xiuhua and Xiaochun, 2010). Viscosity is a measure of the internal resistance of a drilling fluid. The internal resistance (inertia) is a result of the attractions of molecules in a liquid, and is a measure of the combined effects of these attractions and the natural cohesion of suspended particles (IADC, 2000). In a circulating system, drilling fluid flows through various channels. Frictional drag, called shear stress, is exerted on the surfaces of the channel. The shear stress depends on the different velocities travelling in adjacent layers of the fluid. The difference in velocities between the layers is called shear rate. The relationship between the shear stress and shear rate depends on the behaviour of the fluid, which may be Newtonian or non-Newtonian.

Viscosity remains constant for all shear rates, provided temperature and pressure condition remain constant, for a Newtonian fluid (Skalle, 2011). It simply implies that the shear stress and shear rate measured at any point in the process could be used to predict the behaviour of the fluid at other points in the process provided that there is no change in temperature. Viscosity is the ratio of the shear stress to shear rate. The shear stress of the fluid is constantly proportional to the shear rate. For non-Newtonian fluid, the ratio of shear stress to shear rate at one point is not the same as that at another point. This viscosity is described as effective viscosity. The viscosity could be high or low with increase in shear rate. A condition when viscosity is high at low shear rates and decreases with increasing shear rate is known as shear thinning (Xie and Jin, 2015). However, when the viscosity is high at low shear rate and increasing with increasing shear rate, the phenomenon is known as shear thickening. When solids are added to a Newtonian fluid they become Non-Newtonian fluids as in the case of drilling fluid.Non-Newtonian fluids are classified into time independent and time dependent. Bingham plastics and pseudoplastics and dilatant fluids are time independent, while thioxotropic and rheopectic fluids are time dependent.

Rheological models predict the viscous behaviours of non-Newtonian fluids, including drilling fluids. Some of the non-Newtonian constitutive equations are Power law, Bingham Plastic, Herskel-Bulkley, Casson, Carreau and Cross equation (Mackley, 2011). Vipulanandan and Mohammed (2014) used a proposed hyperbolic model to predict the relationship between shear stress and shear rate of polymer modified bentonite drilling mud. The model established better relationship when compared to Herschel-Bulkley and Casson rheological models. The influences of drilling fluid composition to the models parameters were evaluated. In Kevin and Bala (2014) work, Herskel-Bulkley model was used to relate the rheological properties of muds formulated from commercial polymers and polymers from local plant sources. The yield stresses evaluated from the model was used to process the hole cleaning property of mud formulated from the local plant. One advantage of the model was that it described the behaviour of drilling fluid reasonably and indicated the yield stress at very low shear

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rates. While investigating the use of low polymer weight synthetic polymers on the rheological properties of bentonite/water suspension, Rossi *et al.* (1997) fitted the shear stress - shear rate curves to Herschel-Bulkley and Bingham models. Yield stress is the critical shear stress limit with which a fluid can flow. It is the force required to start pumping the drilling mud in the circulation process. The yield stress is responsible for suspending the cuttings when circulation is stopped.

Mepba and Ademiluyi (2007), in relating the rheological characterization of coconut milk yoghurts, used the power law model to relate the viscosity and rotational speed of the viscometer. The consistency coefficient was found to have strong dependency on temperature. The power law was also used in evaluating the quality and influence of Moroccan prickly pear juice (Dehbi *et al.*, 2013). Models relating the flow index behaviour and consistency coefficient to temperature were established and thus characterized the juice as a non-Newtonian fluid. Xie *et al.* (2009) used Power Law to relate the rheological properties of corn starch at different amylose content. Cross rheological equation was used by Xie and Jin (2015) to predict the rheological behaviour of non-Newtonian flows for dam break flow problems. Experiment based method was used to determine the rheological parameters in the equation. The model developed provided a reliable prediction for viscous behaviours in water-kaolin and water-clay mixtures. Starch is mainly used as effective colloids, which decreases the filtration of all kinds of water dispersing drilling fluids and increases the viscosity.

Starch viscosity is largely influenced by the granule shape and swelling power, amylopectin-amylose entanglement and amylose/amylopectin interactions (Omojala, 2013). Starch viscosity changes with temperature. Starch grains possess a hard outer cell wall made from a polysaccharide called amylopectin and inside the shell are bundles of a linear, coiled polysaccharide, called amylose. The linear amylose glucose units are linked via 1, 4 linkages (Figure-1), and the branched amylopectin units are linked via 1, 6 linkages (Figure-2) (Dias, 1999). The water-swellable amylose enables starch to exhibit fluid loss control properties.

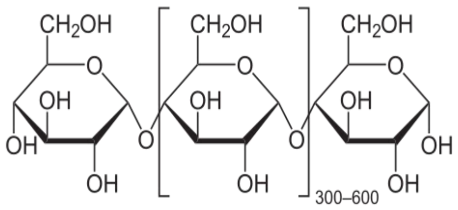

Figure-1. Structure of amylose.

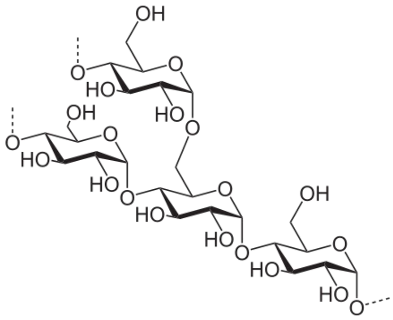

Figure-2. Structure of amylopectin.

Cassava *(ManihotesculentaCrantz)* is a root crop cultivated in many tropical countries including Nigeria, the largest producer of cassava. World production of cassava root was estimated to be 252 million tonnes in 2011 (FAO, 2013). Approximately 65 percent of all cassava produced is used for human consumption, 25 percent for industrial use and 10 percent is lost as waste (Maziya-Dixon, 2005). The Industrial uses of cassava starch are based on its properties and suitability to different purposes: in paper and paper tapes; in textiles industry; as dye stuff; in building, metal and chemical industries; as adhesives and as drilling mud, (Omotioma *et al.,* 2012). Cassava starch has some characteristics, including high paste viscosity, high paste clarity, and high freeze-thaw stability, which calls for increase in the utilization of cassava. Local cassava polymers have been investigated as additive in drilling fluid. Polymers extracted from different cassava cultivars exhibited encouraging rheological and fluid loss control properties in drilling fluids (Idris and Ismail, 1997; Ademiluyi *et al.*, 2011; Egun and Abah, 2013;Samavati *et al.*, 2014; Omotioma *et al.*, 2015). The combination of local cassava polymer and carboxyl methyl cellulose (CMC) provided better rheological and fluid loss control properties in laboratory formulated drilling mud (Oriji and Joel, 2012). The physicochemical properties of local cassava starches differ from one another and differ from other polymers used in drilling fluid. Understanding the rheological behaviour of drilling fluid treated with local cassava polymers would facilitate the use of these local materials in the drilling industry. This study determined parameters of constitutive rheological models that predict shear stress - shear rate relationship for bentonite drilling mud treated with local cassava starches.

2. NON-NEWTONIAN MODELS

Rheological model equations are fitted to experimental data of mud systems to predict shear stress/ apparent viscosity and shear strain rate relationships and provide information on the suitability of the mud for drilling operation. A plot of shear stress and shear rate is known as consistency curve (Xiuhua and Xiaochun, 2010). The rheological models - Power Law, Herschel-Bulkley and Casson models were used in fitting the data derived from the rheological tests. The viscosities at various rotational speeds were converted to shear rate and shear

stress in other to fit the model equations to predict the shear stress and shear strain relationship.
The shear rate (Pa) is given by:

$$\dot{\gamma} = RPM\ x\ 1.703 \quad (1)$$

Shear rate is given by:

$$\tau = \theta\ x\ 1.065 \quad (2)$$

Where θ is the viscosity dial reading at various shear rates.

2.1 Power law model

The Power Law model expresses the relationship between shear stress (τ) and shear strain rate ($\dot{\gamma}$) of a fluid exhibiting non-Newtonian behaviour (Shah *et al.*, 2010). It could also be expressed in terms of apparent viscosity (η_a) and shear strain rate ($\dot{\gamma}$). Mathematical expressions are given as:

$$\tau = k_{PL}\dot{\gamma}^{n_{PL}} \quad (3)$$

$$\eta_a = k_{PL}\dot{\gamma}^{(n_{PL}-1)} \quad (4)$$

Where, n_{PL} is the flow behaviour index and k_{PL} is the consistency coefficient. While k_{PL} corresponds to the viscosity of a Newtonian fluid, n_{PL} shows the degree of departure from Newtonian fluid. When n >1, the fluid is said to exhibit shear thickening effect. For n<1, the fluid exhibit shear thinning effect and for n=1, the fluid exhibit Newtonian behaviour. A fluid exhibits shear thinning behaviour when the apparent viscosity decreases with increase in shear rate.

2.2Casson model

The Casson model favours drilling fluid, even though it was originally modeled for ink pigments (Vipulandan and Mohammed, 2014). This model, like the Herschel-Bulkley model is a hybrid between Bingham and Power law models. It is a two parameter model expressed as:

$$\tau^{0.5} = \tau_{yCS}^{0.5} + k_{CS}^{0.5}\dot{\gamma}^{0.5} \quad (5)$$

Where, τ_{yCS} is yield stress and k_{CS} is the model constant

2.3 Herschel-bulkley model

This model was described as a modified power law model and is said to be a combination of Newtonian, Power Law and Bingham plastic models. It encompasses the yield behaviour of a non-Newtonian fluid and shear thinning ((Xiuhua and Xiaochun, 2010). The shear stress,τ is expressed in terms of shear strain rate, $\dot{\gamma}$ as (Rao, 2014):

$$\tau = \tau_{yHB} + k_{HB}\dot{\gamma}^{nHB} \quad (6)$$

Where, τ_{yHB} is yield stress, k_{HB} is correction parameter, and n_{HB} is flow behaviour index.

3. MATERIALS AND METHODS

Local cassava cultivars, TMS 98/0581 and M98/0068, were procured from and processed at National Root Crop Research Institute (NRCRI), Umudike, Nigeria. An imported starch was provided by POCEMA Limited. The physicochemical properties determinations of the starches were conducted in the laboratories of NRCRI.

3.1 Cassava starch extraction

Cassava starches for TMS 98/0581 and M98/0068 were extracted as described by Eke *et al.* (2007). Fresh tubers of cassava cultivars were washed to remove dirts. The brown surface layers were peeled with stainless steel knife. Peeled cassava tubers were washed with portable water to remove dirt and sand particles and subjected to grating. The mixture of grated cassava in water was filtered through a fine mesh sieve (muslin cloth). The filtrate was allowed to settle for 6 hours. Then the supernatant was decanted, while the sediment was washed three times with portable water to obtain a white, odourless and tasteless starch. The wet starch was thinly spread on a flat stainless metal and sun dried for 6 hours. It was then dried in an oven for about 6 hours to constant weight. Dried starch was milled to fine particles.

3.2 Physicochemical properties determination

The local cassava starches and the imported starch were analyzed for physicochemical properties. Starch content, amylose content, water absorption capacity, swelling power and solubility index were determined by the methods described by Onitilo *et al.* (2007).

3.3 Bentonitemud formulation

Bentonite mud was formulated, according to API 13A (2010) specification, with starch treatment. 22.5g of bentonite with 0.5 percent starch (dry weight of bentonite) was weighed with “A and D” electronic weighing balance (model FX-5000i) and added to 350ml of distilled water in a beaker while stirring with Hamilton Beach mixer. The suspension was stirred for 5 minutes. The beaker was removed from the mixer and the sides were scrapped with spatula to dislodge bentonite polymer clinging to the walls of the beaker. The mixer was further used to stir the suspension for another 15 minutes and the spatula was used to dislodge the solids from the walls of the beaker every 5 minutes. The formulations were repeated with starch treatment of 1.0 and 2.0 percent respectively. The starches were TMS 98/0581 (local cassava), M98/0068 (local cassava) and imported starch. The imported starch served as control. The bentonite muds formulated with these starches irrespective of the concentrations were described as contained in Table-1.The suspensions were then subjected to rheological tests.

Table-1. Mud type and starch additive.

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S. No.	Mud type	Starch type
1	Mud A	Imported starch (control)
2	Mud B	TMS 98/0581 (local cassava)
3	Mud C	M98/0068 (local cassava)

3.4 Rheology tests

The bentonite-starch suspensions were poured into the viscometer cup and subjected to shear in model 800 OFITE 8-speed viscometer. The shear was done at 600, 300, 200, 100, 60, 30, 6, and 3 rpm respectively. At each rotation speed the dial reading was taken when the speed of rotation was stabilized. The rheology test was conducted for each sample at 80 ^oF, 120 ^oF, 150 ^oF and 190^oF. The shear rate and shear stress information were derived from the data collected and used for determination of rheological model parameters.

3.5 Model parameter determination and validation

The parameters for the nonlinear constitutive rheological models (equations 3, 5 and 6) were determined using EXCEL SOLVER. Validation was done with root mean square error (RMSE) as defined in equations (7) (Vipulanandan and Mohammed, 2014) and coefficient of determination (R^2), using SPSS statistical software 23.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{N}} \quad (7)$$

Where y_i is the measured value, x_i is the model calculated value, $\bar{y}$ is the mean of the measured value and $\bar{x}$ is the mean of the model calculated value.

4. RESULTS AND DISCUSSION

4.1 Physicochemical properties of starches

Cassava cultivars starches, as well as the imported starch, differ in their physicochemical properties. Some properties of TMS 98/0581 and M98/0068 are provided in Table 2. The starch content, amylose content and swelling power are within the ranges reported by Onitilo *et al.* (2007) and Eke *et al.* (2007), while water absorption capacity and solubility did not differ significantly. The solubility of starch of different cassava cultivars varies. The swelling capacities of starches were reported to increase with increase in temperature (Oludare and Macdonald, 2010).

4.2 Rheological models comparison and model parameters estimates

The rheological model parameters (Tables 3, 4 and 5) were determined to predict the shear stress - shear rates relationships for muds A, B and C, formulated with the imported starch, TMS 98/0581, M98/0068 and respectively. The parameters were determined for the three rheological models investigated -Power law, Herschel-Bulkley and Casson. From the coefficient of determinations, R^2, Herchel-Bulkley model gave the closest prediction and Casson model was the next. The RMSE for Herchel-Bulkley model was the lowest, while Power Law model was the highest. In Vipulanandan and Mohammed (2014), the RMSE for Herchel-Bulkley model was lower than the Casson model. Figures 3, 4 and 5 show shear stress - shear rate relationships for bentonite mud systems with imported starch, TMS 98/0581 starch and M98/0068 starch respectively, at 80^oF, 120^oF, 150^oF and 190^oF.

Table-2. Physicochemical properties of starches.

Starch	Starch content (%)	Amylose content (%)	Amylopectin content (%)	Water absorption capacity (g/g)	Swelling power (%)	Solubility index (%)	pH
TMS 98/0581	80.46 ± 0.01	22.45 ± 0.02	77.55 ± 0.02	1.80 ± 0.01	9.21 ± 0.01	3.12 ± 0.03	6.10 ± 0.02
M98/0068	81.25 ± 0.01	23.73 ± 0.02	76.27 ± 0.02	1.98 ± 0.01	10.51 ± 0.01	1.31 ± 0.01	6.24 ± 0.01
Imported starch	94.40 ± 0.02	26.40 ± 0.10	73.70 ± 0.02	1.60 ± 0.10	6.30 ± 0.10	7.17 ± 0.15	6.37 ± 0.06

Table-3. Rheological model parameters for mud A (imported starch).

Polymer	Temp	Power law model				Casson model				Herschel-Bulkley model				
(%)	°F	k_{PL} (Pas^n)	n_{PL}	RMSE (Pa)	R^2	τ_{yCS} (Pa)	k_{CS} (Pas^{-1})	RMSE (Pa)	R^2	τ_{yHB} (Pa)	k_{HB} (Pas^n)	n_{HB}	RMSE (Pa)	R^2
0.5	80	7.50	0.24	2.58	0.92	13.15	0.009	0.60	1.00	14.08	0.32	0.65	0.64	1.00
	120	9.07	0.21	2.23	0.93	14.63	0.007	1.04	0.98	14.31	0.58	0.55	1.01	0.99
	150	13.87	0.16	2.34	0.91	20.05	0.005	2.04	0.93	17.05	1.58	0.41	1.73	0.95
	190	23.49	0.10	2.35	0.87	28.81	0.003	1.29	0.96	29.48	0.33	0.59	1.32	0.96
1.0	80	2.81	0.31	1.54	0.94	5.95	0.007	0.35	0.98	6.13	0.26	0.63	0.91	0.98

	120	3.29	0.29	0.67	0.99	6.69	0.006	0.34	0.97	3.59	1.35	0.40	0.43	1.00
	150	5.89	0.20	1.63	0.90	9.32	0.004	0.35	0.98	9.65	0.23	0.61	0.67	0.98
	190	11.59	0.12	2.25	0.76	14.84	0.002	1.10	0.94	16.20	0.07	0.77	0.91	0.96
2.0	80	3.71	0.31	1.91	0.95	8.03	0.009	0.75	0.99	8.13	0.36	0.62	0.65	0.99
	120	2.94	0.32	1.37	0.96	6.42	0.008	0.49	1.00	6.19	0.36	0.59	0.36	1.00
	150	4.09	0.26	1.58	0.94	7.72	0.006	0.82	0.98	7.53	0.36	0.58	0.73	0.99
	190	11.65	0.15	2.45	0.83	15.84	0.004	0.90	0.98	17.29	0.12	0.73	0.69	0.99

Table-4. Rheological model parameters for Mud B (TMS 98/0581 starch).

Polymer	Temp.	Power law model				Casson model				Herschel-Bulkley model				
(%)	°F	k_{PL} (Pas^n)	n_{PL}	RMSE (Pa)	R^2	τ_{yCS} (Pa)	k_{CS} (Pas^{-1})	RMSE (Pa)	R^2	τ_{yHB} (Pa)	k_{HB} (Pas^n)	n_{HB}	RMSE (Pa)	R^2
0.5	80	9.22	0.19	2.38	0.89	14.15	0.006	0.54	0.99	15.30	0.22	0.67	0.46	1.00
	120	10.68	0.18	1.76	0.94	16.09	0.005	1.02	0.98	14.55	0.95	0.47	0.83	0.99
	150	10.01	0.20	2.10	0.93	15.69	0.006	0.99	0.99	14.94	0.71	0.52	0.89	0.99
	190	20.73	0.10	3.07	0.73	24.86	0.003	1.33	0.95	27.52	0.02	0.97	0.39	1.00
1.0	80	9.65	0.18	2.50	0.86	14.24	0.005	0.88	0.98	15.55	0.16	0.70	0.75	0.99
	120	8.60	0.20	2.18	0.92	13.60	0.006	0.65	0.99	14.19	0.32	0.62	0.69	0.99
	150	10.26	0.17	3.30	0.79	14.87	0.005	1.34	0.96	17.50	0.04	0.90	0.61	0.99
	190	16.85	0.11	2.54	0.80	21.04	0.003	0.91	0.97	22.81	0.08	0.78	0.58	0.99
2.0	80	7.95	0.20	2.40	0.89	12.67	0.006	0.95	0.98	13.43	0.26	0.64	0.87	0.99
	120	11.62	0.15	2.26	0.86	16.06	0.004	0.56	0.99	17.20	0.17	0.68	0.39	1.00
	150	12.18	0.15	2.75	0.82	16.76	0.004	1.07	0.97	18.50	0.11	0.76	0.82	0.98
	190	17.72	0.11	2.62	0.81	22.28	0.003	1.03	0.97	23.85	0.12	0.73	0.85	0.98

Table-5. Rheological model parameters for Mud C (M/98/0068 starch).

Polymer	Temp.	Power law model				Casson model				Herschel-Bulkley model				
(%)	°F	k_{PL} (Pas^n)	n_{PL}	RMSE (Pa)	R^2	τ_{yCS} (Pa)	k_{CS} (Pas^{-1})	RMSE (Pa)	R^2	τ_{yHB} (Pa)	k_{HB} (Pas^n)	n_{HB}	RMSE (Pa)	R^2
0.5	80	7.39	0.22	2.17	0.92	12.29	0.007	0.39	1.00	13.02	0.29	0.64	0.40	1.00
	120	8.80	0.19	2.69	0.86	13.50	0.006	0.90	0.98	15.17	0.13	0.75	0.68	0.99
	150	10.47	0.16	2.46	0.85	14.82	0.004	0.68	0.99	16.51	0.10	0.76	0.32	1.00
	190	13.70	0.13	2.05	0.87	18.08	0.003	0.65	0.99	18.99	0.20	0.65	0.61	0.99
1.0	80	9.95	0.19	2.17	0.92	15.33	0.006	0.37	1.00	15.56	0.43	0.59	0.33	1.00
	120	10.00	0.19	2.28	0.91	15.29	0.006	0.54	1.00	15.93	0.33	0.62	0.56	1.00
	150	13.14	0.15	2.50	0.87	18.17	0.004	0.48	1.00	19.60	0.18	0.70	0.23	1.00
	190	21.27	0.09	2.72	0.76	25.39	0.002	1.14	0.96	27.51	0.05	0.85	0.69	0.99
2.0	80	8.15	0.19	2.63	0.84	12.40	0.005	0.92	0.98	14.19	0.09	0.79	0.57	0.99
	120	9.70	0.16	2.63	0.79	13.54	0.004	1.09	0.96	15.54	0.05	0.86	0.65	0.99
	150	9.56	0.17	2.50	0.84	13.86	0.005	0.85	0.98	15.55	0.10	0.77	0.59	0.99
	190	12.29	0.14	2.26	0.86	16.63	0.004	0.82	0.98	18.19	0.11	0.74	0.70	0.99

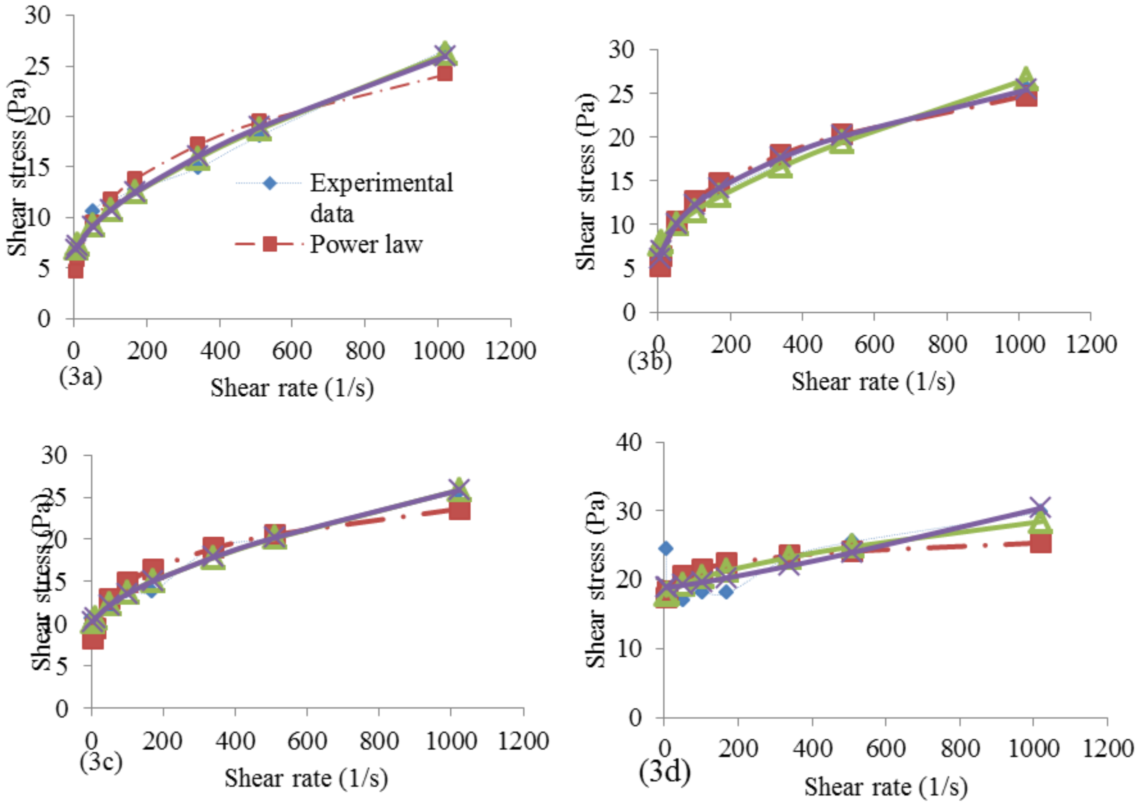

Figure-3. Rheology models predictions for bentonite mud with imported starch at (a) 80 °F, (b) 120 °F, (c) 150 °F and (d) 190 °F.

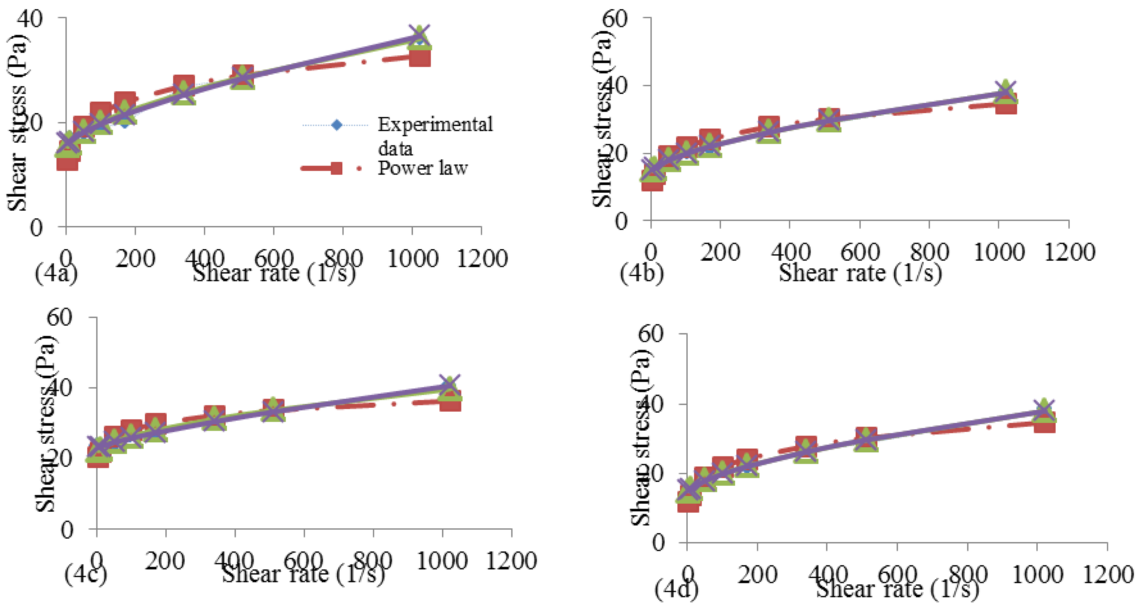

Figure-4. Rheology models predictions for bentonite mud with TMS 98/0581 starch at (a) 80 °F, (b) 120 °F, (c) 150 °F and (d) 190 °F.

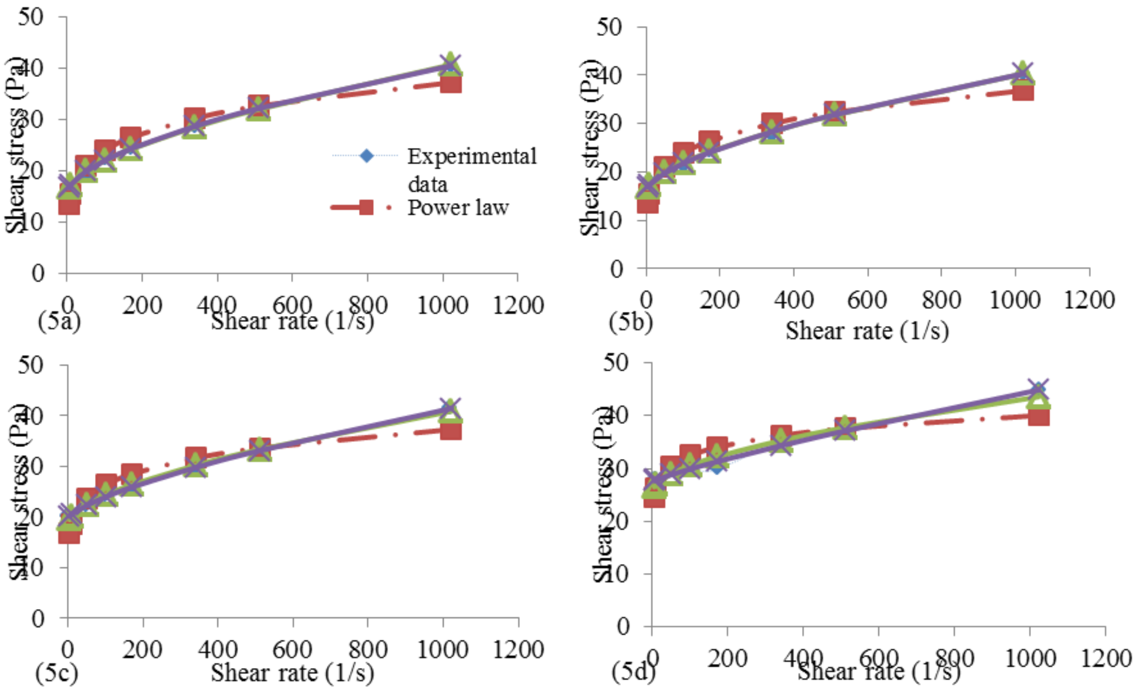

Figure-5. Rheology models predictions for bentonite mud with M98/0068 starch at (a) 80 °F, (b) 120 °F, (c) 150 °F and (d) 190 °F.

4.2.1Power law model

Mud A (Imported starch)

For the polymer concentrations of 0.5, 1.0 and 2.0 percent, the consistency coefficient (k_{PL}) increased with increased in temperature for all the concentrationsand ranges between 2.81 to 23.49 Pa.s^n. High consistency coefficient indicates high shear stress (Equation 3). Consistency coefficients were lower at 1.0 and 2.0 percent starch concentration, which indicate lower shear stress than 0.5 percent starch treatment of mud. The flow behaviour indexn_{PL}, ranges from 0.1 to 0.31. Previous report for potato starch modified system at 77°F provided flow behaviour index of 0.074 (Alsabagh *et al.,* 2014). The mud systems exhibited non-Newtonian behaviours and shear thinning, as the values of flow index behaviour were less than unity (n_{PL}<1). The lower the flow behaviour index the more non-Newtonian, the mud. R^2 ranged from 0.76 to 0.99. Root mean squared error (RMSE) ranged from 0.67 to 2.58 Pa.

Mud B (TMS 98/0581 starch)

For mud B, the consistency coefficient ranged from 7.95 to 20.73 Pa.s^n at temperatures between 80 °F and 190 °F and starch concentration between 0.5 and 2.0 percent. At each concentration, consistency coefficient for 190 °F was significantly different from that of 80 °F, 120 °F and 150 °F. This was due to changes in the property of starch with temperature increase. Native starch gelatinized from 143 °F and the granules swell (Adejumo *et al*., 2011). Continued swelling of the granules increases the viscosity of the mud systems. The consistency coefficient was higher at 1.0 percent than in other concentrations. Hence 1.0 percent starch concentration gave the highest shear stress to the mud systems. The consistency coefficient at 1.0 and 2.0 percent were not significantly lower than 0.5 percent starch concentration, in contrast to mud A condition. The flow behaviour index for Mud B ranged from 0.1 to 0.2, indicating a high pseudoplastic fluid. n_{PL} = 0.2 was 35 percent lower to that of mud A. $R^2$for the model parameters determined, ranged from 0.73 to 0.94, while RMSE ranged from 1.76 to 3.30.

Mud C (M98/0068 starch)

The consistency coefficient increased with increase in temperature for starch concentrations of 0.5 to 2.0 percent, similar to what was observed in mud A. The consistency coefficient was between 7.39 and 21.27 Pa.s^n. 1.0 percent starch provided the highest consistency coefficient and shear stress in this mud system. The lowest flow behaviour index was 0.09, indicating more non-Newtonian mud, while the highest value was 0.22. The flow index behaviour decreased with increase in temperature. R^2 for these model predictions ranged from 0.76 to 9.92 and RMSE was between 2.046 and 2.716 Pa.

4.2.2 Cassonmodel

Mud A (imported starch)

Casson yield stress for mud A ranged from 5.95 to 28.81 Pa. The highestyield stress was found in 0.5 percent starch concentration. The yield stress increased with temperature, which means a corresponding increase in shear stress. Yield stress is responsible for the annular hole cleaning during drilling operation. Poor hole cleaning would result to differential sticking and reduction in penetration rate (Kevin and Bala, 2014). The model constant, (k_{CS}) ranged from 0.002 to 0.009 Pa.s^{-1}. R^2 and RMSE ranges were 0.93 to 1.0 and 0.34 to 2.04 respectively. The prediction of Casson model was better than that of Power Law, due to higher R^2 ranges.

Mud B (TMS 98/0581 starch)

The yield stress for mud A ranged from 12.67 to 24.86 Pa. The lowest yield stress was 53 percent more than the lowest yield stress for mud A, while the highest value was 14 percent lower than that of Mud A. The yield stresses in this mud type was highest at 0.5 percent than other concentration. The model constant lowest and highest values were 0.003 and 0.006 Pa.s^{-1} respectively. R^2 ranged from 0.95 to 0.99 and RMSE was between 0.54 and 1.34 Pa.

Mud C (M98/0068 starch)

The yield stress in Mud C ranged from 12.29 to 25.39 Pa. The yield stress was highest at 1.0 percent concentration, which means M98/0068 is best applied at 1.0 percent (dry bentonite weight). The trend showed an increase in yield stress with increase in temperature. For deeper wellbore condition with increasing temperature, Ofei (2016) postulated that higher yield stress is better than lower yield stress for transportation of cutting. The model constant, k_{CS}, ranged from 0.003 to 0.007 Pa.s^{-1}, similar to that obtained for Mud B. The R^2 ranged from 0.96 to 1.0 and RMSE ranged from 0.37 to 1.14 Pa.

4.2.3Herchel-bulkley model

Mud A (imported starch)

Yield stress was lowest (3.587) for 1.0 percent polymer and 120°F and highest (29.484 Pa) at 0.5 percent and 190°F. The model prediction for same data was 0.46 percent below the lowest yield stress predicted in Casson model and 2.32 percent above highest predicted by Casson model. The R^2 and RMSE ranged from 0.95 to 1.0 and 0.32 to 1.73 Pa respectively. The correction parameter, k_{HB} ranged from 0.07to 1.58 Pa.s^n, while the flow behaviour index,n_{HB} ranged from 0.4 to 0.77. Kevin and Bala (2014) observed flow index behaviour for polymer muds between 0.4 and 0.5. They also informed that n_{HB} is usually between 0.4 and 0.5 for non-dispersed mud and 0.7 and 0.9 for highly dispersed mud. The lower the flow behaviour index the more shear thinning property for hole cleaning (Vipulanandan and Mohammed, 2014).

Mud B (TMS 98/0581 starch)

Yield stress, τ_{yHB} lowest and highest were 13.43 Pa and 27.52 Pa respectively. The lowest was 6 percent above that predicted by Casson model, and the highest was 11 percent above Casson model prediction. Herschel-Bulkley model predictions were closer to the experimental data. R^2 was between 0.98 and 1.00, while RMSE was between 0.39 and 0.89. The correction parameter ranged from 0.02 to 0.95 Pa.s^n. Flow behaviour index range was between 0.47 and 0.97. It was reported that cutting transportation is faster in low flow behaviour index value (Ofei, 2016).

Mud C (M98/0068 starch)

Yield stress was lowest (13.02 Pa) for 0.5 percent starch and 80 °F and highest (27.51 Pa) at 1.0 percent and 190 °F. The correction parameter, k_{HB} ranged from 0.05 to 0.43 Pa.s^n. The flow indices n_{HB} range from 0.59 to 0.86. The R^2 and RMSE ranged from 0.99 to 1.0 and 0.23 to 0.70 Pa respectively.

R^2 have higher values in the Herschel-Bulkley model than the Casson model. The RMSEs in Herschel-Bulkley model were lower than the Casson model. Itmeans that Herschel-Bulkley model is a better model than the Casson model in predicting drilling mud treated with local cassava starch. Both models were better in predicting shear stress - shear rate relationship than the Power Law model. Figures 3 and 4 show comparison of each of the three models and the experimental data for bentonite muds treated with imported starch, TMS 98/0581 starch and M98/0068 starch respectively.

4.2.4 Yield stress predictions using casson and herschel-bulkley model

The yield stress is critical for drilling operation. Borehole cleaning, surge of pressures and penetration rate are impacted by the yield stress (Ofei, 2016). Casson and Herschel-Bulkley models have the yield stress term. The yield stress is lowest at 1.0 percent at 80°F and 120°F, for Mud A (imported starch), but decreased with increase in concentration at 150 °F and 190 °F (Figure 6a). For the Mud C (M98/0068), the yield stresses were highest at 1.0 percent polymer (Figure-6c). However, Mud B (TMS 98/0581) differs such that there were no significant differences in the yield stresses at 0.5, 1.0 and 2.0 starch concentrations (Figure-6b). The study showed a relationship in the yield stress values. The yield stresses of Casson and Herschel-Bulkley models showed good correlations with the experimental values (Figures 7a to c). The yield stress correlation from 80°F to 190°F between Herschel-Bulkley and the experimental results were 0.972 (Mud A), 0.991 (Mud B) and0.978 (Mud C), while that ofCasson model were 0.999 (Mud A), 0.996 (Mud B) and 0.918 (Mud C). Herschel-Bulkley model gave better estimate of the yield stress than the Casson model. Rossi *et al.* (1997) observed that Herschel-Bulkley model gave better estimate than Bingham model. Vipulanandan and Mohammed (2014) observed that the yield stress for bentonite drilling fluid varies from 0 to 28 Pa. The yield stresses for the muds formulated with the local cassava polymers were within this range. However Mud A at 190°Fhad yield stress up to 29.84 Pa.

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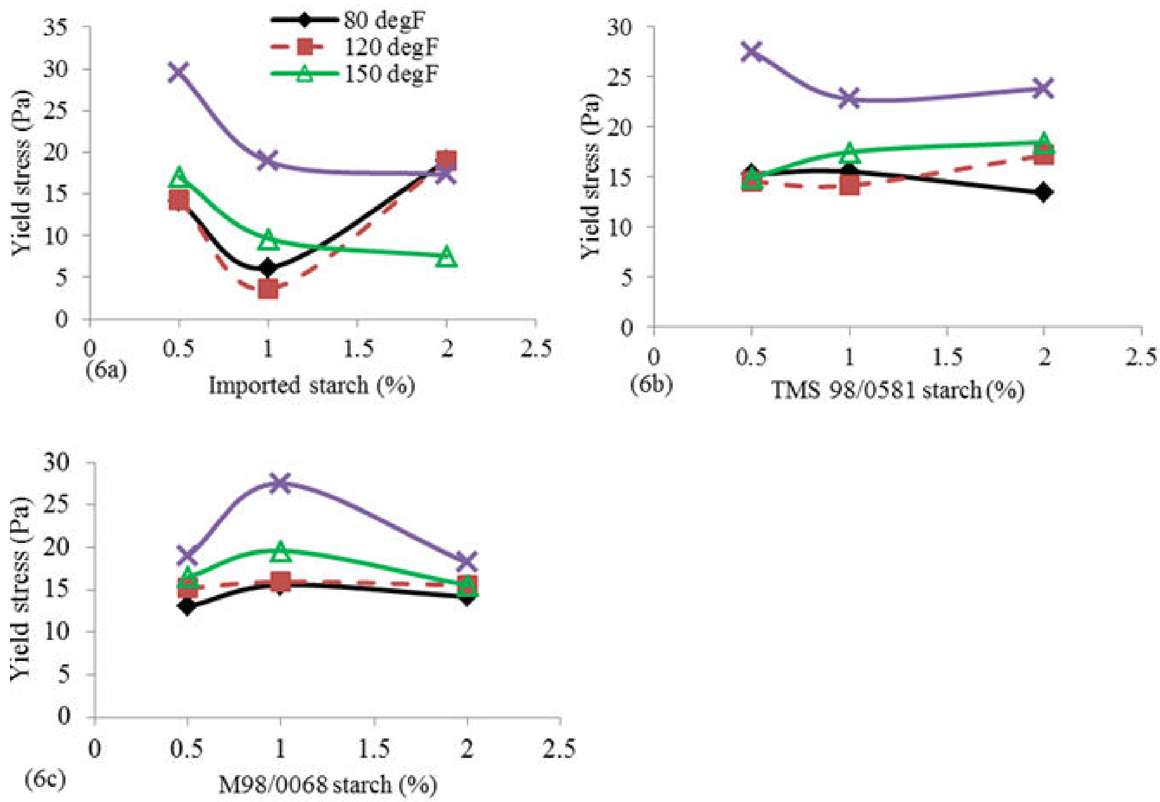

Figure-6. Variation of yield stress of bentonite mud with (a) imported starch (b) TMS 98/0581 starch and (c) M/98/0068starch at different temperatures.

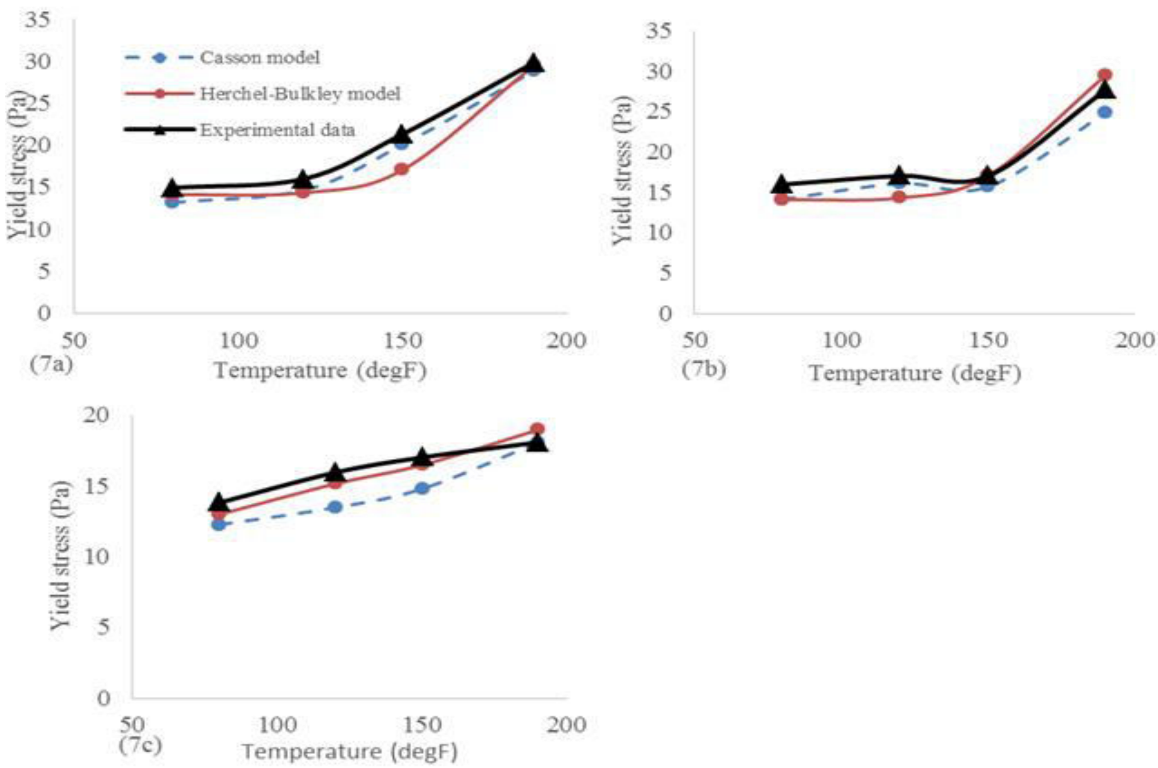

Figure-7. Comparison of yield stress between rheological models and experimental data for mud with (a) imported starch (b) TMS 98/0581 starch and (b) M98/0068 starch.

5. CONCLUSIONS

The parameters of three rheological models, Power Law, Casson and Herschel-Bulkley were determined to predict the shear stress - shear rate relationship for bentonite-starch muds. The starches were extracted from local cassava cultivars, TMS 98/0581 and M98/0068, while an imported starch was procured. Some physicochemical properties of the starches were determined. The Herschel-Bulkley model prediction was the best, while Casson model was better than the Power Law model, based on the coefficient of determination. The yield stress evaluated ranged between 3 to 30 Pa, which is around the range reported for bentonite drilling fluid. It was observed that the yield stress increased with increase in temperature. However, the yield stress variation with the cassava starch concentrations differs. The yield stress was highest at 1.0 percent starch concentration than 0.5 and 2.0 percent for M98/0068, while the yield stresses for TMS 98/0581 starch concentrations were not significantly different. For the imported starch, the yield stress was highest at 2.0 percent concentration at 80 ^{o}F and 120 ^{o}F, while it was highest at 0.5 percent at 150 ^{o}F and 190 ^{o}F. The yield stresses of the experimental data compared to Casson and Herschel-Bulkley models have good correlations. The model parameters obtained in this study could predict the shear stress - shear rate relationship for bentonite mud system treated with local cassava polymers.

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